

*WTEC Panel on*

## **SPIN ELECTRONICS**

# **Final Report**

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## **WTEC Panel on Spin Electronics (“Spintronics”)**

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# ABSTRACT

This report is a comparative review of spin electronics (“spintronics”) research and development activities in the United States, Japan, and Western Europe conducted by a panel of leading U.S. experts in the field. It covers materials, fabrication and characterization of magnetic nanostructures, magnetism and spin control in magnetic nanostructures, magneto-optical properties of semiconductors, and magnetoelectronics and devices. The panel’s conclusions are based on a literature review and a series of site visits to leading spin electronics research centers in Japan and Western Europe. The panel found that Japan is clearly the world leader in new material synthesis and characterization; it is also a leader in magneto-optical properties of semiconductor devices. Europe is strong in theory pertaining to spin electronics, including injection device structures such as tunneling devices, and band structure predictions of materials properties, and in development of magnetic semiconductors and semiconductor heterostructures. The United States is a leader in optoelectronics including optical detection and injection, as well as novel instrumentation — e.g., ballistic electron magnetic microscopy (BEEM). The United States is also the international leader in applications including read heads, magnetic random access memory (MRAM), sensors, and magnetic device production. Additional details are included in an executive summary conveying the panel’s overall conclusions.

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## PREFACE

The history of scientific research and technological development is replete with examples of breakthroughs that have advanced the frontiers of knowledge, but seldom does it record events that constitute paradigm shifts in broad areas of intellectual pursuit. One notable exception, however, is that of spin electronics (also called spintronics, magnetoelectronics or magnetronics), wherein information is carried by electron spin in addition to, or in place of, electron charge. It is now well established in scientific and engineering communities that Moore's Law, having been an excellent predictor of integrated circuit density and computer performance since the 1970s, now faces great challenges as the scale of electronic devices has been reduced to the level where quantum effects become significant factors in device operation. Electron spin is one such effect that offers the opportunity to continue the gains predicted by Moore's Law, by taking advantage of the confluence of magnetism and semiconductor electronics in the newly emerging discipline of spin electronics.

From a fundamental viewpoint<sup>1</sup>, spin-polarization transport in a material occurs when there is an imbalance of spin populations at the Fermi energy. In ferromagnetic metals this imbalance results from a shift in the energy states available to spin-up and spin-down electrons. In practical applications, a ferromagnetic metal may be used as a source of spin-polarized electrons to be injected into a semiconductor, a superconductor or a normal metal, or to tunnel through an insulating barrier. Then, depending on the magnetization direction of a material, relative to the spin polarization of the electrons, a material can function either as a conductor or an insulator for electrons of a specific polarization.

The use of both charge and spin degrees of freedom in semiconductors is expected to enable a revolutionary class of electronics whose functionality will surpass that of existing semiconductor technology. Spin electronics combines semiconductor microelectronics with spin-dependent effects that arise from the interaction between electrons and a magnetic field. Since the characteristic length for spin-dependent effects is on the order of 1 nm compared to 10 nm for semiconductor electronics, spin-electronic devices have the potential to achieve much higher integration densities. Conventional electronics is based on the number of charges and their energies, and device performance is limited in speed due to energy dissipation, whereas spin electronics is based on the direction of spin and spin coupling, and is capable of much higher speeds at low power consumption. The advantages of spin-electronic devices would include non-volatility permitting data retention in non-powered conditions, increased integration densities, higher data processing speeds, low electrical energy demands, and fabrication processes compatible with those currently used in semiconductor microelectronics. There is strong evidence that the technology shift taking place from semiconductor electronics to spin-dependent devices will help to meet the sensing and storage demands of information technology in the 21st century. During the next decade, spin electronics will accelerate development in quantum computing, communications, and revolutionary molecular and chemical systems.

To date, the principal applications of spin-electronic devices have been in read heads for magnetic discs, and in magnetic field sensors. However, the greatest impact of spin-electronic devices is expected to be in magnetic random access memories (MRAM) to be used in conjunction with, or as replacements for, EEPROM (electrically erasable, programmable read-only memory) and flash memory in computer applications, where MRAM's lower writing energy, faster writing times, and no wear-out with writing cycle become significant factors. Although prototype MRAM devices have been employed in niche applications, commercial quantities of MRAM are not yet available. However, several industrial companies in the United States and abroad are poised to make substantial market introduction of MRAM products by the year 2004.

Recognizing the importance of the field of spin electronics and the potential impact that this new technology will have on the competitiveness of the United States in the global economy, the National Science Foundation in conjunction with the Office of the Secretary of Defense, the Defense Advanced Research

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<sup>1</sup> Prinz, G. 1998. *Science* 89, 260.

Projects Agency, the Office of Naval Research, and the National Institute of Standards and Technology, commissioned a worldwide study of the status of spin electronics with particular emphasis on the United States, Japan and Europe. The study was conducted by the World Technology Evaluation Center (WTEC), Inc. utilizing a panel of five experts from United States universities and industry. The panel consisted of Stephan von Molnár, Michael L. Roukes, Robert A. Buhrman, David D. Awschalom, and James M. Daughton, and was supported by participants from several Federal Agencies. Not only did the panel compile a comprehensive literature survey and analysis, but numerous interviews and team site visits to industries, universities, and government laboratories were conducted. The panel summarizes its broad conclusions in the Executive Summary, wherein it is noted that Japan is clearly the leader in new material synthesis, characterization and predictive calculation, while theory pertaining to spin electronics and spin-electronic devices is well developed in Europe. By comparison, the United States is the leader in optoelectronics and novel diagnostic instrumentation.

Chapter 1, written by Professor Stephan von Molnár, poses the question “Spin Electronics – is it the Technology of the Future?” Prof. von Molnár provides an excellent rationale for the conduct of the WTEC study, and comes away with the conclusion that the manifestation of spin electronics in semiconducting hybrid devices represents a vibrant new direction, and that semiconductor spin electronics will play an important role in the future to advance the frontiers of information technology. In Chapter 2, von Molnár reviews materials activities in spin electronics, and concludes that much of the new materials research effort is driven by innovations that can be traced to Japanese leadership in materials development in perovskites and to Japan's early decision in 1996 to fund spin-controlled semiconductor nanostructures at a level of \$6 million. Prof. von Molnár goes on to laud both DARPA (Defense Advanced Research Projects Agency) and NSF (National Science Foundation) for their support of research in materials synthesis and fabrication.

Professor Michael L. Roukes provides, in Chapter 3, an enlightening account of fabrication and characterization of magnetic nanostructures, addressed from both the conventional “top down” and the emerging “bottom up” perspectives. Roukes also summarizes techniques and instrumentation used in the characterization of magnetic nanostructures, and underscores the importance of work in imaging being conducted both in Europe and Japan. Further, Roukes observes that the United States has centers of excellence broadly covering imaging techniques, and is particularly strong in entrepreneurial frontier activities.

In Chapter 4, Professor Robert A. Buhrman provides a concise account of the state-of-the art in spin dynamics including spin injection, spin transport and spin transfer, noting that research in these areas is being actively pursued by a number of laboratories in Japan and Europe. Buhrman makes special note of the well-equipped thin-film growth and nanofabrication laboratories in Japan that can be expected to result in major contributions in spin electronics in the years ahead. Buhrman also observes that Europe's extensive expertise in magnetism, electronic and magnetic materials, and mesoscopic physics portends an upcoming decade of high productivity and keen competition on a worldwide basis in the area of spin electronics.

The optoelectronic manipulation of spin in semiconductors is authoritatively treated in Chapter 5 by Professor David D. Awschalom, who notes at the outset that an additional degree of freedom afforded by semiconductor spintronics allows direct optical access to electronic and nuclear-spin states. In addition to providing general conclusions on the emerging global effort in developing optoelectronic applications of spintronics in Japan, Europe and the United States, Awschalom takes the opportunity to identify several interesting new lines of research and potential applications. Among these may be listed spin-based semiconductor qubits for use in practical quantum processors; spin transistors that combine memory and logic functions where the amplitude and phase of the net spin current can be controlled by either electric or magnetic fields; and ferromagnetic materials used to imprint nuclear spins in semiconductors, thereby offering an additional pathway for manipulating and storing information at the atomic scale.

In the concluding chapter (Chapter 6), Dr. James M. Daughton, from the industrial sector, deals with the salient features of magnetoelectronics device research in Europe and Japan, and contrasts the findings with research conducted in the United States. Daughton traces the development of magnetoresistive structures from AMR (anisotropic magneto-resistance) to GMR (giant magnetoresistance) and to MTJ

(magnetoresistive tunnel junctions) pointing out the rapid application of these new structures in sensors, read heads, galvanic isolators and non-volatile memories (MRAM). In overview, Daughton concludes that device application work in the United States is stronger than that in Japan or Europe, and delineates industrial companies involved in device manufacture and sale. However, in very high magnetoresistive structures, both Japan and Europe lead the United States in published work.

Each chapter of this book is supported by a comprehensive list of references, which in total covers all aspects of spin electronics, spintronics, magnetoelectronics and magnetronics in the United States, Japan, Europe, and other countries. The highlights of this study are to be found in the appendices that range all the way from biographical information on the authors, who are also the WTEC panel members (Appendix A), to site-visit reports on Europe (Appendix B), and on Japan (Appendix C).

I personally had the privilege as a government participant representing the National Science Foundation of accompanying the panel members on several visits to Japanese companies and universities, and I can attest to the wealth of information that is contained in the site-visit reports in Appendices B and C. Of equal interest to the reader should be Appendix D: Highlights of Recent U.S. Research and Development Activities.

It has been for me a most interesting and rewarding experience and a privilege to participate in the WTEC study of spin electronics in the United States, Japan and Europe. Not only did I function as a government sponsor, but also as a visitation team member and planner. During all this time I had the opportunity to interact with the WTEC panelists, and I continue to be impressed with the quality and insight of the panel members and the high regard in which they are held by members of the worldwide spin-electronics community. An added feature of many of my visits and review activities involved graduate students from home and abroad, so that I had many opportunities to encourage the integration of research and education at the graduate level consistent with National Science Foundation policy in this area.

My thanks go to Dr. Stuart A. Wolf of DARPA (Defense Advanced Research Projects Agency), Dr. William F. Egelhoff Jr. of NIST (National Institute of Standards and Technology), and Dr Robert J. Trew (Office of the Secretary of Defense) for their excellent and continuous support of and participation in the WTEC study of spin electronics in the United States, Japan and Europe. The WTEC study of spin electronics could not have been so successfully conducted without the expertise and devotion to duty of WTEC personnel, especially Mr. Geoffrey M. Holdridge, WTEC Vice President for Operations and Dr. Robert D. Shelton, President of WTEC, and Mr. Horoshi Morishita, WTEC Japan representative for arranging the site visits. Also, I wish to acknowledge my colleagues at NSF (National Science Foundation), in particular Dr. Elbert L. Marsh and Dr. Rajinder P. Khosla, who gave of their time and effort to make the spin electronics study the great success that it has been. Finally, I would like to thank Dr. Russell J. Churchill at ARCOVA (American Research Corporation of Virginia) for technical discussions.

For my part, I am convinced that we are standing at the crossroads of two great technologies; namely, magnetics and semiconductor electronics, whose intersection has given rise to the new discipline that we know variously as spin electronics, spintronics, magnetoelectronics or magnetronics, and whose impact on the global economy and society in general can, at this time, only be imagined.

Usha Varshney  
National Science Foundation  
Arlington, Virginia, U.S.A.  
July 2003





## FOREWORD

We have come to know that our ability to survive and grow as a nation to a very large degree depends upon our scientific progress. Moreover, it is not enough simply to keep abreast of the rest of the world in scientific matters. We must maintain our leadership.<sup>2</sup>

President Harry Truman spoke those words in 1950, in the aftermath of World War II and in the midst of the Cold War. Indeed, the scientific and engineering leadership of the United States and its allies in the twentieth century played key roles in the successful outcomes of both World War II and the Cold War, sparing the world the twin horrors of fascism and totalitarian communism, and fueling the economic prosperity that followed. Today, as the United States and its allies once again find themselves at war, President Truman's words ring as true as they did a half century ago. The goal set out in the Truman Administration of maintaining leadership in science has remained the policy of the U.S. Government to this day: Dr. John Marburger, the Director of the Office of Science and Technology (OSTP) in the Executive Office of the President made remarks to that effect during his confirmation hearings in October 2001.<sup>3</sup>

The United States needs metrics for measuring its success in meeting this goal of maintaining leadership in science and technology. That is one of the reasons that the National Science Foundation (NSF) and many other agencies of the U.S. Government have supported the World Technology Evaluation Center (WTEC) and its predecessor programs for the past 20 years. While other programs have attempted to measure the international competitiveness of U.S. research by comparing funding amounts, publication statistics, or patent activity, WTEC has been the most significant public domain effort in the U.S. Government to use peer review to evaluate the status of U.S. efforts in comparison to those abroad. Since 1983, WTEC has conducted over 50 such assessments in a wide variety of fields, from advanced computing, to nanoscience and technology, to biotechnology.

The results have been extremely useful to NSF and other agencies in evaluating ongoing research programs, and in setting objectives for the future. WTEC studies also have been important in establishing new lines of communication and identifying opportunities for cooperation between U.S. researchers and their colleagues abroad, thus helping to accelerate the progress of science and technology generally within the international community. WTEC is an excellent example of cooperation and coordination among the many agencies of the U.S. Government that are involved in funding research and development: almost every WTEC study has been supported by a coalition of agencies with interests related to the particular subject at hand.

The present study, reviewing the status of spin electronics research and development in the United States, Japan, and Europe, is a case in point. Support for this study came from NSF, the Defense Advanced Research Projects Agency, the Office of the Secretary of Defense, the Office of Naval Research, and the National Institute of Standards and Technology. The results of the study have already been incorporated to some degree in the content of a new NSF program announcement entitled, "Spin Electronics for the 21st Century."<sup>4</sup> The findings of this study also have considerable bearing on the National Nanotechnology Initiative, which now is coordinating the nanoscale research and development activities and interests of 15 Federal agencies.

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<sup>2</sup> Remarks by the President on May 10, 1950 on the occasion of the signing of the law that created the National Science Foundation. *Public Papers of the Presidents* 120: p. 338.

<sup>3</sup> [http://www.ostp.gov/html/01\\_1012.html](http://www.ostp.gov/html/01_1012.html).

<sup>4</sup> See <http://www.nsf.gov/pubs/2002/nsf02036/nsf02036.html>.

Indeed, innovations in spin electronics may prove key to keeping the United States and the world on the path of ongoing progress in price and performance of electronic devices widely described as Moore's Law.<sup>5</sup> Near-term applications include high-speed non-volatile memory devices for computing, and there are many other exciting possibilities in the longer term, perhaps even including quantum computing applications. It is especially important for U.S. researchers and policymakers to remain abreast of ongoing developments in this field in both Europe and Japan, and to work with our friends and colleagues around the world to move this field forward for our mutual benefit. This WTEC report is one step in that direction.

As President Truman said over 50 years ago, our very survival depends upon continued leadership in science and technology. WTEC plays a key role in determining whether the United States is meeting that challenge, and in promoting that leadership.

Elbert Marsh  
Deputy Assistant Director for Engineering  
National Science Foundation

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<sup>5</sup> See the Executive Summary of this report (p. xi) for a discussion of Moore's Law and its relationship to spin electronics research.

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## EXECUTIVE SUMMARY

Stephan von Molnár

### INTRODUCTION

Moore's Law, the prediction that the number of transistors per square inch on integrated circuits will double every 18 months, has held remarkably accurate in the electronics industry since the 1970s. The rapid improvement in performance and reduction in cost of computers and communications devices fueled by Moore's Law have been a critical engine of U.S. national security, economic growth and productivity in the past three decades. In recent years, however, electronic devices have been scaled down to sizes where quantum effects begin to interfere with their functioning. By some industry predictions, this physics impasse will be felt commercially as early as the year 2005.<sup>6</sup> By incorporating one of these quantum effects, electron spin, into device design, spin electronics (or "spintronics") offers a possible route to continue with the impressive gains in the capacity and speed of integrated circuits, and so much more. In spintronics both the electron charge and spin carry information. This science was born as an economically viable industry in 1988 with the discovery of the giant magnetoresistive (GMR) device. Exploiting electron spin effects in ultrathin multilayers of magnetic materials, and the large changes in electrical resistance resulting from application of a magnetic field, GMR technology enables impressive increases in storage capacity of hard disks. The next memory device that has been developed and soon will be commercially available is magnetic random access memory (MRAM). The advantages of magnetic devices include nonvolatility, increased data processing speed, decreased electric power consumption, and increased integration densities compared to semiconductor devices. MRAM could enable nonvolatile RAM with the high speed of today's static RAM and the high density of dynamic RAM. Nonvolatile means that the memory is maintained even when power to the device is turned off. MRAM devices would allow for instant-on computers and extended battery life of portable electronics. In addition to storage applications, which are being pursued in the United States by such industrial innovators as IBM, Honeywell, Motorola, and NonVolatile Electronics (NVE), spin electronic elements will result in new approaches to logic design, quantum computing, and quantum communications.

A worldwide study of the status of research and development in spin electronics was carried out by a five-person panel under the auspices of the World Technology Evaluation Center (WTEC), Inc., sponsored by the National Science Foundation, the Department of Defense, the Defense Advanced Research Projects Agency, the Office of Naval Research, and the National Institute of Standards and Technology. This WTEC panel was organized to evaluate research efforts in the field within the United States and to compare them to existing international efforts. Most significant among these is the research and development activity in Europe and Japan. While research in metallic multilayer GMR structures and their integration into various MRAM configurations continues to be a highly active area, the promise of orders of magnitude larger signal-to-noise ratios in magneto-tunneling devices has resulted over the past three years in major research investment both by the private sector and academic institutions. The panel, after having visited some 26 laboratories and obtaining information from at least 40 leaders in the field of spin electronics, has arrived at the following conclusions, which are divided broadly into remarks pertaining to the three geographical areas

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<sup>6</sup> The International Technology Roadmap for Semiconductors (ITRS), as updated in 2002, states that by 2003 there will be two categories of requirements for high-speed communications test equipment for which there are no known manufacturing solutions (updated tables, Table 23a, p. 21), and shows four categories of high performance logic technology requirements expected by 2005 for which there are no known manufacturing solutions (updated tables, Table 35a, p. 31). See <http://public.itrs.net/Files/2002Update/2002Update.pdf>.

(Asia, Europe, and the United States) and focused primarily on those research activities involving spin electronics in semiconductors. A final set of remarks will pertain to metal spin electronics, the more mature and thus less investigated subject of this report.

## **SPIN ELECTRONICS IN SEMICONDUCTORS**

### **Japan**

Although there are nascent efforts in spin electronics in South Korea and China (both mainland and Taiwan), by far the dominant work is being carried out in Japan. The following comments, therefore, refer only to Japan.

- Japan is clearly the world leader in new material synthesis, characterization, and predictive calculation. It is also a leader in magneto-optical properties of semiconductor devices.
- Semiconductor spin electronic programs are growing both in academic and national research laboratory environments. Perhaps because of the influx of new government funds, university research is becoming more applications driven.
- The interaction of industrial and academic research is small.

### **Europe**

- Theory pertaining to spin electronics (including injection device structures such as tunneling devices and band structure predictions of materials properties) is well developed in Europe. These countries are benefiting from the breakdown of bureaucratic and fiscal barriers due to the creation of the European community.
- There are strong efforts in developing magnetic semiconductors and semiconductor heterostructures, principally in Germany and Holland. Important efforts exist to create novel device geometries making use of Si and GaAs-based heterostructures to produce spin sensitive transport properties.
- Interaction of industry with academia is weak.

### **United States**

- The United States is a leader in optoelectronics including optical detection and injection, as well as novel instrumentation — e.g., ballistic electron magnetic microscopy (BEEM). The United States benefits from a research style that emphasizes individual, small group, and entrepreneurial efforts. Furthermore, the focus on and funding for cross-disciplinary interactions represents an important advantage. There also exist very strong interactions between academic and industrial partners, in contrast to the very limited activities of this nature found in Japan and Europe.
- Funding for semiconductor spin electronic-related research is increasing rapidly in the United States, principally from programs initiated by DARPA and also recently by the National Science Foundation.

As a general comment, there is a continuing need for graduate students in the general area of magnetism, magnetic materials, and the integration of magnetism with semiconductor devices.

## **METAL SPIN ELECTRONICS**

### **Japan**

Japan is competitive in the area of magnetic tunneling devices, but lags in other applications based on giant magnetoresistance effects.

### **Europe**

Europe has taken on leadership roles in GMR theory and mesoscopic and giant magnetotransport effects in magnetic materials including oxides.



Although they were the inventors of giant magnetoresistance in the late 1980s, European researchers lag in the applications of metal spin electronics.

### **United States**

The United States is the international leader in applications including (1) read heads, (2) MRAM, (3) sensors, and (4) magnetic device production.

The United States lags in theory and new magnetoresistance effects, which are primarily the domain of the European community.

The panel thus concludes that the United States remains the current leader in metal spins applications, although the new effects that have been identified, principally in Europe, will provide new challenges and opportunities for research and development as the technology moves to the nano scale. The United States, through the DARPA SPINS program and newly initiated NSF “Spin Electronics for the 21st Century” program, is developing a competitive materials and optoelectronics effort. However, to take advantage of the new research funding opportunities, not only in the United States but also in Europe and Japan (many of which not only will ultimately be cross disciplinary but also will bridge international boundaries), the international community must develop and train a core of outstanding graduate students. This remains a major challenge. Insofar as the funding agencies within the United States are concerned, these need to leverage the present U.S. strengths in optoelectronics, novel device concepts, and imaginative new metrologies. The government funding agencies must aggressively pursue such opportunities, both for their fundamental intellectual value and for the development of these new concepts and technologies into commercial applications.



## CHAPTER 1

# SPIN ELECTRONICS — IS IT THE TECHNOLOGY OF THE FUTURE?

Stephan von Molnár

### INTRODUCTION

The future potential of spintronics in the areas of information storage and ultimately quantum computing has been long recognized. The many approaches current spintronics research is taking, as detailed in this report, bear testament to its future value. Two recent discoveries have rekindled interest in the utility of semiconductors as both sources and carriers of spin information. The first of these, by Awschalom and coworkers (Awschalom and Kikkawa 1999), demonstrated that optically injected spin-polarized carriers maintain their coherence over nanosecond time scales. This means that they can be transported over distances far in excess of tens of micrometers, making the transport of coherent spin information from device to device a practical reality. The second discovery, by Ohno and coworkers in Japan (Ohno et al. 1996), resulted in the fabrication of low concentration Mn substitution in GaAs epilayers with ferromagnetic ordering temperatures in excess of 100K. Other semiconducting materials with  $T_C$  higher than room temperature are in the offing. Thus the natural integration of spin-sensitive and normal semiconductor functionalities will lead to new opportunities for integrating electronics, magnetics, and photonics into single technologies with multifunctional capabilities.

As the potential consequences of these developments have become clearer — implicit in the question posed in the title of this chapter — spin electronics has attracted increasing attention from the U.S. government agencies that fund electronics R&D.

### THIS STUDY

U.S. government program managers wanted to know more about current work in the field of spin electronics, especially research going on abroad. Questions about the status of spintronics worldwide led to the organization of this study under the auspices of several agencies. Sponsors included the National Science Foundation (NSF), the Office of the Secretary of Defense: Research and Engineering (OSD), the Defense Advanced Research Projects Agency (DARPA), the Office of Naval Research (ONR), and the National Institute of Standards and Technology (NIST). Agency sponsors were interested in any insights and recommendations that might be gleaned from a survey of ongoing research in the United States, Europe, and Japan — where most of the work on spin electronics is being conducted. The panel and sponsors also wanted to identify opportunities for international collaboration.

Organizational work for the study began early in 2001, with a series of planning meetings and the selection of panel members with the background and experience to render credible judgments about the quality of work being examined. A brief period of further planning and preparation followed, during which the panel tried to identify the centers of excellence emerging around the world and the researchers associated with them, in preparation for its overseas travel and visits. On November 2, 2001, after travel and visits were

completed, the panel held a public workshop in Arlington, Virginia, where for the first time preliminary findings and conclusions were presented to the public.

Personal visits and interviews are at the heart of a study like this. For firsthand, up-to-date information, the panel visited 26 international laboratories, conducted 6 personal interviews in locations other than the interviewees' laboratories, and undertook 7 additional telephone and e-mail interviews. Reports on the laboratories visited and individuals interviewed — and the impressions that these visits made on the panelists — are appended to this volume as site reports (in a form panel members hope will make them useful as reference sources). A recent article in *Science* (Wolf et al. 2001), which was based in part on this study, should also be regarded as an excellent additional source of information.

### **The Panel**

To produce a worthy study, WTEC needed a group of distinguished scientists and industrialists with outstanding accomplishments in the various sub-disciplines important for the technology of spin electronics. The sponsors were fortunate to obtain the services of a highly respected, accomplished group of individuals.

In alphabetical order, they are as follows:

1. David Awschalom, University of California at Santa Barbara. Professor Awschalom's research has led to the astounding conclusion that spin packets can be transported over hundreds of micrometers in semiconductors and manipulated without losing their coherence (Awschalom and Kikkawa 1999). His research in a broad range of experiments on magneto-optoelectronics gives him a particularly sharp insight into this subject.
2. Robert Buhrman, Cornell University. Professor Buhrman's extraordinary insight into this subject is exemplified by his recent development of methods for observing magnetic domain structures at unparalleled resolution (Monzon 1999; Monzon and Roukes 1999). He also is the first to observe spin current-induced switching in magnetic heterostructures (Rippard and Buhrman 1999).
3. James Daughton, Chief Scientific Officer of Non-Volatile Electronics Corporation. Dr. Daughton brings to this study a deep understanding of the science underlying magnetoelectronics as well as a unique appreciation for the challenges that have to be met to produce marketable devices. As the former CEO of the NVE Corporation, which specializes in magnetoelectronic devices and their applications, he brings to the panel singular appreciation for the difficult road from concept to product (Katine et al. 2000; Daughton 2000a).
4. Michael Roukes, California Institute of Technology. As one of the first researchers to investigate spin injection into magnetic heterostructures (Daughton 2000b), and with an outstanding record of innovation in nanostructures and their characterization (Roukes 2001), Professor Roukes's understanding of the challenges that face the technologist in magnetoelectronics is unique.
5. Stephan von Molnár, Florida State University and MARTECH. Professor von Molnár has had a longstanding interest and activity in magnetic semiconductors and was involved in many of the early studies on simple concentrated semiconducting materials and their device structures. He also collaborated on the first diluted magnetic semiconductors based on the III-V type systems.

### **Focus of the Study**

This study focuses essentially on four technical topics:

- First, fabrication and characterization of magnetic nanostructures. As a subtopic, the panel is also reporting on materials development in Japan and Europe vis-à-vis that in the United States.
- Second, magnetism and spin control in magnetic nanostructures. Once having manufactured the devices, how does one control and manipulate the spins in a way to provide new functionality to the device or structure? This involves a variety of important problems, including transport through a variety of interfaces, which will be described in detail.
- Third, magneto-optical properties of semiconductors. Up to this point, the most successful methods, in fact the only highly efficient methods developed for injecting polarized spins into semiconductor

structures, have been the optical techniques. The properties and successful demonstrations of spin electronic devices using magneto-optics are therefore a profound and important aspect of current research.

- Finally, magnetoelectronics and devices—a very broad subject which encompasses not only the major focus of this study on semiconducting devices, but which will also include a review of the metal systems. The latter is a more mature research and development effort and has already resulted in major breakthroughs, not the least of which is the magnetic tunnel junction in which the resistivity of the junction depends on the direction of polarization of the two magnetic metal counter electrodes. These junctions are currently being integrated into various potential products such as MRAM and magnetoresistive (MR) sensors.

The panel also attempted to obtain information on various nontechnical issues including, but not limited to, industry and academic cooperation in Japan, Europe, and the United States; the existence of international and interdisciplinary cooperation; and any long range research and educational challenges that have been identified as important for progress in this very important field.

### **SPIN ELECTRONICS: A SIGNIFICANT FIELD OF SCIENTIFIC INQUIRY?**

In order to obtain some measure of the importance of spintronics as a scientific activity, and to provide a timeline for the development of this subdiscipline, statistics have been collected on the number of research papers that have been published on this subject in major journals.

It is possible to separate spin electronic phenomena into two, perhaps three, major categories. The first of these is the so-called giant magnetoresistive effect (GMR), which has dominated the applications of this technology over the past decade. This effect was first observed in alternating multi-layers composed of magnetic and non-magnetic metallic metals and alloys, and depends on the effective single spin densities of states in a magnetically polarized medium. Resistivity is always larger if the transition is from a spin polarization in one direction to a density of states of spin polarization in the other. This is also true of scattering events, which, at least in the simplest case of Fermi's golden rule, also involve the product of the two spin-dependent electronic densities of state.

Another closely related physical phenomenon is the tunneling magnetoresistive effect in which the two magnetic metals are separated by an insulating layer. Once again, the resistivity is strongly dependent on the sense of polarization of the two counter electrodes. Finally, there are more complex structures, which involve a metallic or degenerately semiconducting magnetic electrode. This acts as a source of spin-polarized electrons injected into a semiconductor where the spins may be modulated by a number of external processes such as electronic gating. Thereafter, the electrons are ejected into a detector capable of identifying the sense of polarization. The detector may be optical, another magnetic electrode or a more complex device.

For the purposes of this report, the activities have been arbitrarily separated into spin-dependent transport, by which is meant only those studies which depend on the GMR effect, and into a second category which contains tunneling magnetoresistance and semiconductor spintronics, lumped together in a group called spin injection, detection, and manipulation.

Figure 1.1 depicts the percentages of papers written on spin-dependent transport for the six years, 1996 through 2001. The year 1996 was chosen because it was the beginning of the first program on “spin-controlled semiconductor nanostructures” funded by the Japanese government. At that point, interest and activity in this field, at least in the United States, was limited to only a very small number of laboratories. Figure 1.1 shows that Europe has been most active in the research on spin-dependent transport, followed closely by Japan and the United States. The GMR effect was discovered in Europe in 1988 in two locations, France (Baibich et al. 1988) and Germany (Barnas et al. 1990), independently of each other. The right hand panel of Figure 1.1, which summarizes the publication activity for spin injection and manipulation, on the other hand, shows that the effort in the United States over the same time period far outweighed that in

Europe, Japan and various joint efforts involving a number of collaborations among researchers in different parts of the world.

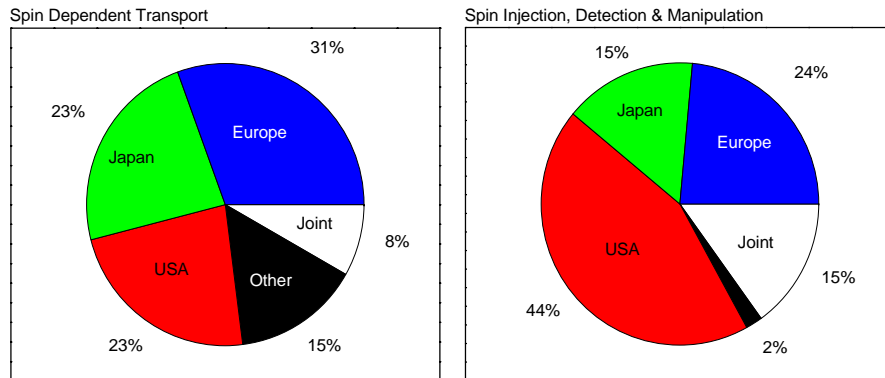


Figure 1.1. Percentages of papers written on spin-dependent transport from 1996 through 2001.

More telling, in some respects, are the bar charts in Figure 1.2, which show, on the left, that papers on spin-dependent transport are on the decline, whereas papers on spin injection, detection and manipulation have increased every year during which the statistics were collected. It should also be noted that the data collected for the year 2001 are incomplete<sup>7</sup>. One may conclude, therefore, that spin-dependent transport, although extremely important for present day technologies, is by now a rather mature technology. Much of the new innovation is presumably carried out in industry, most likely not published, but perhaps patented. The area involving semiconductors is in its nascent stages and is only now receiving the research attention it deserves, given that much present day electronics technology is based on semiconductors.

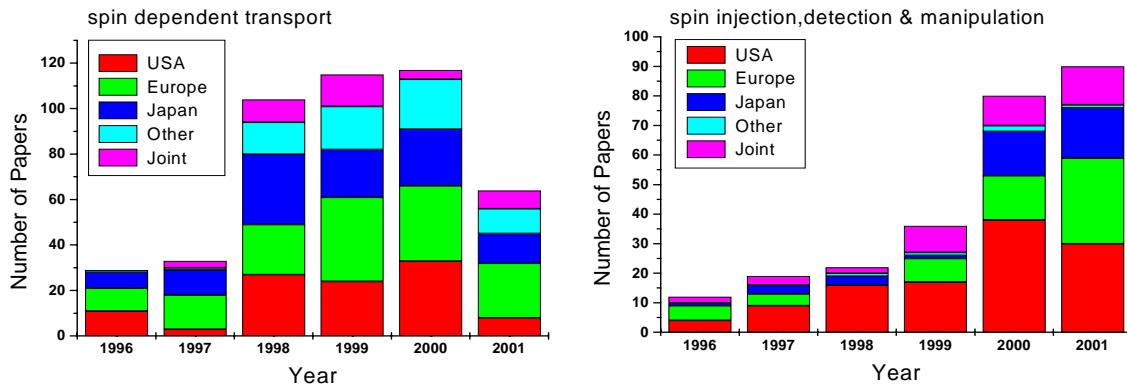


Figure 1.2. Publication activity for spin-dependent transport (left) and spin injection, detection and manipulation (right), 1996-2001.

As already mentioned, the impetus for increased focus on semiconductor spintronics has its genesis in the discovery in 1996 by Hideo Ohno and his colleagues (Ohno et al. 1996) that GaAs when doped with modest (~ 5%) portions of manganese could reach ferromagnetic transition temperatures in excess of 100K. The other major discovery by Awschalom and colleagues of nanosecond spin life and coherence times in normal n-type GaAs (Awschalom and Kikkawa 1999) provided a demonstration that transport of spin information and the manipulation of these spins in technologically useful semiconductors were indeed possible.

<sup>7</sup> Data were obtained from a total of 721 referenced papers published during 1996 – 2001 inclusive. Publications were obtained from searching the expanded science citation index. Data for 2001 represent an incomplete year, cut off ~ August 30, 2001.

## CONCLUSIONS

If there is a single idea to be derived from the study, it is that spin electronics and its manifestation in semiconducting hybrid devices represent a vibrant new direction for the field. The technology has already demonstrated resounding success in architectures utilizing spin-dependent transport in metallic multilayers and tunnel junctions. The panel is confident that the many problems associated with injecting and detecting spins in semiconductor hybrid structures, as well as their manipulation, will be solved in the foreseeable future and that semiconductor spin electronics will play an important role in the future, particularly as it relates to information technologies including memory and logic.

## ACKNOWLEDGEMENTS

Panel members express their gratitude to their many hosts for the excellent hospitality extended during the laboratory visits, as well as to the individuals who agreed to be interviewed in person or by e-mail and telephone. The WTEC panelists recognize that all of these activities required the sacrifice of valuable time. The panel also expresses its thanks to Professor K. Goto of the Asian Technology Information Program (ATIP), and H. Morishita, WTEC representative in Japan, who tirelessly chaperoned many of its members during travels in Japan. The valuable help of D.M. Treger and A.Y. Chtchelkanova, Strategic Analysis, is also appreciated, as is the assistance in data collection by Daisy Kwok, Strategic Analysis, and by Dr. Dan Read, who, with the help of several graduate students at Florida State University, collected the publication data.

The domestic staff of WTEC, particularly G. Holdridge, has been invaluable in managing the study and performing all the detailed editorial tasks resulting in the present report. The panel, especially S. von Molnár, thanks them.

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## CHAPTER 2

# MATERIALS FOR SEMICONDUCTOR SPIN ELECTRONICS

Stephan von Molnár

### DISCUSSION

A generic spin electronic device consists of a spin injection electrode, an interface, a medium in which coherent, polarized injected spins may be manipulated, and another interface beyond which the coherence and direction of the spins may be detected. Although spin injection and detection have been demonstrated by optical techniques (see Chapter 5) in order to produce an all electronic device, the ferromagnetic injector and detector must be materials having high spin polarization and compatibility with the transporting medium.

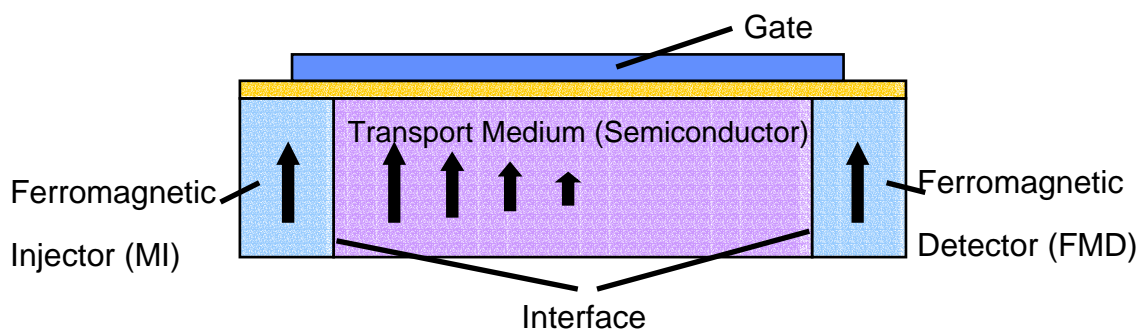


Figure 2.1. Generic semiconducting spintronic device with polarized electrodes.

Figure 2.1 shows such a generic spin electronic device, which includes a gate above the semiconducting transport medium for spin and charge manipulation. In the past, the ferromagnetic injector had been a ferromagnetic metal or alloy containing 3d transition elements with fractional spin polarization of the conduction electrons (Johnson and Silsbee 1987; Monzon and Roukes 1999; Gardelis et al. 1999; Hammar et al. 1999). However, as Schmidt et al. (2000) have argued, to get measurable spin polarization in the transport medium, the ratio of the conductivity of the injector  $\sigma_{\text{FM}}$  to the conductivity of the transport medium (semiconductor)  $\sigma_{\text{SC}}$  has to be smaller than or at least close to one, i.e.  $\sigma_{\text{FM}}/\sigma_{\text{SC}} \sim 1$ . This theoretical calculation neglects interface scattering, among other assumptions, but it does point toward the difficulties that arise when a magnetic metal is in contact with a nonmagnetic transport medium such as a semiconductor. A partial solution to the problem is either to produce the injection by tunneling spin-polarized electrons through an insulator into the semiconductor or by tunneling non-polarized electrons through a magnetic insulator spin filter (Hao, Moodera, and Meservey 1990; Fiederling et al. 1999; Jonker et al. 2000). A second, more practical, solution would be to start with a 100% polarized ferromagnetic injector. From the previous discussion, it is clear that the electrode materials necessary to produce a successful semiconductor spin electronic device require considerable materials and interface research. In this chapter,

the focus will be on the materials themselves. The next chapter by R. Buhrman will describe in detail the vagaries of interfaces and their ability to help and/or hinder successful injection of spin-polarized carriers.

There have been numerous attempts to inject transition metals or their alloys into semiconductors, either directly (Johnson and Silsbee 1987; Monzon and Roukes 1999; Gardelis et al. 1999; Hammar et al. 1999) and also recently in a tunneling geometry (LaBella et al. 2001). The latter, using an Ni tip in a scanning tunneling configuration, produces a remarkable ~92% spin-polarized current in GaAs. Major efforts to seek additional solutions utilizing less conventional ferromagnets are currently in progress. These fall broadly into the two categories that are discussed in the present chapter: (a) magnetic semiconductors and (b) half-metals, many of which have the additional advantage that their magnetic transition temperatures exceed room temperature, making them popular candidates for practical applications.

In this report, much of the discussion will focus on the concentrated magnetic semiconductors, such as the Eu chalcogenides,  $\text{EuX}$  ( $X=\text{O}, \text{S}, \text{Se}, \text{Te}$ ) (Methfessel and Mattis 1968; Wachter 1972; Holtzberg, von Molnár and Coey 1980). These materials, although they contain a magnetic species, the rare earth, at every lattice site, have transition temperatures far below room temperature and thus are primarily suited for fundamental studies and proof-of-concept type devices. On the other hand, much is known about their magnetic and transport characteristics. Furthermore, the doped materials are 100% spin-polarized for low carrier concentrations (von Molnár 1970; Santos et al. 2001; Steeneken et al. 2002). This also makes them favorable from the point of view of the Schmidt (2000) argument, because the conductivity of this completely polarized injector can be tuned to be comparable to that of the semiconductor transport medium. This report also describes briefly the diluted magnetic semiconductors (DMS), which include both II-VI:Mn with transition temperatures never higher than a few Kelvin (Haury et al. 1997), and the III-V:Mn DMS (Munekata et al. 1989) in which ferromagnetic transition temperatures as high as 110K have been confirmed (Matsukura et al. 1998) and where claims of transition temperatures in excess of 900K (Sonoda et al. 2002) have been reported. Confirmation of these higher transition temperatures is pending. Other Mn-doped semiconductors that are being reinvestigated as potential room temperature ferromagnetic spin sources are the chalcopyrites such as  $\text{CdGeP}_2\text{:Mn}$  (Methfessel and Mattis 1968; Medvedkin et al. 2000; Mahadevan and Zunger 2002). Several nontraditional DMS variants — among them  $\text{TiO}_2\text{:Co}$  (Masumoto et al. 2001; Shim et al. 2002) and  $\text{ZnO:Co}$  (Ueda, Tabata, and Kawai 2001; Yang et al. 2002) — may also show promise. The class of DMS also includes the mixed valence perovskites, which in some cases exhibit ferromagnetic order above room temperature. These complex materials have been researched heavily over the past decade and will not be summarized in this report, with the exception of some discussion on tunneling devices by James Daughton in Chapter 6. The reader is directed to a review in 1996 by Coey et al., as well as a more recent review by Ramirez (1997).

The discussion of half-metals will be limited to oxides including  $\text{Fe}_3\text{O}_4$  (Penicaud et al. 1992) and  $\text{CrO}_2$  (Watts et al. 2000), a brief description of Heusler alloys (Coey 2001), and several transition metal pnictides including MnAs (Beam and Rodbell 1962), MnSb (Akinaga et al. 2000a), CrAs (Akinaga et al. 2000c), and CrSb (Zhao et al. 2001). As a matter of orientation, it is useful to describe the difference between magnetic semiconductors below their magnetic ordering temperature and the half-metallic ferromagnets by referring to Figure 2.2 (Wolf et al. 2001), which gives a schematic density of electronic states for the two cases. The principal observation, both in Figures 2.2a and 2.2b, is that only one of the two sub-bands is occupied, which means that in both examples the electrons are expected to be completely spin-polarized. One should be forewarned, however, that these are schematic densities of states, and as will be shown for the case of  $\text{CrO}_2$ , the density of electronic states may be far more complicated than is indicated here. The splitting between the two spin-polarized sub-bands may naively be thought of as the result of an effective Zeeman splitting of the bands as indicated in Equation 2.1.

A concentrated magnetic  
semiconductor below  $T_c$

The half-metallic ferromagnet  
 $\text{CrO}_2$

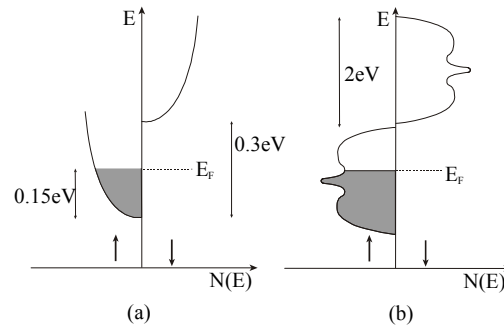


Figure 2.2. Schematic density of states for EuS and  $\text{CrO}_2$  (Wolf et al. 2001). Note that the energy scale is almost ten times larger in figure 2.2b.

$$E = g^* \mu_B H + 2J \vec{s} \cdot \langle \vec{S} \rangle \quad \text{Equation 2.1}$$

Although a mean field approximation, this expression points towards several important physical results. The first term is the normal Zeeman term composed of the product of the effective “g” factor,  $g^*$ , the Bohr magneton,  $\mu_B$ , and the applied magnetic field strength,  $H$ . The second term represents the effective exchange interaction between the spin of the conduction electron,  $\vec{s}$ , with the average magnetization  $\langle \vec{S} \rangle$  seen by the electron through its magnetic coupling strength,  $J$ . This second term is often orders of magnitude larger than the first; and  $\langle \vec{S} \rangle$  may extend over the entire lattice, in which case it represents the magnetization dependence of the electron energy. This splitting is, for example, of order 0.5 eV in EuS (Methfessel and Mattis 1968; Wachter 1972). It may also represent the value of the spin,  $\vec{S}$ , averaged over the region occupied by an impurity electron. In this case, that second term may result in magnetic polaron formation, which is local ferromagnetic order in a paramagnetic or antiferromagnetic host (von Molnár 1970). These effective exchange interactions produce very large energy changes in the spin up and spin down band states, regardless of whether or not they are occupied. For example, figure 2.3 shows arguably the first spin electronic device (Esaki, Stiles, and von Molnár 1967), a metal/magnetic insulator/metal junction in which the thickness of the insulator was great enough (on order 10 nm) to prevent direct tunneling from one side to the other.

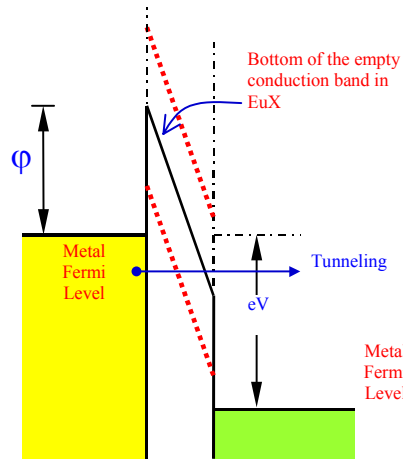


Figure 2.3. Fowler-Nordheim tunneling. The bottom of the conduction band (--) is split in the presence of an applied field or below the magnetic ordering temperature, thereby facilitating an exponential increase in tunneling current as the effective tunneling distance decreases.

Large bias voltages, however, induce internal field emission (Fowler-Nordheim tunneling), which demonstrates that the field emission current depends directly on the state of magnetization of the insulator. This result provides direct evidence for the large band splitting found in Eu chalcogenides. The magnetic insulator thus serves as an efficient spin filter discriminating against spins in the opposite direction to the direction of magnetization of the insulating film. Other tunneling geometries utilizing doped conducting EuO as a spin source are being investigated. Work on the Eu chalcogenides has also demonstrated that the insulator (Holtzberg et al. 1964), when doped with carriers, enhances the exchange interaction, thereby increasing the magnetic ordering temperature with doping for low carrier concentration changes. This latter effect turns out to be very important for discussion of the DMS systems. Although II-VI DMS have provided important insight into spin injection as spin filters and spin transport media (Fiederling et al. 1999; Jonker et al. 2000; Kikkawa et al. 1997) that will be discussed in subsequent sections, their use as polarized spin sources is, for all practical purposes, unimportant for spin electronic semiconducting devices. The discussion of DMS in this chapter therefore will concentrate on the III-V materials. Recent successes by the Japanese groups headed by Ohno (Ohno 1998; Dietl, Ohno, and Matsukura 2001) and Munekata (Slupinski, Munekata, and Oiwa 2001) demonstrate that the versatility of DMS is still being explored. The definitive

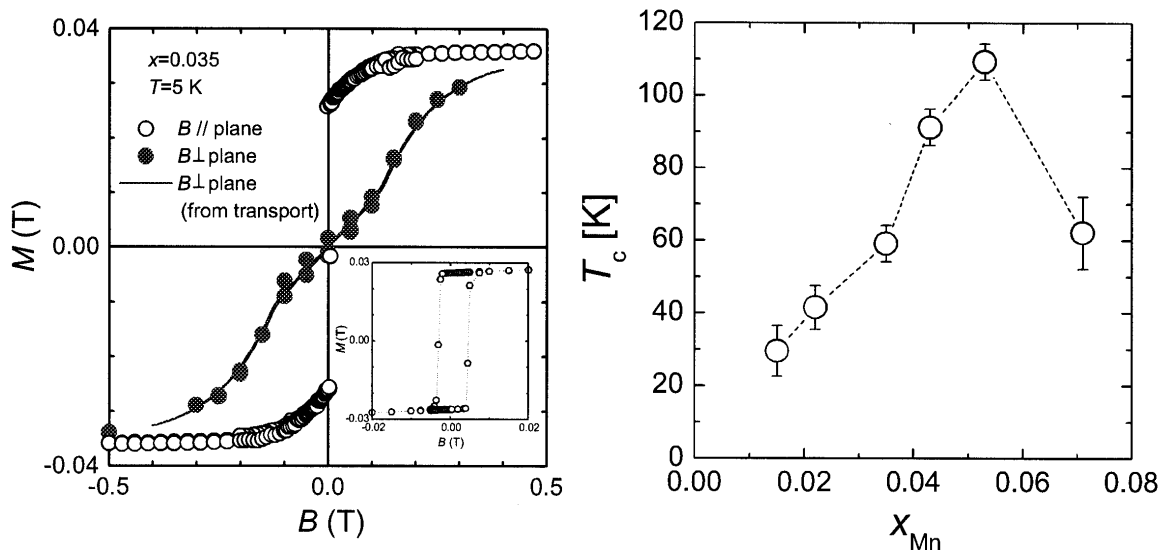


Figure 2.4. III-V dilute magnetic semiconductors GaMnAs with  $T_C$  as high as 110K for  $X_{Mn} \sim 0.05$  (reprinted by permission from Ohno 1999, © 1999 Elsevier).

recent work in the (Ga,Mn)As system (Ohno 1999) is summarized in Figure 2.4, which shows, in the left hand panel, magnetic hysteresis measurements at 5K for a material containing 3.5 atomic percent Mn. Similar curves can be obtained for concentrations ranging from approximately 1.5 to 7 atomic percent Mn as indicated in the right hand panel. It is seen that the maximum value of the ferromagnetic transition temperature  $T_C$  is obtained at approximately 5%. These numbers, however, depend to a large extent also on annealing conditions, as has been reported by Hayashi et al. (2001) and Endo et al. (2001). Further impetus to continue research in the DMS-type materials was given in several articles by Dietl, Ohno, and their colleagues (Dietl et al. 2000) in which they predicted magnetic ordering temperatures in excess of room temperature for five atomic percent Mn doping in GaN and ZnO. These predictions have resulted in major U.S. efforts, centered at the University of California at Santa Barbara, Notre Dame University, the University of Florida, and various programs in Japan. So far, the most spectacular result is that of Sonoda et al. (2002), who produced data on (Ga,Mn)N of magnetization versus temperature up to approximately 750K. Utilizing a Brillouin function extrapolation of their data, they found an estimated ferromagnetic ordering temperature,  $T_C$ , at approximately 940K. Similar results have recently been reported by other laboratories (Thaler et al. 2002) including  $T_C$ s as high as 270K in GaP (Theodoropoulou et al. 2002). There is, therefore, high probability that a single phase material can be produced and that transition temperatures will reach practical values greater than room temperature. Observation of an anomalous Hall effect at room temperature would provide confirmation that the nitrides and phosphides are indeed homogeneous ferromagnets.

Multiphase materials in which one of the components is magnetic with high transition temperature may turn out to be useful, particularly in magneto-optical applications. It is generally believed, however, that single phase materials will provide the best opportunities for effecting efficient spin injection into semiconductors. Thus the new materials provided through combinatorial synthesis — initiated by Matsomoto et al. (2001), which indicated ferromagnetism at room temperature for anatase type  $\text{TiO}_2\text{:Co}$  — caused great excitement. The structural nature of the material is, however, still in question. For example, recent work by Chambers et al. (2001) also shows large hysteresis at room temperature, both through magneto-optic and magnetic measurements. The resulting magnetization per Co dopant varies widely with preparation, however, which suggests that perhaps either elemental Co or an unknown Co-Ti-O compound have been produced within the anatase matrix. Additional studies also support the contention that the material is multiphase (Kennedy and Stampe 2002). Clearly, considerable research must yet be done to determine the physical and chemical properties of these DMS systems. It should be noted that the initial work on the (Ga,Mn)As also evidenced multiphase structures in which the Mn combined with As to form the ferromagnet MnAs with a ferromagnetic  $T_C$  approximately equal to 300K. Only after considerable experimentation was it possible to make these materials as demonstrable homogenous DMS (Munekata et al. 1989).

Nonetheless, a number of fascinating new discoveries in multiphase and novel nonequilibrium magnetic pnictides have been made. The first of these is the deposition and burial of 3 nm islands of MnSb in a GaAs matrix. This material has been shown to have enormous low field magnetoresistive properties. Akinaga et al. (2000b) report a room temperature magnetoresistance ratio reaching 880% at .1 T and 320,000% at .2 T. These authors were also able to explore hysteretic switching behavior at various bias fields. Clearly such effects should find utility in various magnetoresistive switch applications. Other examples are reports of unstable zinc blend forms of CrAs (Akinaga et al. 2000c) and CrSb (Zhao et al. 2001) that have been successfully prepared by ultrathin film deposition onto GaAs substrates. These materials are room temperature ferromagnets that are predicted to be completely spin-polarized. Clearly there is great potential for these metastable magnetic metal pnictides, since they may serve as excellent spin sources grown epitaxially onto technologically important semiconducting substrates.

Although the above mentioned pnictides appear to be half-metals, there is also considerable interest in other better known half-metallic materials such as  $\text{Fe}_3\text{O}_4$  (magnetite),  $\text{CrO}_2$ , and the family of Heusler alloys. Magnetite, although it is not a diffusive but a hopping conductor, both above and below a structural phase transition called the Verwey transition ( $T_v \sim 120\text{K}$ ), is a ferrimagnet with a transition temperature of 865K (Mott 1990). A ferrimagnet is a material in which the magnetic ions are coupled anti-ferromagnetically where the two sub-species of magnetic ions have different moments such that there is a net magnetization upon ordering. Recent experiments pioneered by Coey et al. (Versluijs, Bari, and Coey 2001) in Ireland have shown that small-area point contacts can yield enormous magnetoresistive effects. Their initial results,

defined by the inverse slope of the I-V characteristic at 0 bias voltage, demonstrate a remarkable negative magnetoresistance. Furthermore, the curves are hysteretic, making it possible to use these materials as memory elements and switches. The effects are very large, and although these initial results indicate the potential, they were made on break junctions of single crystal material. The possibility of structuring single crystal films of magnetite and performing nanofabrication patterns on them should lead to highly controlled room temperature giant negative magnetoresistive devices.

In principle, the Heusler alloys for which the term “half-metals” was originally coined would appear to be a tantalizing materials system. They suffer, however, from the fact that their materials properties can vary widely unless these complex three component materials are produced stoichiometrically. The formula is ordinarily  $\text{Ni}_2\text{MnX}$  ( $X=\text{Ga,Ge,In}$ ). Of these only the Ga material shows a well defined transition temperature above room temperature and a well defined hysteresis (Dong, Chen, and Palmstrom 1999). The others exhibit nonclassical magnetization behavior as a function of temperature and cannot simply be described by well established models. Furthermore, it is very difficult to produce thin films of these on semiconductors of technological significance. A notable exception is  $\text{NiMnSb}$  with a  $T_C \sim 730\text{K}$ , which has been studied in the tunneling geometry (Tanaka et al. 1999). Research needs to be continued, and it is expected that developments in the United States, Europe, and Asia will lead to some breakthroughs in this materials system.

$\text{CrO}_2$  has been a source of great interest for possible spintronics applications ever since it was discovered through Andreev reflection measurements that this material, at least at low temperatures, is essentially 100% spin-polarized (Soulen et al. 1998). This is the only binary oxide that is both a ferromagnet and a metal. Although it is widely used in recording applications, until recently there was little known about its electronic structures, although various band structure calculations indicate that it is half-metallic (Schwarz 1986).  $\text{CrO}_2$  crystallizes in the rutile structure, has a ferromagnetic transition temperature of 400K, and an integral magnetic moment of  $2\mu_B$  per Cr ion. The material is difficult to produce in single crystal form epitaxially onto any substrate other than rutile (Chamberland 1977), although textured materials can be grown onto sapphire (Ishibashi et al. 1978). There are no reports of  $\text{CrO}_2$  ever having been produced in textured or epitaxial thin film form onto GaAs or Si. Furthermore, magnetotransport properties of this material are complex (Watts et al. 2000). The Hall resistivity, as a function of magnetic field, does not behave like a ferromagnetic metal, for temperatures between that of liquid He and 100K, but rather shows a crossover as a function of field indicative of both hole and electron contributions. The data are most easily analyzed in terms of a two-band approximation. In the spirit of this type of analysis, one finds that there are both highly mobile holes moving in concert with more numerous but less mobile electrons (Watts et al. 2000). Thus the band structure is somewhat more complex than initially assumed. However, all transport data examining the spin polarization, which includes various forms of analysis of Andreev reflection data (Ji et al. 2001; Parker et al. 2002) as well as Tedrow-Meservey type tunneling spectroscopy (Parker et al. 2002), strongly support the contention that the carriers are completely spin-polarized at low temperatures in this material. There is also evidence from spin-polarized photoemission that 80% of the polarization exists even at room temperature. Suffice it to say that the existence of highly spin-polarized carriers at room temperature and above has to be confirmed in an all electronic device structure before  $\text{CrO}_2$  becomes a candidate for spin sources or detectors for application.

## CONCLUSIONS

This review of materials activities in spin electronics for semiconductor applications has demonstrated that much of the new materials effort is driven by Japan's innovation. In the opinion of the WTEC panelists, this dominance may be traced back to Japan's recent history of leadership in materials development in, for example, the mixed valence perovskites. It is not an overstatement to suggest that much of the fundamental work on single crystals of manganite and high  $T_C$  materials was performed on single crystals emanating from Tokura's group in Japan. Furthermore, the government of Japan made an early decision to fund the project “Spin Controlled Semiconductor Nanostructures” in 1996 with an award in excess of \$6,000,000. This program, led by Professor H. Ohno, Tohoku University, was a great success and pulled together a large number of the practitioners of materials research in transition metal and rare earth compounds and alloys.

Finally, and this cannot be emphasized too strongly, there exists a strong synergistic effort between theory and experiment. A very good example of this synergy is the large scale computational effort of the group of Katayama-Yoshida and the response by many groups, including that led by Koinuma, using combinatorial synthesis to attempt to find the predicted properties. Although the United States has recognized that materials research is going to be a vital component of any successful new spin electronics semiconductor technology, and there are a number of excellent efforts in semiconductor spintronics, the support for this work has been primarily championed by DARPA. A broader program involving other government funding agencies will be necessary to compete favorably in the area of materials synthesis and fabrication. It is, therefore, noteworthy that the NSF announced, in November 2001, a new initiative entitled “Spin Electronics for the 21<sup>st</sup> Century.”

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## CHAPTER 3

# FABRICATION AND CHARACTERIZATION OF MAGNETIC NANOSTRUCTURES

Michael L. Roukes

### BACKGROUND AND OVERVIEW

Three classes of modern technological advances have greatly invigorated the investigation of magnetism:

- *Heteroepitaxy* — which enables the creation of entirely new types of crystalline magnetic alloys and ferromagnetic semiconductors, as well as the definition of extremely high quality interfaces between materials systems
- *Micro- and nanofabrication methods* — that allow patterning ferromagnetic materials down to the dimensions of single domain magnetism and the definition of electrical devices exhibiting pronounced “spintronics” phenomena
- *Magnetic imaging* — new methods that provide resolution of the local structural and magnetic properties of new materials and devices on the nanometer length scale.

Concerted application of these advances now provides the capability to observe, control, and engineer magnetic phenomena at the nanoscale. This, in turn, is enabling the creation of entirely new magnetic materials and spintronic devices (Wolf et al. 2001; Prinz 1998).

### FABRICATION OF MAGNETIC NANOSTRUCTURES

#### Overview: “Top Down” vs. “Bottom up” Approaches

There are two distinct paths that can be taken toward fabrication of nanometer scale structures. The first approach is to pursue fabrication from the top down; namely, using subtractive patterning techniques to “sculpt” existing materials into desired forms. The second is synthetic, in other words building through additive assembly of subunits. In this case the concern is with assembly atom-by-atom from the bottom up. Each approach has its particular advantages.

Tried and true top down lithographic methods yield structures that possess seemingly arbitrary complexity from a wide range of materials. State-of-the-art methods achieve structural dimensions into the sub-10 nm domain, but the resulting features are rather coarse and irregular on the atomic scale. However, scaling the process upward slightly, to yield ten or one hundred nanometer features, allows definition of structures that are very well controlled, with the achievable variety comparable to that at the micron scale through conventional microfabrication processes.

In contrast, a variety of bottom up approaches are being explored, most still in their infancy. Although it is possible to realize individual molecular-scale electrical devices, fabrication is still somewhat of an art rather

than a technology. Here, by an electrical device, the meaning is identical to that for top down structures: forming a device requires connections that transition from the macroworld continuously downward to the nanoscale where device functionality is obtained. Fabrication is still in the realm of “one-of-a-kind”: it is laborious, and the yields are exceedingly low. Nonetheless realization of such structures begins to open the window to performing research on atomic scale spin transport.

A complement to patterning individual devices is the creation of nanophase materials through various chemical self-assembly processes. These can provide novel forms of “bulk” properties based upon alteration of structural configurations at the mesoscale, i.e., at the realm between the microscopic and the macroscopic. Such materials can be embedded within more conventional devices at the micro- or even macroscale to yield new forms of functionality. Here again the emergent properties are derived, as above, at the nanoscale, but the properties involve the response of ensembles of nanoscale entities rather than a single one. Novel forms of chemical self-assembly and epitaxial growth are being employed in this field. In some sense, the distinction between “materials” research and fabrication of “nanostructures” is blurred; however, this research area is clearly a separate thrust given the unique and central theme in top down methods of building robust connections to individual nanometer scale devices.

#### **Advances with “Top Down” Techniques**

Advances in nanofabrication techniques such as electron beam lithography yield local, 2D precision that verges on the atomic scale (Vieu et al. 1997). However, achieving success, not to mention reproducibility, in the single digit nanometer scale regime is problematic, at best, by such top down lithographic methods. Given the intrinsic randomness of the electron-sensitive materials (“resists”) that enable nanoscale patterns to be written and transferred, structures generated by this approach cannot be defined with atomic precision. Scanned probe approaches to lithography involving the atomic force microscope (AFM) or scanning tunneling microscope (STM), in general, must deal with similar limitations.

Progress in top down defined magnetic nanostructures is ongoing on many fronts. Early demonstrations of spin injection with metals were performed via top down methods; namely, in devices patterned by microlithography (Johnson and Silsbee 1985). The most recent investigations, particularly in semiconducting materials, have been enabled by state-of-the-art electron beam nanofabrication (Monzon and Roukes 1999). This has led to refined interpretation of spin injection in metals (Jedema, Filip and van Wees 2002). Techniques involving innovative fabrication of nanostructures for shadow mask making have enabled reproducible patterning of extremely fine-scale magnetic nanostructures (Matsuyama, Komatsu and Nozaki 2000). An alternate approach to electron beam lithography is achromatic interferometric lithography, which, when combined with various forms of pattern transfer, can yield arrays of highly reproducible magnetic nanostructures (e.g., Savas et al. 1999). Ion irradiation lithography, using a mask patterned by electron beam lithography, is a possible route to mass production of magnetic nanostructures (Devolder et al. 1999; Terris et al. 2000). Another possible approach to realizing such nanostructures *en masse*, is through techniques of nanoimprint lithography (Wu et al. 1998; Moritz et al. 2002).

#### **Advances with Bottom Up Techniques**

Modern techniques for materials growth now enable growth of crystalline materials epitaxially, i.e., one atomic layer at a time. This truly remarkable example of atomic scale control is attained by working within constraints imposed by nature. Through a careful balance of material deposition rates and the temperature dependent surface mobilities of the just-deposited species, each successive layer that is deposited can assume atomic registry with the one beneath. Epitaxial growth has revolutionized how researchers think about semiconductor materials and has enabled a host of new digital “alloys” to be created.<sup>8</sup> Although this is a

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<sup>8</sup> For an early discussion, see Sundaram, Gossard and Holtz (1991). For a recent spintronics example, see Luo et al. (2002).

very real first step toward nanotechnology — that is, assembly of functional structures with atomic precision — the atomic control achieved is, except for special cases,<sup>9</sup> in only one dimension.

There is also an emerging class of chemical self-assembly processes that derive remarkably precise features and structures on a size continuum spanning from the mesoscale to the nanoscale (Whitesides and Boncheva 2002). These processes are based upon special and remarkable symmetries in natural chemical reactions, which occur under special conditions. The conditions provide hierarchical “super” structure in addition to the nanoscale specificity, order, or crystallinity defined at the sub-nm scale by the chemical bonds themselves. Macroscale order emerges in these special cases, yielding a naturally occurring super-periodicity or granularity to the chemical assembly. An important example in this class is the growth of self-assembling quantum dots (Collier, Vossmeier and Heath 1998), which are becoming technologically important for biooptics and photonics. This area is now being rapidly advanced and includes some novel applications to spin electronics (e.g., Black et al. 2000).

Figure 3.1 shows an example of a vertically coupled quantum dot, a hybrid device that involves both bottom up epitaxial growth of a semiconductor heterostructure and top down patterning to impose lateral electron confinement. This structure has been developed in the laboratory of Prof. Tarucha at the University of Tokyo in Japan, where it has been used to study electron addition spectra and the spin-dependent single and two electron states in quantum confined systems. This represents a class of devices that may ultimately hold significant potential for quantum computing (Loss and DiVincenzo 1998).

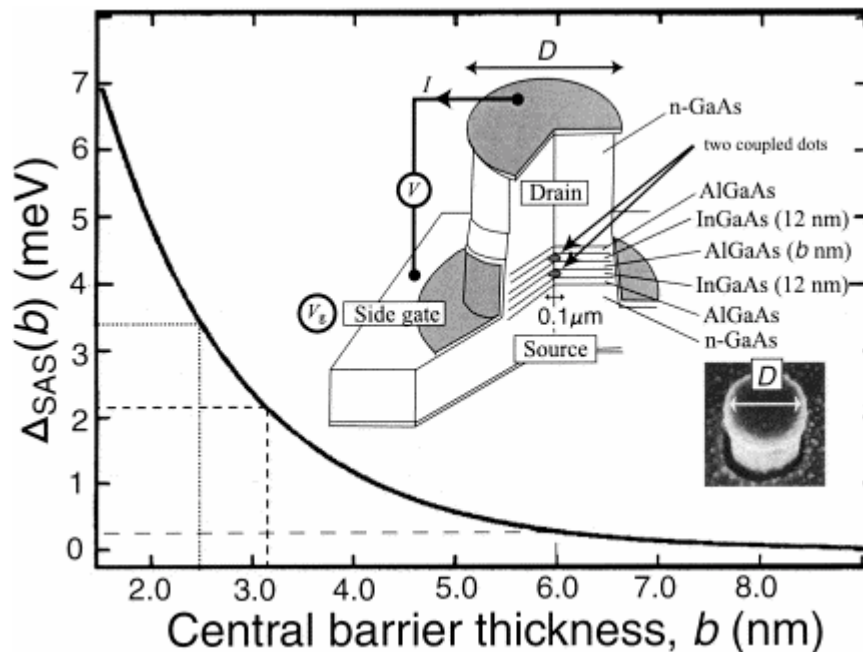


Fig. 3.1. Vertically coupled quantum dots used to construct the quantum dot molecule (Amaha et al. 2001).

By contrast, it is possible to manipulate atoms directly via the STM to achieve true atomic assembly from the bottom up.<sup>10</sup> By its nature, this process is atomically precise. So far, however, this is not a general approach; the requisite conditions for success are quite specialized and restrictive, and a relatively small subset of materials (elements) have been studied to date. Although it extends a remarkable technique for fundamental research, this approach involves a complex and large apparatus, by atomic standards. Hence, it is a slow process that appears to offer little prospect for upward scalability, either for large entities or for mass

<sup>9</sup> The technique of “cleaved edged overgrowth” allows formation of quantum wires and dots with atomic precision (Pfeiffer et al. 1993). For a recent example see de Picciotto et al. (2001).

<sup>10</sup> For an early example, see Eigler and Schweizer (1990).

production. Such techniques clearly hold important prospects for the future in nanotechnology. But it is far from clear at present how one might define complex systems such as complex multi-element spintronic devices. Nonetheless, important progress is being made in assembling magnetic materials involving just a few atoms (e.g., Crommie 2000).

One must conclude that there is still quite a separation between the fields of nanoscale devices and the techniques of bottom up or self-assembly. The advent of preprogrammed, bottom up self-assembly of arbitrarily complex systems, with connections to the macroworld, and complexity comparable to those built every day by top down approaches in microelectronics, is rather remote at this point. In other words, it seems clear that the top down approach will likely remain the method of choice for a good while longer for realizing preplanned, arbitrarily complex devices at the nanoscale that are connected to form functional electronic systems.

### **CHARACTERIZATION OF MAGNETIC NANOSTRUCTURES**

Imaging and metrology of magnetic structures are at the heart of the systematic development and characterization of magnetoelectronic materials and devices (Freeman and Choi 2001). The requirements are quite demanding. In the case of nanometer-scale magnetic systems, not only must the spatial resolution of the imaging methods employed be at, or better than, the minute structural dimensions of the samples; but the technique must also have the requisite sensitivity to sense a very small total magnetic moment. The ultimate limit is sensing individual magnetic moments from magnetic nuclei or electron spins.

Current approaches that satisfy these requirements span the scale of size and complexity from true facilities-based approaches involving synchrotron radiation (Kortright et al. 1999) or small-angle neutron scattering (Wiedenmann 2000) to large single laboratory instruments such as those used for electron holography (Mankos, Scheinfein and Cowley 1995) to table top instrumentation used in various forms of magnetically-scanned probe microscopy (Dahlberg and Proksch 1999). The section below summarizes several representative investigations using these approaches from among the wide spectrum of emerging applications.

These techniques employ two basic means of interacting with the sample, which Freeman and Choi (2001) have recently categorized as “field mapping” and “magnetization mapping.” The former involves imaging of the external, fringing fields around magnetic structures; the latter involves direct spatial imaging of the magnetization within the sample.

#### **Magnetic Imaging: Broad Field Techniques**

X-ray magnetic circular dichroism has emerged as an important technique for showing the local magnetic environment of thin films and interfaces with extremely high resolution (Stohr 1995; Freeland et al. 1999; Idzerda, Chakarian and Freeland 1999; Wende et al. 1998). Also complementing this approach is small angle neutron scattering (Loffler, Wagner and Kostorz 2000), which yields information about magnetic environments down to the atomic scale. Among such high resolution approaches, a unique advantage of electron holography (Smith et al. 2000) is its ability to provide information about the magnetic environment of individual nanostructures.

#### **Magnetic Imaging: Scanned Probe Techniques**

In comparison to these facilities- and laboratory-scale approaches, an exciting new slate of compact instruments have been developed that are based on the principles of scanned probe microscopy. The forerunner of these approaches is magnetic force microscopy (MFM) (Proksch 1999), which involves a micro- or nanomagnet affixed to the end of a mechanical force detector. Its first realizations allowed scanning across ferromagnetic samples to provides sensing of local field gradients; significant refinements to the technique have since emerged.

Scanning tunneling microscopy (STM) is one of the premier current tools for studying atomic structure. STM is a powerful, but rather specialized experimental technique that permits studies of the first few crystal planes at the surface of crystalline samples. In general, it requires extremely careful sample preparation and utilization of ultrahigh vacuum techniques, to allow imaging over reasonable time periods without obfuscating adsorbates. However, what is important in the present context is that this technique has recently been successfully extended to yield additional information, at the atomic scale, regarding the local magnetic properties of surface, or near-surface atoms in crystalline samples. This approach, called spin-polarized scanning tunneling microscopy (SP-STM) (e.g., Wiesendanger et al. 1990) achieves contrast, or resolution, of magnetic properties through the spin-dependent tunneling probability between a magnetic sample and a special magnetized probe tip. This probe provides spin-polarized electrons for tunneling, and its polarization may arise from either direct incorporation of ferromagnetic materials or, alternatively, from circularly polarized optical excitation (to create a population of spin-polarized carriers). Preparation of these special tips, and understanding and controlling the artifacts they introduce into the measurement, have not been trivial challenges. SP-STM is being increasingly employed to elucidate, at the atomic scale, magnetic properties at surfaces. A striking success is the recent, direct observation of the predicted 2D antiferromagnetic state of a pseudomorphic Mn monolayer grown on W(110) surface (Heinz et al. 2000; Bode, Getzlaff and Wiesendanger 1998).

Ballistic electron magnetic microscopy (BEMM) is a recent, promising variant on SP-STM (Rippard and Buhrman 1999). This new method is based upon ballistic electron emission microscopy (BEEM) (Kaiser and Bell 1998), a technique that allows the injection of hot carriers into semiconductors across a Schottky barrier. In BEMM, the variation is that the scanned STM tip injects current across thin ferromagnetic films layers separated by a thin film of normal (i.e., non-ferromagnetic) metal. Magnetic imaging results from spin-dependent scattering of electrons traversing the ferromagnetic films, in direct analogy with the giant magnetoresistance (GMR) effect in the current perpendicular to the plane (CPP) geometry. The spin valve structure atop the Schottky barrier is an integral part of the magnetic imaging. Structures to be imaged are fabricated on top of this somewhat complex structure. Since BEMM is derived from scanned tunneling, it can provide atomic resolution in the same manner as its unpolarized analog STM. High resolution BEMM images permit resolution of magnetic domains on the submicron scale. However, to achieve this resolution a fairly sophisticated underlying structure has to be deposited for each sample to be studied.

Each of these techniques has its own regime of applicability given the significant, respective complexity for each. In other words, none can truly be called generic. Ballistic microscopy enables observation of the properties of buried interfaces, whereas SP-STM interactions probe only surface or near-surface atoms. The former involves preparation of samples upon special substrates comprising special magnetic and/or electrical layers for the BEMM and BEEM processes, respectively. Given the extended path of the imaging current through these layers, there is an attendant angular spread of the emitted electrons that blurs spatial resolution compared to that obtainable with SP-STM, which is strictly at the surface. However, imaging in SP-STM requires careful preparation, and subsequent characterization, of a spin-polarizing tip.

### **Magnetic Imaging: Methods Based Upon Electron Microscopy**

Electron microscopy is one of the most important and widely employed imaging tools. State-of-the-art, commercially available systems are capable of providing atomic resolution. There are several methods in which these systems have been successfully modified to provide local information of magnetization and magnetic fields with high spatial resolution.

Scanning electron microscopy with polarization analysis (SEMPA) (Dahlberg and Proksch 1999; Stohr 1995; Freeland et al. 1999; Idzerda, Chakarian and Freeland 1999) is a technique that provides information about sample magnetization with high spatial resolution. It employs a narrowly focused, scanned high energy beam of electrons in conjunction with polarization-sensitive detectors. Scanning the sample with the beam induces low energy secondary electron emission in the usual way. What is different is that magnetic materials imprint information about their local magnetization onto the secondary electrons in the form of an induced spin polarization (McVitie et al. 1995; Scheinfein et al. 1990). This polarization can be analyzed by spin-sensitive readouts such as the Mott detector (Barnes et al. 1999). Given that SEMPA measures the magnitude and direction of the magnetization, it is unique in producing a direct vectorial map of the

magnetization. However SEMPA is a surface technique only; the small inelastic mean free path of the secondary electrons assures that only those generated within the outermost atomic layers of the sample can emerge (Abraham and Hopster 1987).

Local high spatial resolution mapping of magnetic fields can be realized by two variants on transmission electron microscopy. Lorentz microscopy employs a transmission electron microscope (TEM) to probe the local field-induced deflection of a high energy (100 to 1000 keV) electron beam. This deflection arises from the Lorentz force in regions where a local magnetic field exists and is directly proportional to the average field along the electron trajectory. Lorentz microscopy can yield lateral resolution of  $<10$  nm but requires thin samples to permit appreciable electron transmission (McVitie et al. 1995). A second technique is that of electron holography (Cohen 1967), an electron interferometric method also based upon a high resolution TEM. Here a reference beam is added to the transmitted beam and phase shifts arising from the local field (actually local vector potential) provide a contrast mechanism. The interference fringes that result can be interpreted to reconstruct the local fields about an object (Tonomura et al. 1982).

### Microdevices for High Resolution Magnetic Measurements

The immediate successor to the MFM technique was scanned superconducting quantum interference device (SQUID) microscopy (Kirtley and Wikswo 1999). Scanned SQUID magnetometry provides direct information about the local fields at the microscale. One of the powerful attributes of this technique for imaging small magnetic systems is that no magnetic field is involved (from the sensor) in the measurement. Hence, the perturbation imposed upon low coercivity samples is truly minimal. However, the geometry of the nanoscale superconducting loop used is, of necessity, slightly larger than the dimensions of the smallest nanomagnets used in MFM. Hence the SQUID approach is not able to provide comparable spatial resolution. But its high sensitivity has enabled an exciting new class of important studies of domain reversals in individual single domain nanomagnets (see Figure 3.2).

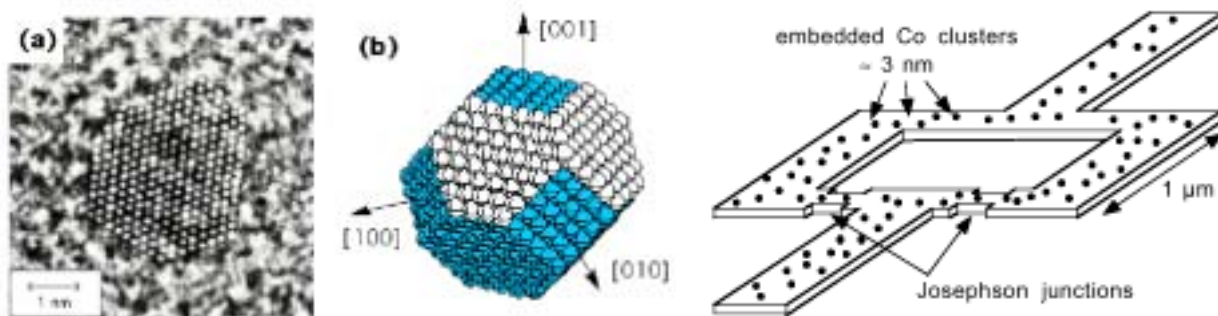


Fig. 3.2. High resolution transmission electron microscopy of a typical 3 nm cobalt cluster exhibiting an fcc structure (left, a); drawing of the cobalt cluster (center, b); schematic drawing of a microbridge-DC SQUID containing a low density of 3 nm cobalt clusters (black dots) (right, c). No more than 5 particles are located in a microbridge (CNRS, Grenoble, France; Wernsdorfer, Mailly and Benoit 2000).

An alternative approach that is similarly non-perturbating is scanned Hall micro- or nanosensors (Chang et al. 1992). This method has several very significant advantages: it is much simpler to implement than the SQUID-based approach, and it is operable at room temperature. Recently it has become apparent that cryogenically cooled nanoscale semiconducting Hall probes can provide sensitivity comparable with SQUID magnetometers (Monzon, Patterson and Roukes 1999) but without the need for low temperatures. The devices and technology of scanning such Hall probes have become rather sophisticated (Geim et al. 1997; Schweinböck et al. 2000) and is being applied to provide new insights into micro- and magnetic systems, as well as into studies of vortex excitations in novel superconducting materials.

In the past ferromagnetic resonance has been carried out using uniform external fields both for magnetic polarization and microwave excitation. Hence the entire sample has typically contributed to the resultant signal. Recently a scanned probe technique for magnetic resonance called magnetic resonance force microscopy (MRFM) has emerged, which provides local information for the cases of EPR and NMR. This

technique has been extended to ferromagnetically coupled spin systems (Zhang, Hammel and Wigen 1996) in a technique called ferromagnetic resonance force microscopy (FMRFM). Resolution of layered magnetic structures (Zhang et al. 1998) and direct imaging of magnetostatic modes in ferromagnetic micro- and nanostructures (Midzor et al. 2000) has been demonstrated (Figure 3.3). With the use of nanomagnets providing very strong local gradient fields, the technique is now beginning to illustrate how local imaging can occur even in the case of long-range ferromagnetically coupled spin systems (Hammel et al. 2003).

An alternate approach that provides local detection of ferromagnetic resonance involves coupling a spatially confined microwave field to the sample, rather than using a nanomagnet probe as in the case of FMRFM. In this technique called scanning near field microwave microscopy (Lee et al. 2000), the spatial resolution is determined by the size of the microfabricated loop used to generate a local microwave frequency magnetic excitation field; currently resolution slightly below the 100  $\mu\text{m}$  scale has been attained.

- Lateral scan: local **detection** of magnetization associated with magnetostatic mode
- Suppression of all modes toward edge of sample
- Non-monotonic dependence of  $n=3$  mode

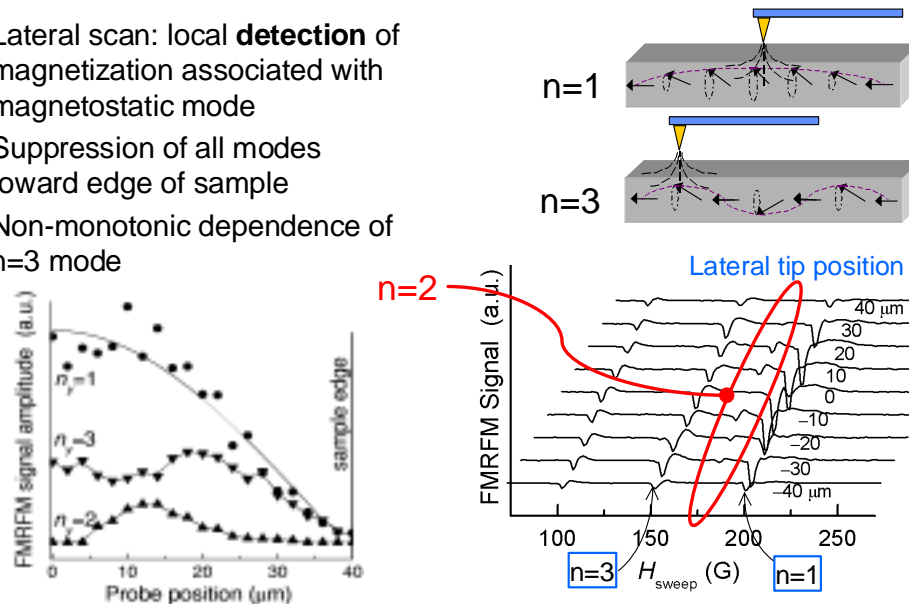


Figure 3.3. Ferromagnetic resonance force microscopy (reprinted by permission from Hammel et al. 2003; © 2003 IEEE).

Most of the techniques described above have, to date, provided information about the time average magnetic properties, or dynamics, for processes slower than the microsecond scale. By contrast, powerful new optical techniques have been developed that enable tracking the evolution of fast microscopic magnetic events in real time. Among these are optically pumped SQUID magnetometry (Awschalom and Warnock 1989) and time resolved Kerr microscopy (Choi et al. 2001). The application of such techniques will play a very crucial role in elucidating spin relaxation processes in magnetic nanostructures, as well as in unraveling the precise details of magnetization reversal processes. This information is essential to the iterative refinement of advanced magnetic materials and devices.

## NEAR TERM PERSPECTIVE AND INTERIM CONCLUSIONS

Crucial to the advancement of spin electronics as a whole is the concerted development of the subfields of fabrication and imaging of magnetic nanostructures. A significant effort is now underway worldwide in both areas.

Fabrication of magnetic nanostructures is being pursued broadly, through both top down and bottom up methods, by many different laboratories. At present the most productive approaches, in terms of realizing magnetoelectronic nanoscale devices, are the top down methods — especially those techniques based upon electron beam lithography, given the immense flexibility it provides. However, scanned probe methods are

beginning to provide both an alternate means to top down fabrication and a way to define unique structures by bottom up assembly with spatial definition at the atomic scale. Simultaneously, techniques of self-assembly are beginning to allow fabrication of micron-scale devices that derive new functionality from having embedded within them uniform ensembles of nanoparticles.

### Regional Comparisons

Laboratories equipped to employ electron beam lithography to realize nanometer scale structures are becoming increasingly well distributed throughout major research centers in Japan and Europe. By contrast, scanned probe assembly and chemical self-assembly techniques are being pursued by only a few centers of excellence within these countries.

Advanced imaging techniques are not as widely deployed. Several groups in Europe are among the pioneers in scanned probe techniques for magnetic systems. Electron beam imaging techniques providing field resolution, in turn, have been pioneered both in Japan (especially electron holography) and in Europe.

At the present time, the United States has centers of excellence in all the above areas, although the representation in some cases is through only one or two laboratories in each of the respective areas.

The site reports included in the appendix to this report provide details on activities ongoing in both Europe and Japan. In general, Japan is providing significant support for advanced commercial research instrumentation related to spin electronics and is strong in nanoelectronic device fabrication. Spintronic devices are emerging there, supported by a growing university research capability. Europe has several important centers of excellence in this field, with significant long-term support, both in terms of research budgets and the provision of permanent research staff. This kind of long-term support has enabled European labs to pursue long range projects, including engineering of complex, novel imaging instrumentation and advanced fundamental research in nanofabrication. The U.S. emphasis has been on its traditional strengths in entrepreneurial frontier activities. The second step, obtaining sustained support for infrastructure that enables advanced engineering, is now rare in the United States, especially due to a narrowing focus at industry laboratories.

### Conclusions

Spin electronics, and especially techniques for imaging and fabrication of nanoscale magnetic devices, are clearly still in their infancy. Concentration upon the core areas of spintronics is crucial to the success of the field. Success in realizing the potential payoff of spintronics — for applications ranging from low power, high density memory to solid state, spin-based quantum computation — will become more readily guaranteed as more laboratories enter the field. This, in turn, will require expanded support from funding agencies and from university research centers.

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## CHAPTER 4

# SPIN INJECTION, SPIN TRANSPORT AND SPIN TRANSFER

**Robert A. Buhrman**

### BACKGROUND AND OVERVIEW

#### Spin injection and detection

The efficient injection of charge carriers having a strong net spin polarization of controllable orientation into nonmagnetic electronic materials, particularly semiconductor device structures, along with the subsequent manipulation and detection of this injected spin polarization, is essential to the successful performance of a wide range of potential spintronics devices. The pioneering spin injection experiment of Johnson and Silsbee (1987), as well as the discovery of the giant magnetoresistance (GMR) effect (Baibich et al. 1988; Barnas et al. 1990) discussed elsewhere in this report, demonstrated over a decade ago that a strong nonequilibrium spin population can be generated in a normal metal by sending a current into it from a ferromagnetic electrode. This approach is effective because the current emanating from a ferromagnetic metal is generally substantially spin-polarized, typically >40% for the transition metal ferromagnets (Soulé et al. 1998; Upadhyay et al. 1998), since the electrical conductivity of its majority (spin up) electrons differs significantly from that of its minority spin (spin down) electrons.

Subsequent to the initial metallic spin injection work, Datta and Das (1990) proposed a current modulator device based on the electric field modification of spin precession in a narrow gap semiconductor. In this device, the spin-polarized electrons would be injected with the use of a ferromagnetic electrode that forms an ohmic contact with the semiconductor and would be detected with a second ferromagnetic electrode (spin analyzer) contact. This seminal proposal stimulated a number of efforts to realize this and related spin-based semiconductor device structures. The recent optical demonstrations of long spin coherence times and long spin diffusion lengths in compound semiconductors and successful experiments involving the optical manipulation of spins in semiconductor structures, discussed elsewhere in this report, have given renewed impetus to efforts aimed at realizing electrical spin injection into semiconductors. Yet, despite quite extensive research efforts on electrical spin injection from ferromagnetic metals, the results that have been achieved until quite recently have been limited.

In pursuing electrical spin injection into semiconductors in a manner analogous to the successful approach used for injection into normal metals, it was realized that the nature of the ohmic contact between the ferromagnetic metal and semiconductor was critical. For this reason InAs and related low band gap semiconductors have been the semiconductor material of choice since this material system, when contacted with most metals, has its Fermi level at or near the interface pinned in the conduction band. Thus the semiconductor in the vicinity of the metal acts as a semimetal, and a clean interface should provide an essentially ideal ohmic contact. While excellent materials and very careful processing and measurement techniques have been employed in such ohmic spin injection experiments, the resultant injected spin polarization in the semiconductor that has been inferred from the measurements has generally been rather small, or nil (Gardelis et al. 1999; Hu et al. 2001; Hammar et al. 1999; Monson 1999; Monson and Roukes

1999). In many cases the signals indicating a small, injected spin polarization could also be possibly attributed to a local Hall effect arising from the stray field of the ferromagnetic injector and/or spin detector electrodes (Hammar et al. 2000; Jedema, Filip, and van Wees 2001; Monson and Roukes 1999).

In these spin injection techniques, the anticipated nonequilibrium spin population is either measured potentiometrically with the use of another ferromagnetic electrode (Johnson and Silsbee 1987) or detected by the resistance presented when the current flows into a second ferromagnetic electrode, whose magnetic orientation is variable with respect to that of the injecting electrode. This latter spin valve detection scheme requires that the detector electrode be placed no farther from the ferromagnetic injector than the characteristic length for spin relaxation in the normal metal. The potentiometric detection scheme requires (1) that the spin-injected volume be sufficiently small so that a substantial increase in the spin-dependent chemical potentials can be induced and/or (2) a sensitive measurement of a small potential difference arising from the spin imbalance.

Over the past decade and more, researchers have analyzed interfacial spin transport (van Son et al. 1987; Valet and Fert 1993; Hershfield and Zhao 1997) in electronic multilayer systems in the diffusive regime. This is the appropriate transport regime to assume when considering both normal metal and semiconductor (semimetal) spin-injection experiments that utilize ohmic contacts to a ferromagnetic injector. While the key aspects regarding interfacial spin transport have been well established, it was the recent contribution by Schmidt and colleagues (2000) that explicitly drew broad attention to a fundamental difficulty in obtaining a significant nonequilibrium spin population in a semiconductor or semiconductor via diffusive transport from a ferromagnetic electrode. Due to the large disparity between the high (spin-dependent) density of states in the ferromagnet and the low (spin-independent) density of states in the semiconductor or semimetal, a simple model calculation shows that in most experimental configurations a substantial injected spin polarization can only be achieved if the spins in the ferromagnet are nearly 100% polarized. This half-metallic condition is possibly to be found in only a limited set of comparatively challenging materials such as, e.g., the Heusler alloys and  $\text{CrO}_2$ , not the conventional and more tractable ferromagnetic metals (e.g., Co, Fe, Ni, and their alloys). The appreciation of this key point regarding electrical spin injection has shifted the focus of much current research to different transport and spin injection regimes, as discussed below, with much of the remaining effort focusing on the successful development of fully polarized half-metallic ferromagnets for ohmic contact, spin injection applications. Of course an alternative approach is to employ a ferromagnetic semiconductor, or a paramagnetic semiconductor in the presence of a strong magnetic field, like the spin source, as discussed elsewhere in this report. Assuming the density of states of the ferromagnetic semiconductor is similar to that of the nonmagnetic semiconductor, this approach avoids the fundamental difficulty with spin injection from ferromagnetic metals, but until a room temperature ferromagnetic semiconductor is developed, which may be imminent, this approach is limited to low temperature applications.

Johnson and coworkers (Hammar and Johnson 2000; Johnson 1998; Johnson 2001) have been pursuing an approach to creating a spin polarization in a semiconductor that might avoid this obstacle to ohmic spin injection by taking advantage of the splitting of the spin degeneracy of electrons confined in a semiconductor 2D quantum well structure. The splitting is due to the spin orbit effect that can arise from an asymmetry in the confining potential (Bychkov and Rashba 1984). The result can be induction of a nonequilibrium spin polarization if the 2D electron gas is carrying a current (Vorob'ev et al. 1979). In this approach the spin polarization can be detected potentiometrically with the use of a ferromagnetic contact to the current-carrying 2D semiconductor structure.

Returning to the issue of spin injection from a ferromagnetic metal, if the impedance of the interface between the ferromagnet and semiconductor is high compared to that of the semiconductor structure, then the relative conductivities of the electrodes will not play a role in defining or limiting the interfacial spin-dependent transport. This situation can be achieved by employing either a ballistic transport structure or by utilizing a potential barrier at the interface that determines the current flow. In the first case, a ferromagnetic ballistic point contact to, e.g., an InAs semimetal layer, can be expected to result straightforwardly in the injection of a current into the semiconductor whose polarization would be relatively high (~40%) as determined by the ballistic spin-dependent interfacial transmission probabilities. These can be calculated from band structure

differences in a manner similar to that employed for ferromagnetic/normal metal interfaces (Stiles 1996; Kirczenow 2001). If the objective is to both inject and detect electrically a spin-polarized current after passing through, and possibly being manipulated within, the semiconductor, then a fully ballistic device will be required. Preferably this would be a device that consists of a semiconductor layer containing only one or a few modes or electron channels that ballistically link a ferromagnetic injector, or spin polarizer, to a ferromagnetic collector, or spin analyzer. While this type of ballistic device structure has been analyzed in considerable detail (Datta and Das 1990; Tang et al. 2000), its realization poses considerable experimental challenges.

If a potential barrier such as a tunnel barrier or a Schottky barrier is present at the ferromagnet/semiconductor interface, then the spin-dependent density of states of the ferromagnet should result in the injection of a spin-polarized current into the semiconductor when the interface is appropriately biased. Rashba (2000) has recently published a model calculation that provides a quantitative analysis of the conditions necessary for this approach to be effective when combined with a second potential barrier at the semiconductor/ferromagnetic collector interface for the purpose of spin valve detection of the spin polarization of the exiting current. For effective spin injection across a potential barrier the requirement for the barrier and the bias conditions is basically that the transport be limited by the spin-dependent transport rates across the interface and not by the spin-independent transport through the semiconductor. For a Schottky barrier device, this requires that the diode be back biased. Of course, it is also essential that there be no significant spin-flip scattering at the interface or strong spin-orbit scattering as the injected carriers pass through the depletion layer of the semiconductor.

With the use of a scanning tunneling microscope (STM) that employed a ferromagnetic tip, Alvarado and Renaud (1992) showed some time ago that a vacuum tunnel barrier could indeed be used to effectively inject spins into a semiconductor. More recently LaBella and coworkers (2001) have been using a similar STM technique to examine the spatial dependence of the effectiveness of spin injection by tunneling and to correlate the local spin injection probability with semiconductor surface structure. In these experiments the circularly polarized electroluminescence that is emitted as the injected electrons recombine is employed as the means of assessing the degree of polarization of the injected current. This optical detection of nonequilibrium spin polarization avoids the difficulty of electrical detection and is comparatively direct. However, careful experimentation and thorough analysis are still required to ensure that all alternative sources of circularly polarized optical emission have been ruled out or properly taken into account when deducing a spin polarization in this manner (Jonker et al. 2001).

The highly successful development of ferromagnet/insulator/ferromagnet tunnel junctions with high tunneling magnetoresistance has demonstrated that insulator tunnel barriers can also result in the conservation of spin during the tunneling process. Consequently a number of research groups have begun to pursue experiments focusing on spin injection via ferromagnet/insulator/semiconductor (FIS) tunnel junctions. However, while silicon dioxide can be used to form a very good and thin tunnel barrier on Si surfaces, the spin-dependent tunneling properties of such tunnel barriers have yet to be reported, and MIS diodes are quite difficult to fabricate with good electrical properties on compound semiconductor surfaces.

The alternative approach, particularly appropriate for compound semiconductors, is to form Schottky barriers with ferromagnetic electrodes, and this is currently being pursued by a number of groups investigating spin injection. The epitaxial growth of the ferromagnetic thin film on the semiconductor to form an abrupt, high-quality Schottky barrier interface is expected to be quite important, and this task is receiving careful attention (Chen et al. 2000). Here again electroluminescence is generally, if not universally, employed to establish the degree of spin polarization that is achieved in such spin injection experiments. An interesting variation on the spin-injection investigation is the "spin ejection" measurements recently reported by Crowell and coworkers (Isakovic et al. 2001). Here a careful and extensive examination has been made of the spin-dependent transport of spin-polarized carriers that are optically excited in a GaAs layer and then transit across a Schottky barrier into a Fe or FeCo electrode. Photocurrents with spin polarizations of the order of 1% have been observed to flow from the semiconductor to the ferromagnet under reverse bias. With respect to spin injection, perhaps the most striking result that has been reported to date by U.S. researchers is the work of the Hanbicki group (Hanbicki et al. 2002) where a back biased Fe/AlGaAs Schottky diode has been

reported to yield a spin injection efficiency of 30%, corresponding to an injected spin polarization from the Fe electrode of approximately 13%. Here also the spin polarization is deduced from analysis of the circular polarization of the sample's electroluminescence under reverse bias.

A different spin injection technique that does not necessarily require a spin-conserving ferromagnet/semiconductor interface employs spin-polarized electrons having energies that are much greater than  $E_F$ . One such "hot electron" spin injection approach is first to tunnel-inject electrons into a ferromagnetic layer at energies  $\gg E_F$  (Monsma et al. 1995; Rippard and Buhrman 2000). Since the majority spin and minority spin electrons have much different inelastic mean free paths, hot electron passage through, e.g., a 3 nm Co layer, is sufficient to result in a ballistic electron current that is more than 90% polarized. This highly polarized hot electron current can then continue on, possibly through a nonmagnetic spacer layer, to an underlying metal/semiconductor interface where a portion of the polarized beam will enter the semiconductor. If there is no substantial spin-flip scattering at the interface, then the ballistic electron current entering the semiconductor will be highly polarized; and the injection energy, relative to the bottom of the semiconductor conduction band, will be tunable via the tunnel injection bias. However, the overall efficiency, as defined by the ratio of the spin-polarized current injected into the semiconductor to the current tunnel injected into the spin filter, is low due both to the attenuation of the hot electron current in the spin filtering process and to the low ballistic transmissivity of any metal/semiconductor interface.

### Spin Transport

Spin lifetimes and coherent spin transport in semiconductor systems and thin film heterostructures are of primary concern to the spintronics field. While optical methods are quite effective in examining spin transport and coherence times in "bulk" semiconductors and quantum well structures, optical measurements can only indirectly infer the spin transmission efficiency for spin injection across interfaces. With regard to electrical spin injection and electrical spin detection, the issues of spin-dependent transport and spin-flip scattering during transit of Schottky barrier interfaces are of particular concern. Equally important is the related issue of spin relaxation and spin-orbit scattering of hot electrons while passing through the depletion region of a semiconductor layer. Thus an electrical means of directly examining spin-dependent transport across Schottky barrier interfaces, perhaps with a scanned probe instrument or a nanofabricated device approach, would be particularly valuable.

On the theoretical side, an extensive examination of the coherence of mobile spins in semiconductor systems has recently been completed by Flatté and colleagues (Flatté and Byers 2000). Related to this work is the interesting question of whether the quasi-independent electron model can adequately account for experimental results or whether many body or correlated electron processes are important in various aspects of spin transport. Flatté and others have examined this issue in the diffusive transport regime and have concluded that an independent electron approach is quite capable of quantitatively explaining the results of optical measurements of spin lifetimes, particularly the room temperature measurements. Sham and colleagues (Sham 1999; Sham and Ostreich 2000) have considered the low temperature regime where collective electron processes may well be important in determining the spin relaxation rates and spin lifetimes, although experimental results in this regime are quite limited.

On the device front, Flatté and Vignale (2001) have considered the possibility of constructing unipolar electronic devices by utilizing ferromagnetic semiconductor materials with variable magnetization directions. They have shown that such devices should behave very similarly to p-n diodes and bipolar transistors and suggest that these could be applicable for magnetic sensing, memory, and logic. Another interesting device is the spin-polarized solar battery that has recently been proposed and analyzed by Zutic and colleagues (Zutic, Fabian, Das Sarma 2001; 2001b).

### Spin Transfer

Some time ago, Berger showed that the spin-polarized current in a ferromagnet could exert a nonequilibrium exchange force on a domain wall, causing the domain wall to be dragged along in the direction of the spin current. More recently Slonczewski (1996; 1999) and Berger (1996) predicted that a spin-polarized current that is caused to flow between one relatively thick, and hence fixed, ferromagnetic layer through a

nonmagnetic layer to another thin-film “free” nanomagnet in an FNF current perpendicular to the plane (CPP) device configuration could, by spin-dependent scattering of the polarized current, transfer spin momentum from the current to the free layer. Depending on the direction of the spin current flow, this “spin transfer” effect can either force the free layer into parallel or antiparallel alignment with the fixed layer once the spin transfer force is strong enough to overcome the coercive field of the free nanomagnet. Since this spin transfer effect depends on the local spin current density, it dominates any effect of the Oersted self field generated by the current once the sample diameter is small enough ( $\leq 200$  nm) for a Co nanomagnet (Myers et al. 1999; Katine et al. 2000). Alternatively, if a strong external pinning field is applied to such a nanoscale CPP structure, the effect of spin transfer can be the excitation of strong, uniform spin wave precessional modes in the nanomagnet (Tsoi et al. 1998a; Tsoi et al. 1998b; Rezende et al. 2000). This nanomagnet precession could be a source of microwave radiation and possibly a source of a precessing spin current. Recent work has definitively demonstrated these spin transfer switching and spin wave excitation effects. These spin transfer phenomena open up the possibility of new types of nanoscale magnetic devices for memory and other spin electronics applications. Efforts to understand, enhance and utilize spin transfer phenomena are now being pursued at a number of research labs.

## RESEARCH ACTIVITIES IN JAPAN

The emergence and rapid growth of the field of spintronics is being driven by important contributions from scientists in all the major industrial nations that strongly support broad based research and development efforts and which have a strong research infrastructure.

In Japan, as discussed elsewhere in this report, a very extensive spintronics materials R&D effort is leading the field to a great degree, both experimentally and theoretically. Japanese researchers and their external collaborators are making very effective use of these new and improved materials systems for spin transport and spin injection research. A recent notable achievement in spin injection, published simultaneously with a report of a fairly similar low temperature spin injection experiment in Europe, has been the use of the ferromagnetic semiconductor  $\text{Ga}_{1-x}\text{Mn}_x\text{As}$  as a low temperature source for electrical spin injection into a GaAs layer across a p-n diode interface (Ohno et al. 1999). In this work, which was carried out through a collaboration between researchers at Tohoku University and the University of California, Santa Barbara, spin injection was convincingly detected through measurement of the circular polarization of the light emitted when the spin-polarized injected holes and unpolarized injected electrons recombined in an underlying InGaAs quantum well layer. The development of other ferromagnetic semiconductors with higher Curie temperatures for such spin injection applications is now a major focus of a number of Japanese research groups. The development of fully spin-polarized, half-metallic ferromagnets for spin injection and magnetic tunnel junction applications is also receiving rather widespread attention.

Extensive expertise and capabilities have been developed at a number of Japanese research laboratories in the area of transport studies of mesoscopic semiconductor systems, and several have been or now are beginning to apply these capabilities to the study of spin transport, spin manipulation, and spin injection. Almost certainly the most extensively equipped research laboratory in the area of mesoscopic and semiconductor device physics is at the NTT Basic Research Laboratories. A few years ago, Nitta and co-workers (1997) reported some seminal work demonstrating that the spin orbit interaction in a quantum well structure can be varied with the application of an electric field, applied through a gate voltage bias. This and related work were important steps towards the realization of the control of the precession of the polarization of an injected spin current as proposed by Datta and Das (1990). Yamada's group at the Japan Advanced Institute of Science and Technology (JAIST) also has established an extensive mesoscopic materials science and nanofabrication laboratory and has recently reported a careful measurement and study of the gate controlled spin splitting of the 2D electron gas in InGaAs/InAlAs heterojunction structures (Sato et al. 2001). A particularly large spin orbit coupling constant was obtained in this system, which could be important for the spin FET applications.

The NTT group, in collaboration with two European research teams, has also been pursuing spin injection research. A recent experiment made use of an interdigitated permalloy structure to make ohmic contacts to an InAs channel (Hu et al. 2001). By switching the magnetic orientation of alternating permalloy electrodes

the spin polarization of the injected current could be assessed from measurement of the changes in the resistance of the channel. The estimated spin polarization of the current through the ferromagnetic-2D electron gas interface was 4.5% in the experiment. While alternative explanations of the data based on local Hall effects and anisotropic magnetoresistance have to be considered when examining this type of spin injection data, the careful study of the temperature dependence of the effect gives good support to the spin injection interpretation. As is happening elsewhere in spin injection research, the NTT group has recently been examining the issue as to whether the presence of potential barriers at the ferromagnetic/ semiconductor interface will enhance the spin injection efficiency.

Spin-dependent tunneling between gated quantum dots is the basis of a recent proposal for a quantum bit that is receiving attention worldwide, both theoretically and experimentally. Professor Tarucha's group at the University of Tokyo (Sasaki et al. 2000), in collaboration with NTT researchers and with members of the mesoscopic electronics group at Delft, has been fabricating this type of spin device structure and is currently pursuing measurements to establish the longitudinal spin lifetime in the quantum dot. Theoretical work on the orbital and spin levels in such quantum dots is underway at NEC Fundamental Research Laboratories, where they are beginning to pursue spin-dependent transport in various nanoscale systems, including magnetically doped carbon nanotubes.

While spin-dependent transport in semiconductor systems is the focus of the majority of the spin electronics research activities in Japan, apart from extensive research and development efforts on magnetic tunnel junctions, there are also some notable activities in the area of spin injection and spin transport in metallic systems. For example, Prof. Otani at Tohoku University has been pursuing an innovative program in nanoscale magnetic phenomena in metallic systems, including studies of electrical spin injection and magnetic reversal in devices and measurements of spin transport lengths and spin injection efficiencies. Prof. Otani is moving to the Institute for Physical and Chemical Research (RIKEN), where he will be organizing and leading a new nanomagnetism research project.

## **RESEARCH ACTIVITIES IN EUROPE**

There is a very strong history of top rank research activities throughout Europe in the areas of magnetism and magnetic materials, semiconductor materials, and device physics research, particularly notable work in transport studies in the mesoscopic and nanoscale regimes. A number of research groups are now taking advantage of this expertise and of their world-class research capabilities to pursue a broad range of important spin injection and spin transport studies.

The investigation of spin-dependent interfacial transport in ferromagnetic nonmagnetic normal metal (FN) thin film multilayer systems some time ago led to the discovery and development of the giant magnetoresistance (GMR) effect. The understanding and theoretical models that were established in GMR research provided many of the foundation and the experimental approaches for the first generation of spin injection experiments, both into metals and into semiconductors. As noted above, these initial studies focused on diffusive spin transport across ohmic interfaces, with one major approach being the potentiometric detection of the nonequilibrium spin-dependent chemical potential that should develop near a FN interface due to the spin-polarized current flowing to or from the ferromagnet. Recently, Prof. van Wees's group at Groningen (Jedema, Filip and van Wees 2001) has reported the successful room temperature electrical detection with nanoscale potentiometric probes of a spin polarization injected into a Cu nanostructure by a current flowing from a nearby permalloy electrode. However, extensive efforts to detect a nonequilibrium spin population in a semiconductor when injected with a current flowing from a ferromagnetic electrode through an ohmic contact were not successful (Filip et al 2001). These results, together with the rather small spin polarizations deduced from other experiments on ohmic electrical spin injection into semiconductors, led Prof. Mollenkamp's group at Wurzburg (Schmidt et al. 2000), in collaboration with the Groningen team, to reexamine the spin injection issue. This important contribution, which was based on the understanding gained from the prior GMR related analyses, has had a major impact in evolving the current direction of much spin injection research worldwide.



The Wurzburg group has recently applied its extensive semiconductor materials capabilities to the successful demonstration of the low temperature electrical spin injection of polarized carriers, from a strongly paramagnetic semiconductor ( $\text{Be}_y\text{Mn}_x\text{Zn}_{1-x-y}\text{Se}$ ) in a high magnetic field, across a p-n diode interface into a nonmagnetic semiconductor layer (Fiederling et al. 1999). The circular polarization of the light emitted by the injected carriers as they recombined indicated that an injected spin polarization of approximately 90% was achieved in this important demonstration of effective spin injection.

In Europe, as elsewhere, a number of research groups are now pursuing experiments concerned with fabricating and employing high quality ferromagnetic metal/semiconductor Schottky barrier interfaces for room temperature spin injection applications. Prof. Ploog's group at Berlin has recently reported quite promising results from electrical injection across a back biased Fe-GaAs Schottky diode, with the spin injection efficiency again being determined from the optical emission of the recombining carriers (Zhu et al. 2001).

Other leading research teams in Europe engaged in semiconductor spin injection studies include the Heitmann group at Hamburg and the Bland group at Cambridge. Part of these spin injection efforts is also focused on developing half-metallic or nearly half-metallic materials, such as  $\text{CrO}_2$  and the Heusler alloys, as sources of fully polarized or nearly fully polarized spin sources for ohmic injection into the low bandgap semiconductors, InAs and (In,Ga)As. This is also a focus of Prof. Guenterodt's program at Aachen, Dr. Cohen's at Imperial College, and Prof. Coey's at Trinity College. At Trinity, there is a fairly unique focus on point contact spin injection.

Considerable attention is also being paid in Europe to the question of interfacial spin transport in the ballistic regime. To date, published reports in this area have been primarily theoretical, with recent contributions from Grundler at Hamburg (Grunder 2001), C.M. Hu and T. Matsuyama at Hamburg (Hu and Matsuyama. 2001), from Halle (Bruno and Pareek 2001), from a Wurzburg and Delft collaboration (Molenkamp, Schmidt, and Bauer 2001), and from Orsay (Fert and Jaffres 2001), but experimental work in the ballistic regime is said to be underway at several laboratories.

Ballistic and quasiballistic spin transport in the high energy, hot electron regime has been a major focus of Prof. Lodder's group at Twente. Their work continues on the study and development of the spin valve transistor, which utilizes for its functionality the spin-dependent inelastic scattering length of injected hot-carriers as they pass through a ferromagnetic multilayer base to a semiconductor collector. The knowledge regarding the spin-dependent scattering of hot electrons that this program is developing could also be quite useful for future hot electron spin injection experiments (Monsma et al. 1995; Jansen et al. 2001b).

The control of the spin orientation of carriers in a 2D electron structure by application of a gate electrode bias has been the subject of considerable research interest in Europe for some time. Researchers at Hamburg are particularly active in this area and have had significant collaborations with the NTT spin electronics group on this topic recently (Hu et al. 2001).

The proposal of Loss (Basel) and collaborators of a qubit based on gated spin-dependent tunneling between quantum dots is stimulating experimental programs to attempt to realize this new type of quantum computation device. An example of a recent quantum dot study relevant to this area is the study by Kouwenhoven and coworkers at Delft, in collaboration with NTT researchers, of the Kondo effect in an integer spin quantum dot (Sasaki et al. 2000).

Given the very strong research base and expertise in Europe in the area of GMR and magnetic tunnel junction research, it is not surprising that there is strong interest in the application of the spin-dependent scattering of polarized currents to manipulate the magnetic orientation of thin film nanomagnets. An important early demonstration of spin transfer phenomena was the point contact spin injection experiments of Tsoi and coworkers at Grenoble (Tsoi et al. 1998a; 1998b), which demonstrated that strong spin-polarized currents could excite uniform spin wave modes in thin film magnetic multilayers. At Lausanne, Wegrowe and coworkers have been actively pursuing the study of current-induced magnetization reversal in magnetic nanowires for the past few years (Wegrowe et al. 1999). Recently the magnetism group at Orsay has also begun research into the spin transfer effect, demonstrating the reversible, hysteretic switching of a free Co

nanomagnet with a spin-polarized current (Grollier 2001). A number of other research groups are also indicating interest in this new area of spin-based research.

## CONCLUDING COMMENTS

Spin injection, spin transport, and spin transfer research is being actively pursued in a number of top rank laboratories in Japan and in Europe. After a period of time in which experimental progress in the area of spin injection was slow, there now is a rapidly developing understanding of the advantages and challenges of various alternative approaches for spin injection, and the past year has seen rapid progress. Materials quality and materials control are clearly key issues in spin injection and spin transport research, particularly the challenge of forming nearly ideal ferromagnet/semiconductor interfaces for high efficiency spin injection. For progress to continue it will perhaps be necessary to substantially advance understanding and control of spin lifetimes at and near metal/semiconductor interfaces; new approaches for the study of spin-dependent transport at such interfaces would be highly desirable. The broad and impressive strengths in Japan in the area of new materials discovery and development can be expected to result in a number of additional leading contributions to the emerging spin electronics field. Similarly, the very well equipped thin film growth and nanofabrication laboratories that participate in spin electronics research in Japan can be expected to make major contributions in the years ahead. In Europe, broad theoretical and experimental capabilities are being brought to bear on the fundamental questions of spin transport in heterogeneous systems. The extensive expertise in the areas of magnetism, electronic and magnetic materials, and mesoscopic physics that is very well established in Europe also indicates that the upcoming decade will be a very productive and competitive time for spin-based electronics research efforts worldwide.

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## CHAPTER 5

# OPTOELECTRONIC MANIPULATION OF SPIN IN SEMICONDUCTORS

David D. Awschalom

### INTRODUCTION

In contrast to metals, an additional degree of freedom afforded by semiconductor spintronics allows direct optical access to electronic and nuclear spin states. During the last few years, optical measurements have demonstrated that it is possible to create, manipulate, transport, and store electron spin coherence in a variety of solid state materials. In addition, controlled interactions with nuclear moments via coherent electron spins have suggested the possibility of high density quantum storage at the nuclear level. A number of laboratories have developed research programs aimed at engineering a new generation of optoelectronic devices using a coherent ensemble of long-lived spin states (electron or nuclear) in which the direction or phase of the ensemble can be rapidly manipulated optically or electronically. This offers the potential of high performance optoelectronics, using the Faraday rotation produced by the ensemble, with very high speed optical switches, modulators, encoders, and decoders as candidate devices. The intrinsic speed of these devices may be in the femtosecond regime, and the power required to change the phase may be small if the phase of the spin ensemble can be manipulated by moving it within spin-engineered semiconductor heterostructures having differing  $g$  factors.

Quantum approaches exploit the ability of spins to exist in a superposition of states, where device operations rely on a controllable interaction to effect the desired changes in the amplitude or phase of the superposition. Quantum effects such as superposition and entanglement may ultimately be used as computational resources in future quantum computers. An active search is in progress for quantum mechanical two-state systems that would allow computations to be carried out before stored information is lost. Uses of quantum bits range from communication applications such as quantum key distribution, quantum encryption, quantum dense coding, quantum teleportation, and ultra precise clock synchronization to quantum computation, where solutions to problems such as the factoring of large numbers, data base searches, and functional optimization can be carried out in fractions of the time it would take a Boolean-based conventional computer. Spin-based semiconductor qubits may be one of the first implemented in a practical scalable quantum processor.

Significant challenges in this area that are being addressed by experiment and theory include the optimization of electron spin lifetimes, the detection of spin coherence in nanoscale structures, transport of spin-polarized carriers across relevant length scales and heterointerfaces, and the manipulation of both electron and nuclear spins on sufficiently fast time scales. In response, recent experiments suggest that the storage time of quantum information encoded in electron spins may be extended through their strong interplay with nuclear spins in the solid state. Moreover, optical methods for spin injection, detection, and manipulation have been developed that exploit the ability to precisely engineer the coupling between electron spin and optical photons. It is envisioned that the merging of electronics, photonics, and magnetics will ultimately lead to new hybrid spin-based multifunctional devices.

## OPTOELECTRONIC MANIPULATION OF SPIN COHERENCE IN SEMICONDUCTORS AND NANOSTRUCTURES

During the last few years, time-resolved optical experiments have revealed a remarkable resistance of electron spin states to environmental sources of decoherence in a wide variety of direct bandgap semiconductors and heterostructures (Awschalom and Kikkawa 1999; Kikkawa and Awschalom 1998; Kikkawa and Awschalom 1999; Kikkawa et al. 1997; Gupta et al. 1999). In these experiments, optical pulses create a superposition of the basis spin states defined by an applied magnetic field and follow the phase, amplitude, and location of the resulting electronic spin precession (coherence) in bulk semiconductors, heterostructures, and quantum dots. The data identify narrow ranges of doping concentrations where spin lifetimes in semiconductors are enhanced by orders of magnitude, culminating in the observation of spin lifetimes in bulk semiconductors that exceed a hundred nanoseconds. Time and spatially resolved measurements show that spin lifetimes can exceed hundreds of nanoseconds, and spin packets can be transported over a hundred microns in some of these systems. In heterostructures and quantum dots, nanosecond spin dynamics persist to room temperature, providing pathways to achieve practical coherent quantum magnetoelectronics. These results are summarized in Figure 5.1, in particular the time and position evolution of coherent spins in n-doped GaAs.

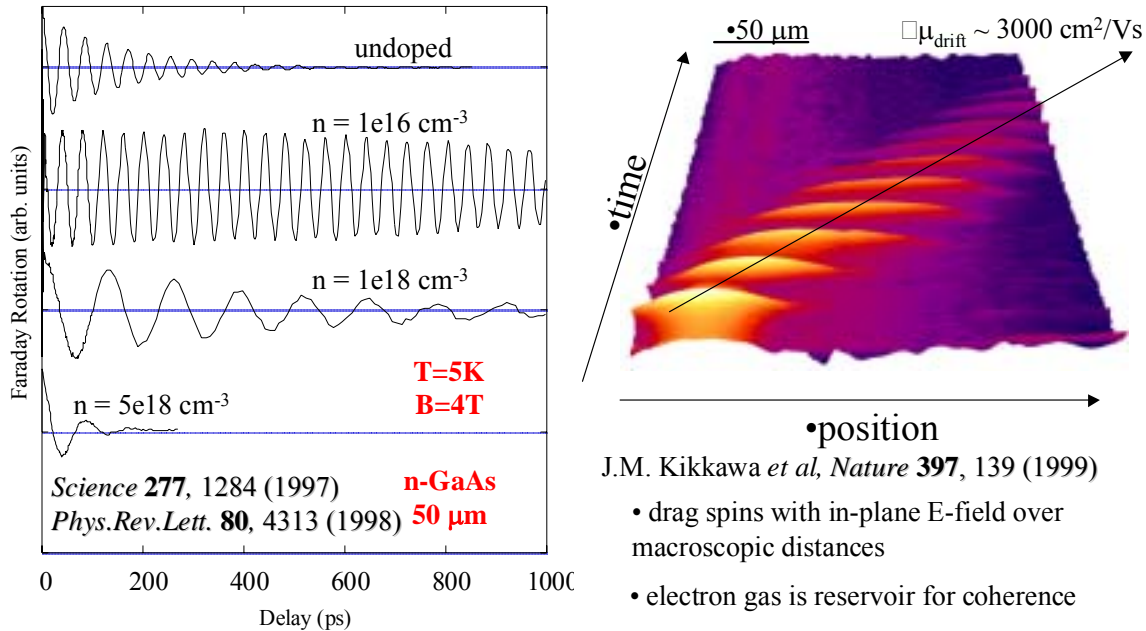


Figure 5.1. Creating and transporting spin coherence in semiconductors (Kikkawa and Awschalom 1998; Kikkawa and Awschalom 1999; Kikkawa et al. 1997; reprinted by permission from *Nature* 397, 139; © 1999 Macmillan Publishers Ltd.).

Recently, electrical gating has been integrated with semiconductor heterostructures involving materials with different  $g$  factors in order to control optically generated coherent electron spin precession. Spin gates have been fabricated where the electron  $g$  factor can be continuously tuned by displacing an electron wave function across a specially designed AlGaAs quantum well with parabolically graded Al concentration (Salis et al. 2001a). These spin-engineered devices demonstrate gate voltage mediated control of coherent spin precession over a 13 GHz frequency range in a fixed magnetic field of 6 T, including complete suppression of precession, reversal of the sign of  $g$ , and operation up to room temperature.

The lack of inversion symmetry in semiconductor quantum wells leads to a spin splitting of the conduction band (via spin-orbit coupling) and is a driving force behind spin dephasing in these systems through D'Yakonaov-Perels scattering. To increase the lifetimes in quantum wells, it has been possible to engineer spin orbit interactions by growing III-V heterostructures with a decreased crystal symmetry ( $\langle 110 \rangle$

orientation) (Ohno et al. 1999b). The resulting room temperature lifetimes are several nanoseconds and comparable to those observed in II-VI semiconductor heterostructures (Kikkawa and Awschalom 1998; Kikkawa and Awschalom 1999; Kikkawa et al. 1997). Time-resolved optical measurements of electron spin dynamics in the  $\langle 110 \rangle$  GaAs quantum wells reveal a strongly anisotropic electron  $g$  tensor, and the origin of previously discovered all-optical nuclear magnetic resonance (discussed below) (Salis et al. 2001b). These structures provide a laboratory in which all three components of the electron  $g$  tensor are measured, and a strong anisotropy is observed even along the in plane directions. These differences may serve as a basis for novel quantum computing schemes that exploit their distinct values along specific crystal axes in a single nanostructure.

A number of new device concepts have already emerged based on spin relaxation and optically induced dynamics. For example, the electron spin may provide optoelectronic spin switches for high speed modulators. With the aim of exploiting short spin lifetimes at room temperature, measurements in InGaAs/InP quantum wells reveal spin relaxation times  $< 5$  picoseconds and may be tuned with quantum well design parameters (Tackeuchi et al. 1999). The relaxation mechanism has been identified as a D'yakanov-Perel process and has led to the demonstration of a  $< 4$  picosecond all-optical gate operation.

## **SPIN TRANSPORT IN HETEROSTRUCTURES AND COHERENT SPINTRONICS**

Understanding the fundamental properties of spin transport in the solid state is essential for the development of semiconductor-based spintronics. In analogy to conventional devices whose performance is characterized by carrier mobilities and lifetimes, spin mobilities and coherence times are figures of merit for spintronic devices. Recent theoretical work has shown that it is essential to consider the influence of electric fields induced by carrier motion to understand the motion of spin, and that room temperature spin coherence times in bulk and quantum well structures appear to be dominated by precessional decoherence due to spin-orbit coupling (Flatté and Byers 2000). These models describe how the low field mobility and diffusion of spin packets depend sensitively on the doping and reveal new opportunities to control spin interactions by engineering strain and crystal orientation (Ohno et al. 1999b).

The spatial selectivity and temporal resolution of optical techniques have been used to monitor the decoherence and dephasing of electron spin polarization during transport not only through bulk semiconductors, but also across heterojunctions in engineered structures. Data show that spin coherence is largely preserved as electron spins cross interfaces over a broad range of temperatures (Malajovich et al. 2000). A phase shift is imposed on the electron spins during the crossing that is set by the difference in electron  $g$  factors between the two materials, and can be controlled with epitaxial growth techniques. Further measurements have established an increase in spin injection efficiency with bias driven transport: relative increases of up to five fold in electrically biased structures (with efficiencies approaching 90%) and 40 fold in p-n junctions have been observed (Malajovich et al. 2001). Based on the extended spin lifetimes discovered previously, a new “persistent” spin conduction mode appears upon bias, sourcing coherent spin transfer for at least 1 or 2 orders of magnitude longer than in unbiased structures. These experiments present promising opportunities for devices such as spin transistors that combine memory and logic functions where the amplitude and phase of the net spin current can be controlled by either electric or magnetic fields.

## **ROLE OF DISORDER IN SPIN-BASED ELECTRONICS**

As the majority of studies to date have been performed in high quality MBE-grown semiconductor systems, a deeper understanding of the effect of defects on spin coherence is clearly important for the development of spin-based electronics. In this context the III-V semiconductor GaN is intriguing in that it combines a high density of charged threading dislocations with high optical quality, thereby allowing optical investigation of the effects of momentum scattering on coherent electronic spin states. Despite densities of charged threading dislocations of  $\sim 5 \times 10^8 \text{ cm}^{-2}$ , studies reveal electron spin coherence times in n-type MOCVD-grown GaN epilayers that reach  $\sim 20$  ns at  $T = 5\text{K}$ , with observable coherent precession at room temperature (Beschoten et al. 2001). Investigations of samples doped in the vicinity of the metal/insulator transition reveal a dependence on both magnetic field and temperature qualitatively similar to previous studies in n-type GaAs,

suggesting a common origin for spin relaxation in these systems despite a difference of eight orders of magnitude in defect density.

### MAGNETIC DOPING IN SEMICONDUCTOR HETEROSTRUCTURES: INTEGRATION OF MAGNETICS AND ELECTRONICS

Magnetic doping with elements such as paramagnetic  $Mn^{2+}$  ions resulted in a wide variety of new physical phenomena in II-VI and III-V semiconductors. In II-VI systems, the  $Mn^{2+}$  ions act to boost the electron spin precession up to terahertz frequencies and exhibit optically induced coherent precession as well. The large electronic Zeeman splittings in magnetic II-VI semiconductors at low temperatures have enabled the successful design and operation of a prototype spintronic device: a spin LED that shows a high electron spin polarization in applied magnetic fields of a few Tesla at low temperature (Fiederling et al. 1999; Jonker et al. 2000). The concurrent development of spin LEDs using recently discovered ferromagnetic III-V semiconductors (e.g., (Ga,Mn)As and (In,Mn)As) has led to remanent hole spin injection at zero applied field and operation at higher temperatures (albeit with a lower polarization efficiency) (Ohno et al. 1999a). In an effort to bridge these limitations and achieve high electron spin injection and remanent operation, spin-polarized Zener tunneling devices have recently been fabricated (Johnston-Halperin et al. 2002). Here, a Zener tunnel diode is used to transfer polarization from the valence band of p-type GaMnAs to the conduction band of n-GaAs, thus enabling spin-polarized electron transport within GaMnAs. For future devices, theoretical proposals suggest that the domains in a unipolar magnetic semiconducting film could be configured to produce transistor-like behavior, with potential applications in nonvolatile memory and reprogrammable logic.

In some Mn doped III-V materials, such as InMnAs/GaSb heterostructures, the presence of light drives the paramagnetic ions into ferromagnetic order, resulting in optically controlled ferromagnetism in semiconductors (Koshihara et al. 1997; Oiwa et al. 2001). Figure 5.2 demonstrates the power of this technique in optically modulating the ferromagnetic properties of these semiconductor heterostructures. While this is currently a low temperature effect, extension to higher temperature may have important applications in areas including optical storage, photonically driven micromechanical elements, magnetic toners, and photonic magnetoresistive random access memory (MRAM). In addition, photons may be used to induce changes in organometallic spin configurations, such as the optical conversion of ferroelectric organic molecular crystals into antiferromagnetic ionic crystals (Ogawa et al. 2000). This photo-induced phase transition converts these systems from a low spin ( $S=0$ ) to a high spin ( $S=2$ ) state within laboratory time frames.

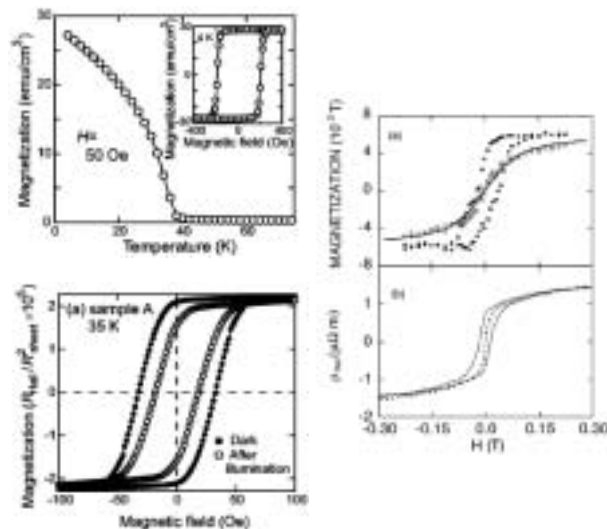


Figure 5.2. Optically induced ferromagnetism in semiconductors (Koshihara et al. 1997; Oiwa et al. 2001).



More recently, these materials have been employed to show electric field control of the ferromagnetism using an insulating field effect transistor device (Ohno et al. 2000). Here the ferromagnetic transition temperature of InMnAs is changed with a gate voltage and represents a powerful connection between electronics and magnetics in the solid state. In addition, magnetic semiconductor interfaces and magnetic semiconductors provide a new route to tuning properties of materials in spin electronics. For example, the domains in a unipolar magnetic semiconducting film could be configured to produce transistor-like behavior, suggesting applications in nonvolatile memory and reprogrammable logic (Flatté and Vignale 2001).

There are extraordinarily large photo-induced effects in the manganites, a class of systems that serves as a laboratory in which to examine spin, charge, orbital, and lattice degrees of freedom. In particular, a strong optically induced metal/insulator transition is seen in PrCaMnO, where nine orders of magnitude change in the resistance is observed upon illumination at low temperatures (Miyano et al. 1997). This represents a collapse of the charge ordered state, operates within extremely fast times, and suggests a direction for developing rapidly switched integrated conductors. Furthermore, both electric field and photoinduced switching between insulating and conducting states is observed in SmSrMnO manganite films grown by pulsed laser deposition (Oshima et al. 1999).

Hybrid ferromagnetic/semiconductor structures are being explored for their potential in new optoelectronic device technologies. For example, an extremely large photo-induced magnetoresistance is observed in composite MnSb:GaAs films (Akinaga et al. 2000; Akinaga et al. 2001). An enhancement of the conductivity occurs upon illumination, resulting in a 50% effect at room temperature with only 3-5 monolayers of magnetic material. These effects may lead to integrated magnetic isolators with high efficiencies and high levels of integration. In addition, MBE-grown MnAs:GaAs multilayers have been configured into distributed Bragg reflectors (DBRs) for magneto-optics and demonstrated to achieve  $\sim 1$  degree Faraday rotations at room temperature (Tanaka et al. 2001). These optically active vertical cavities are designed to integrate optical communication devices with Faraday isolators, traditionally separate technologies.

Along with efforts to place ferromagnetic materials upon semiconductors, there are schemes being developed to integrate ferromagnetic materials within semiconductors. The *in situ* annealing of Mn-implanted GaAs and GaMnAs produces ferromagnetic clusters within the host semiconductor (De Boeck et al. 1996). This process results in room temperature ferromagnetism within optically active GaAs and may be compatible with III-V optoelectronic devices.

In complement to these classical approaches to spin-based devices, the introduction of coherent spins into ferromagnetic structures could lead to a new class of quantum magnetoelectronics. As an example, some quantum computation schemes rely on the controllable interaction of coherent spins with ferromagnetic materials to produce quantum logic operations (DiVincenzo et al. 2000). To investigate the nature of the carrier-mediated ferromagnetism in these materials, it is desirable to disentangle the electronic and magnetic interactions through alternative semiconductor growth techniques. Digital ferromagnetic heterostructures (i.e., digital alloy) have been fabricated by alternately depositing semiconductors such as GaAs and submonolayer MnAs using low temperature molecular beam epitaxy (Kawakami et al. 2000). Magnetic measurements indicate ferromagnetism in the digital structures. Further, by varying the spacing of the MnAs layers, systematic investigations of the length scale of the ferromagnetic interaction find that the Curie temperature varies with the MnAs spacing with evidence for magnetic decoupling beyond  $\sim 10$  nm. In fact, single layers of 0.5 ML MnAs embedded in a GaAs host are shown to be ferromagnetic. Recently there is experimental evidence that these ferromagnetic materials can also be used to “imprint” nuclear spins in semiconductors (Kawakami et al. 2001), thereby offering an additional pathway for manipulating and storing information at the atomic scale.

## OPTICAL MANIPULATION OF NUCLEAR SPINS

Nuclear spins have been proposed as candidates for storing both classical and quantum information due to spin lifetimes that exceed those of electrons by at least several orders of magnitude and to the degree of control provided by conventional nuclear magnetic resonance (NMR) techniques. For future applications that

exploit delocalized electrons, the hyperfine interaction in III-V semiconductors has been studied through a resonant technique based on periodically excited electron spin polarization (Kikkawa and Awschalom 2000). Time-resolved measurements of electron spin precession have provided unambiguous signatures of all optical NMR in modulation doped GaAs quantum wells (QW) and represent the spatial focusing of NMR mechanisms to the nanometer length scale (Salis et al. 2001c).

Using these techniques, surprisingly efficient dynamic nuclear polarization within  $\langle 110 \rangle$  oriented III-V quantum wells is observed in a geometry where the electron spins are injected almost transverse to the applied magnetic field (Salis et al. 2001b). The small absolute value of the electron g factor combined with efficient nuclear spin polarization leads to large nuclear fields that dominate electron spin precession at low temperatures. These effects allow for sensitive detection of all optical nuclear magnetic resonance induced by periodically excited quantum well electrons and include direct signatures of quadruple coupling.

### ARTIFICIAL ATOMS IN THE SOLID STATE: QUANTUM DOTS

It has been proposed that the spin of an electron confined to quantum dots is a promising candidate for quantum bits and that arrays of quantum dots can be used in principle to implement a large scale quantum computer (Loss and DiVincenzo 1998; Burkard et al. 1999). Quantum operations in these proposals are provided by coupling electron spins in neighboring quantum dots by an exchange interaction between them. This interaction can be switched by applying controlled gate voltage pulses, thus allowing realization of the fundamental quantum gates like the exclusive OR. The readout of such a spin qubit can be performed efficiently with a single electron transistor (SET) as a spin-polarized electric current passing through the dot (Engel and Loss 2001) or through integration in solid state microcavities (Imamoglu et al. 1999). In the former case, there have been recent demonstrations of magnetically tunable quantum dot molecules, where electrical tuning of quantum states within quantum dot ‘molecules’ has successfully brought electron spin levels into crossing regimes (Amaha et al. 2001). This sophisticated SET structure contains a pair of quantum dots that can be gated into molecular-like states and offers a viable all-electrical approach to quantum spin electronics. The latter case of coupling quantum dots via the quantum electrodynamic modes of an optically active semiconductor microcavity has been demonstrated in GaAs (Michler et al. 2000) and has also proven to be a source of single photons on demand. Electron micrography of the device as well as quantum dots embedded in this upper cap is shown in Figure 5.3. This is a potential scheme for entangled photons and photonic readout of localized electron spin states for communication and computing. Alternatively, qubit rotations can be implemented by local electrostatic shifting of the electron into a region with a different effective magnetic field, such as occurs at heterointerfaces and in magnetic semiconductor structures.

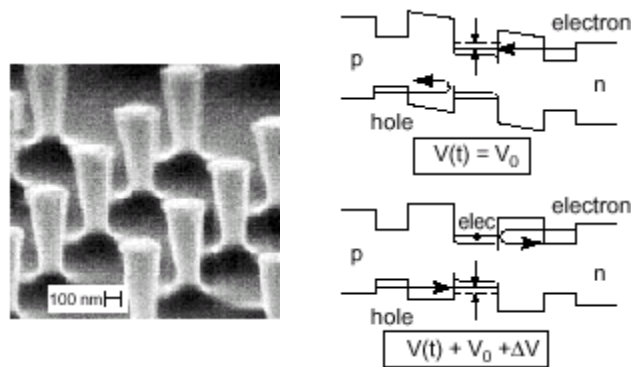


Figure 5.3. Quantum dot single photon turnstile devices (Michler et al. 2000).

Recent experiments have demonstrated that electron spin coherence persists over nanosecond time scales at room temperature in chemically synthesized CdSe quantum dots (Gupta et al. 1999), as well as CdSSe quantum dots in commercial colored glass filters (Gupta et al. 2001a). These systems provide quantized spins in single nanocrystals (one electron/dot) that are fabricated with a 5-10% size distribution and can be tuned to provide diameters ranging from 2–10 nm. In addition, the materials preparation technique provides flexibility in tuning the surface states and is presently leading to a number of new opportunities for quantum

spintronics. An important new development in this area is the synthesis of n-type colloidal semiconductor nanocrystals (ZnO, CdS, CdSe) that reveal a charge relaxation time exceeding 100 hours and that introduce a chemistry for electrically doping these systems (Shim et al. 2000). In addition, magnetic doping has been demonstrated in CdS nanocrystals, with nominally one Mn ion/dot and large electron spin splittings (Hoffman et al. 2000). These structures have spin splittings even in a zero external field (10-100 meV) due to internal bias fields. Finally, photoluminescence measurements of traditional self-assembled InAs semiconductor quantum dots grown within optical microcavities have demonstrated quenching of the longitudinal excitonic spin relaxation at low temperatures (Paillard et al. 2001). This behavior was discovered under conditions of resonant excitation and suggests opportunities for spin-driven optoelectronic switching and storage within integrated devices.

Direct optical manipulation of charge-based coherent wave packets has been achieved in individual quantum dots (Bonadeo et al. 1998). Many proposals exist for a hybrid technique of spin-to-charge conversion that may be desirable for combining the longer spin coherent lifetimes with the sensitivity of charge detection. Recent experiments have revealed that the longitudinal relaxation time for electron spins in insulating quantum dots are several nanoseconds and offer promise for their utilization as computing elements in quantum electronics (Paillard et al. 2001). The challenge of performing a suitably large number of qubit rotations within the spin coherence time has been addressed by a new technique developed in quantum wells that produces rotations of electron spins on 100 femtosecond time scales (Gupta et al. 2001b). In these experiments, intense laser pulses energetically tuned below the semiconductor bandgap generate a light-induced effective magnetic field via the optical Stark effect and successfully operate on quantum- confined electron spin states.

Another proposal suggests that individual phosphorous nuclei embedded in silicon may be treated as quantum bits whose entanglement proceeds through the hyperfine interaction with localized electron spins and with a gate-controlled exchange interaction between neighboring spins (Kane 1998). Along with a related scheme applied to Si-Ge compounds (Vrijen et al. 2000), the choice of group-IV semiconductors has the advantage of reduced spin-orbit coupling that could lead to even longer spin coherence times (Gordon 1958).

## OUTLOOK AND GENERAL CONCLUSIONS

There is a rapidly emerging global effort aimed at developing optoelectronic applications of spintronics, particularly in Japan, Europe, and the United States. It is clear that Japan is presently the world leader in exploratory magnetic semiconductor materials, with outstanding fabrication and characterization facilities that are used effectively. There is a clear focus on device concepts and demonstrations that exploit high speed optoelectronic switching and magneto-optical storage. The scientific programs in Japan are limited but growing quickly, often driven by emerging interests in potential quantum information technologies. Much of the research in this area is coordinated by national programs integrating universities, government laboratories, and relevant industries.

A rapidly developing materials program is appearing in Europe, with aggressive experimental physics largely based within universities. In particular, there are extremely active theoretical physics and materials science groups that strongly interact with many of the new programs.

Experimental efforts in the United States are limited and often correlated with the few universities that have strong materials science programs. Furthermore, theoretical work in this area requires strengthening and care in integrating with physics and materials research.

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## CHAPTER 6

# MAGNETOELECTRONIC DEVICES

James M. Daughton

### OVERVIEW

Since the discovery of giant magnetoresistance (GMR), magnetoresistive devices have progressed rapidly from the anisotropic magnetoresistance (AMR) structures that were the dominant thin film magnetoresistive material into the 1990s. GMR development, followed by work in magnetic tunnel junctions (MTJ), is now being amplified by the latest work in spin electronic devices (SPINS). The resulting improvements in magnetoresistance have been accompanied by rapid exploitation of these new structures in sensors, read heads, galvanic isolators, and nonvolatile memory (MRAM). The ultimate drivers for research in magnetoelectronics — that devices be “faster, smaller, and cheaper” — ultimately also define the technological challenges.

One of the ways to make magnetoelectronics *faster* is to achieve higher signals. Magnetoresistance has risen from about 2% for AMR thin films to 20–50% for GMR layers to 50% for MTJ structures. Even higher magnetoresistance is being sought, and considerable effort is being expended toward that end, both in academia and in industry. Another critical means to increase the speed of memory and galvanic isolators is the integration of magnetic devices with integrated circuits. This integration reduces parasitic capacitance and inductance significantly compared to the alternative of separating the magnetic device from the integrated circuit onto separate substrates or into separate electronic packages. The integration of magnetic devices and integrated circuits has largely been the purview of larger companies.

Integration of magnetic devices with integrated circuits can also make magnetoelectronics *smaller* by reducing parts counts and interconnects. The new SPINS research may represent the ultimate in shrinking device size through integration. In addition, the magnetic devices themselves can and are being reduced in size. Line widths of the scale of 0.15  $\mu\text{m}$  are now under development for hard disk drive read heads and MRAM. Three technical challenges that result from microscale device sizes are contending with (1) demagnetizing fields, (2) the ultimate stability and noise of magnetic structures, and (3) the problem of switching fields (currents). The use of antiferromagnetic/ferromagnetic film coupling has significantly improved device stability and is still an active area of research. The use of spin momentum transport to reduce currents for switching is a new area of strong research interest around the world.

Provided smaller devices can be made to work, shrinking the size of devices should eventually also make them less expensive. The development of practical devices of very high density for read heads and MRAM is very active in many companies, but news about progress and results is very tightly held for competitive reasons.

## SALIENT FEATURES OF MAGNETOELECTRONICS RESEARCH

Much of the practical R&D in magnetoelectronics in Europe and Japan, as well as in the United States, is being carried out in companies reluctant to reveal very much about their work, and thus the view of magnetoelectronics based on WTEC-sponsored visits and published information is bound to underestimate the practical efforts in this field. The pre-product development work in general in Europe and Japan seems to be about on a par with the efforts in the United States. However, the very large lead that the United States has in magnetoelectronics applications probably conceals a superior R&D base associated with products and product development, much of which remains proprietary to companies. Despite the difficulty of seeing a complete picture of magnetoelectronic device development in the United States and abroad, it is clear that advances in both spin-dependent transport devices and their applications have been extremely rapid over the past 13 years.

### Magnetoelectronic Device Structures

Giant magnetoresistive (GMR) multilayers (Fig. 6.1a), first discovered in 1988 (Baibich et al. 1988; Barnas et al. 1990), consist of nanometer-thickness, interleaved, alternating layers of ferromagnetic and nonferromagnetic metals, such as cobalt and copper layers or iron and chromium layers. With the proper thickness of the nonmagnetic metal, indirect electron exchange provides a mechanism to induce an antiparallel alignment of the magnetic layers (Parkin, More, and Roche 1991). The resistivity of the structure drops significantly if a sufficient magnetic field (typically 100 Oe to 1000 Oe) is applied to overcome the antiparallel coupling between magnetic layers, with the change in resistivity ( $\Delta\rho$ ) divided by the resistivity at large fields ( $\rho$ ) being typically in the range of 10%–60%. This very large (“giant”) magnetoresistance is attributed to changes in the scattering of polarized conduction electrons as the relative magnetization orientations in the ferromagnetic layers change from antiparallel to parallel.

A spin valve (Fig. 6.1b) is a simpler structure consisting of only two ferromagnetic layers sandwiching a thin nonmagnetic metal, with one of the two magnetic layers being “pinned,” so that the magnetization in that layer is relatively insensitive to moderate magnetic fields (Dieny et al. 1991). The other magnetic layer is called the “free” layer, and its magnetization can be changed by application of a relatively small magnetic field. As the magnetizations in the two layers change from parallel to antiparallel alignment, the resistance of the spin valve rises, typically 5% to 10%. In the spin valve, the magnetic layers are typically alloys of nickel, iron, and cobalt, and the nonmagnetic interlayer is usually copper. Pinning is usually accomplished by using an antiferromagnetic layer that is in intimate contact with the pinned magnetic layer. The two films form an interface that acts to resist changes to the pinned magnetic layer’s magnetization.

Recent improvements to the basic spin valve are illustrated in Figure 6.1c. The simple pinned layer is replaced with a synthetic antiferromagnet, two magnetic layers separated by a very thin ( $\sim 10 \text{ \AA}$ ) nonmagnetic conductor, usually ruthenium (Parkin and Mauri 1991). The magnetizations in the two magnetic layers are strongly antiparallel coupled and are thus effectively immune to external magnetic fields. This structure improves both standoff magnetic fields and the operation temperature of the spin valve. Another improvement is the nanooxide layer or NOL, which is formed at the outside surface of the soft magnetic film. This layer reduces resistance due to surface scattering (Egelhoff et al. 1999), thus reducing background resistance and thereby increasing the percentage change in magnetoresistance of the structure. NOL layers have allowed spin valves to increase GMR from about 10% to about 20% over the two years prior to this WTEC study, and their insertion into GMR structures is still a major development area.

The structures described above are all termed current-in-the-plane (CIP) structures. In relatively recent developments, NOLs have been inserted into current-perpendicular-to-the-plane (CPP) structures (creating vertical rather than horizontal current flow) with the intriguing results of moderately high GMR and intermediate specific resistance values (Takagishi 2001). The work on NOLs has been largely motivated by applications in read heads, and most of the leading work in this area has been done in Japan and the United States; there is little NOL activity in Europe.

Figure 6.1d illustrates a magnetic tunnel junction (Moodera et al. 1995; Miyazaki et al. 1995), or MTJ, in which a pinned layer and a free layer are separated by a very thin insulating layer, commonly aluminum



oxide. The tunneling resistance is modulated by a magnetic field in much the same way as the resistance of a spin valve. The MTJ has typical magnetoresistance ratios of 20% to 40% and requires a saturating magnetic field equal to or somewhat less than that of spin valves. Because the tunneling current density is usually small, MTJ devices tend to have high resistances. Recent results are showing that greater than 40% magnetoresistance is attainable down to about  $100 \text{ Ohm-}\mu\text{m}^2$ . Research is concentrating on increasing magnetoresistance and decreasing the tunneling resistance, both factors being essential for high performance memory and read heads (Tehrani et al. 2001).

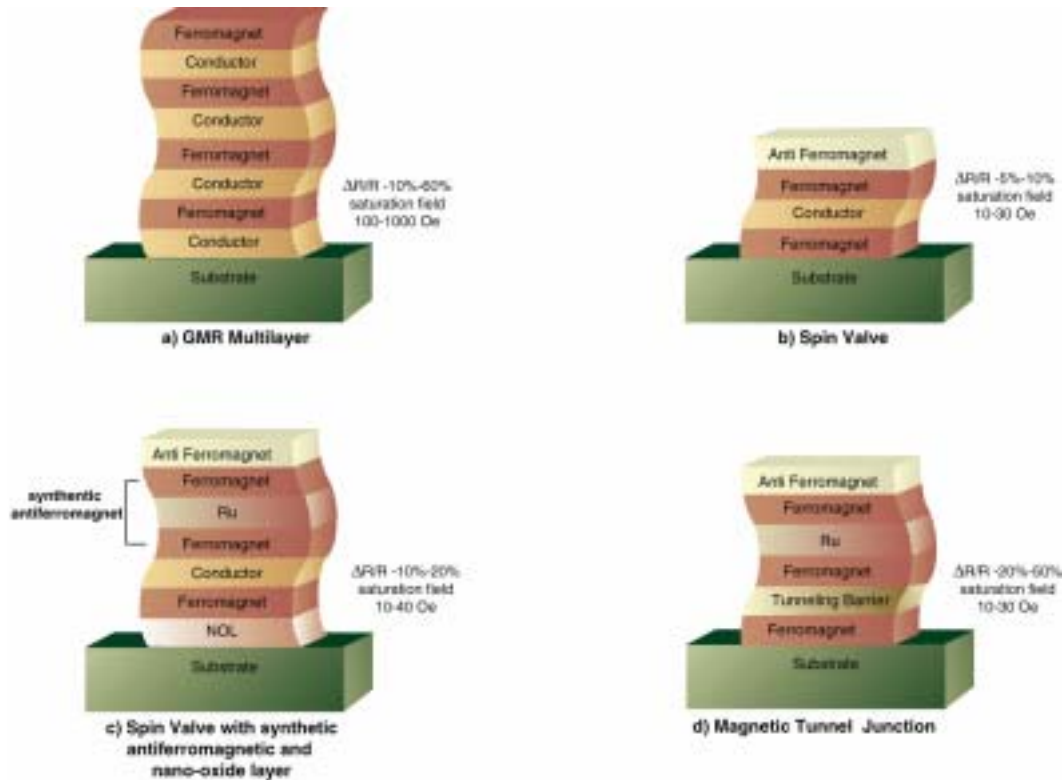


Figure 6.1. Spin dependent transport structures.

### Applications of Magnetoelectronic Structures

Important GMR and MTJ applications include magnetic field sensors, read heads for hard drives, galvanic isolators, and magnetoresistive random access memory (MRAM).

General purpose GMR sensors have been introduced in the past five years (Daughton et al. 1994; Infineon ND), and several companies are producing GMR sensors for internal use. Figure 6.2a illustrates a sensor chip with GMR multilayer material as the basic sensing material. The GMR multilayer is etched to form resistors, which are connected as a Wheatstone bridge. The substrate is an integrated circuit that is then connected to the bridge using integrated circuit wiring techniques. Resistors on the chip can be trimmed with lasers to allow the circuit to “trigger” at the desired magnetic field. No commercial sensors using MTJ structures are yet available but are under development (Tondra et al. 1998).

GMR spin valve read heads are dominating applications in hard drives. Although some alternative configurations have been proposed, nearly all commercial GMR heads use the spin valve format as originally proposed by IBM (Tsang et al. 1994). There has been development interest in MTJ and GMR multilayers for read head applications, but no significant products have appeared. The magnetoresistance of spin valves has increased dramatically from about 5% in early heads to about 15–20% today using synthetic antiferromagnets and NOL (Koui et al. 2001; Huai et al. 2001). As hard drive storage densities approach 100 Gbits/square inch, sensor stripe widths are approaching  $0.1 \mu\text{m}$ , and current densities are becoming very

high. It is unclear if the conventional spin valve read head can be extended to those levels, or if a new form of read head will have to be introduced. Tunnel junctions with low tunneling resistance and CPP structures with NOL are at the forefront of read head research. Of growing concern is the noise introduced by thermal instabilities in very small read heads (Xue and Vitora 2001).

GMR-based galvanic isolators (Fig. 6.2c) are a combination of an integrated coil and a GMR sensor on an integrated circuit chip. They were introduced as products in 2000 (NVE ND). This product can eliminate ground noise in communications between electronics blocks, thus performing a function similar to that of opto-isolators. The GMR isolator is ideally suited for integration with other communications circuits or in the packaging of a large number of isolation channels on a single chip. The speed of the GMR isolator can eventually be 10 to 100 times as fast as today's opto-isolators, depending primarily on the switching speed of the magnetic materials and the speed of the associated electronics.

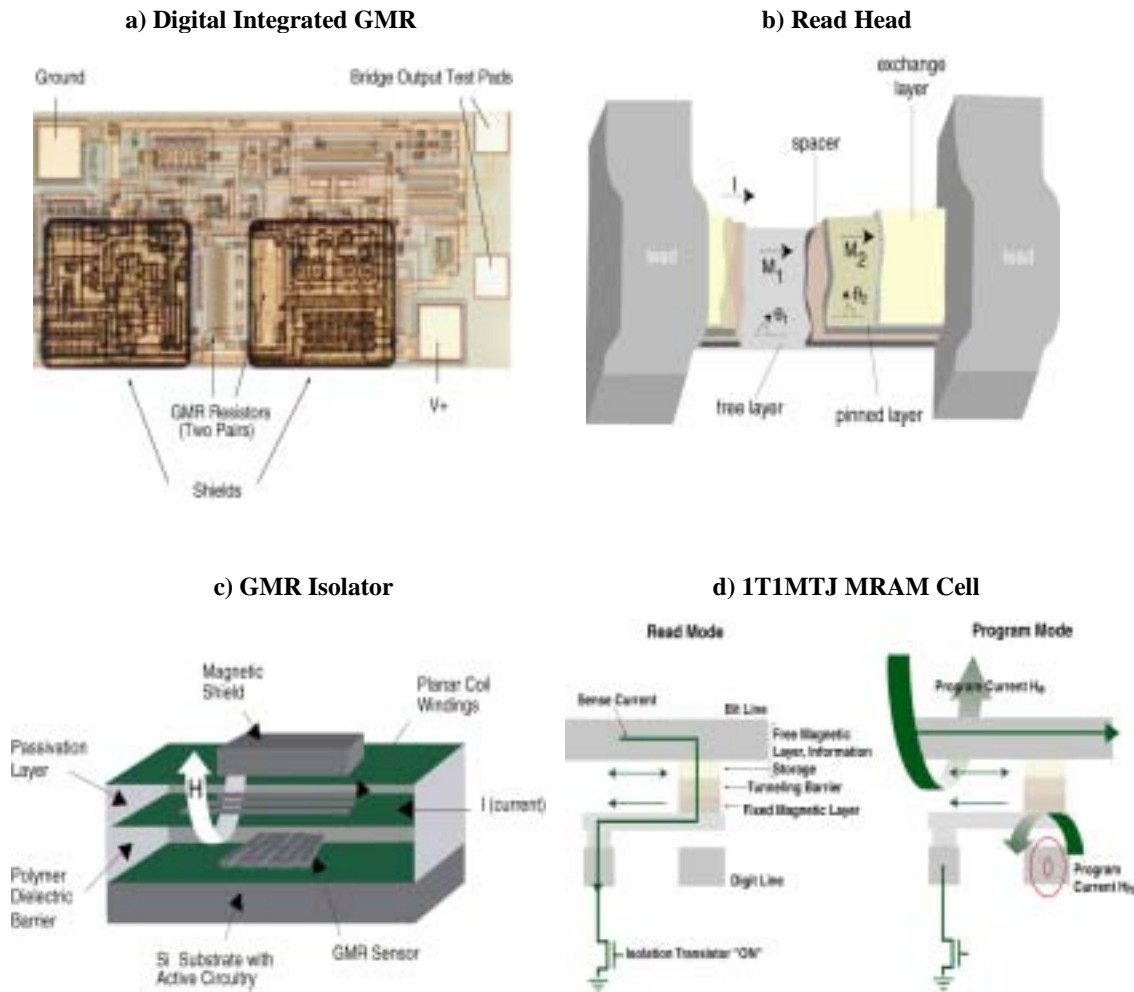


Figure 6.2. Device applications (reprinted by permission from Daughton et al. 1994; © 1994 IEEE).

MRAM uses magnetic hysteresis to store data and magnetoresistance to read data. Memory cells are integrated on an integrated circuit chip, and the function of the resulting device is like a static semiconductor RAM chip, with the added feature that the data are retained with power off. MRAM is not yet available commercially, but development activity is high. Many developers are using MTJ cells (Scheuerlein et al. 2000; Naji 2001), while some are using the pseudospin valve GMR cell (Katti et al. 2001). Motorola has announced a 256K development level MRAM (Naji 2001), using the MRAM cell illustrated in Figure 6.2d. Spin tunneling current is used to test the magnetic state of the cell, and current through one of the electrodes of the tunneling device, in combination with a current through an external strip line, is used to write the cell

to the desired state. Improvements in density have been proposed with vertical cells of cylindrical shape (Zhu, Zheng, and Prinz 2000) and thermally assisted writing (Beech et al. 2000). Producibility improvements using a transistor per cell for writing result in a lower density. Smaller capacity memory has also been suggested (Daughton 2000). Potential advantages of the MRAM compared with silicon EEPROM and flash memory are 1000 times faster write times; no wear out with write cycling (EEPROM and flash wear out at about one million write cycles); lower energy for writing; and data access times that are about 1/10,000 of the access times of hard disk drives. Key challenges in the development of MRAM are improving yield (related to cell uniformity), improving density, and attaining thermal stability at small dimensions. Methods have been proposed for eliminating the read-select transistor in the MTJ cell (Zheng 2001) and for improving cell yield (Arrott 2001).

### **Future Devices and Applications**

Beyond the progression over the past decade from the use of bulk (AMR) materials with a thin film magnetoresistance limited to about 2%, to GMR and spin tunneling and now to SPINS devices offering 15% to 40% magnetoresistance, several possible new structures suggest startling additional improvements in magnetoresistance (Verslujs and Coey. 2001; Akinaga et al. 2000; Jo et al. 2000). These new structures or materials hint at hundreds of percent changes (at room temperature), with the ultimate promise of “on-off” devices controlled by magnetism. Most of these new structures are being developed in Europe and Japan; little work on new materials is being done in the United States.

Future device applications for SPINS are very promising. In order to use the spin information of electrons in semiconductors, it will be necessary to control spin injection, spin transport, and spin detection. Three spin injection techniques have already been demonstrated: (1) injection using a polarized light source (Kikawa et al. 1997); (2) injection from a ferromagnetic semiconductor (Ohno et al. 1999); and (3) some limited success with injection from a ferromagnetic metal (Jonker et al. 2001). Injection from a contact with a high resistivity ferromagnetic or a half-metallic ferromagnetic material may also be possible. Detection of spin states in semiconductors has been achieved through optical detection (Jonker 2001), and some limited success has been achieved with a diffuse iron contact into GaAs (Crowell 2001). Other potential detection schemes include the extraordinary Hall effect and the use of tunnel junctions.

The use of electric fields for manipulating spin-polarized electrons should be possible. One of the recent remarkable results in SPINS has been the modification of the Curie point of ferromagnetic semiconductors with a gate voltage (Ohno et al. 2000), which offers the possibility of magnetizing the ferromagnetic semiconductor with a combination of a magnetic field and a gate voltage. It has recently been shown that spin-polarized currents from one ferromagnet can switch another (Katine et al. 2000), and for small devices, spin current-induced switching is projected at lower currents than by passing currents through etched windings. It is within the realm of possibility that a combination of controlled spin current from a ferromagnet with a gate voltage to raise and lower the Curie point could be used to switch a ferromagnetic semiconductor with very small currents.

In these new SPINS research areas, Japan and Europe have some lead over efforts in the United States.

### **COMPARISON OF RESEARCH IN JAPAN AND EUROPE WITH THAT IN THE UNITED STATES**

In read heads for hard drives, IBM and Seagate in the United States are the two largest producers; Read Rite is a third supplier. In Japan, Fujitsu and TDK (which has purchased Headway in the United States) are major producers. There are no major GMR head producers in Europe.

Motorola, IBM, Micron, Honeywell, and Cypress have MRAM efforts in the United States. Infinion has teamed with IBM, and Philips has a research effort in MRAM. NEC and Toshiba have some MRAM development in Japan.

NVE sells GMR sensors in the United States, and Infinion sells GMR sensors in Europe. A number of other companies make GMR sensors for internal use.

Japan and Europe both lead the United States in published work on alternative and very high magnetoresistance structures. Akinaga's work in Japan on manganese antimonide, Coey's work in Ireland on iron oxide particles (see Trinity College site report in Appendix B), Garcia's work in Spain on constricted ferromagnets, and Blamire's manganate tunnel junctions all have yielded magnetoresistance over 300%. There is very little published work in the United States on these alternative structures.

Europeans seem to be very strong in magnetoresistance theory as well as in spin injection. There is a general realization that GMR and MTJ theory still have some major unexplained results; the Europeans are working through details while researchers in the United States have shifted toward the newer frontiers such as tunneling magnetoresistance, spin current switching, and spin injection into semiconductors. An example of new thoughts on GMR is the work coming from Brian Hickey and his group at Leeds University (see special section on EPSRC Spintronics Network included in University of Nottingham site report, Appendix B).

Overall, the device application work in the United States is stronger than that in Japan and Europe.

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## APPENDICES

### APPENDIX A. BIOGRAPHIES OF TEAM MEMBERS

#### PANEL MEMBERS

##### **Stephan von Molnár**

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Stephan von Molnár received his Ph.D. in Physics from the University of California, Riverside (1965). He joined the Research Staff of the IBM Watson Research Center in 1965, where he held various management positions, and has been a Professor of Physics and the Director of MARTECH, the center for Materials Research and Technology, at Florida State University since 1994. His expertise includes magnetotransport properties of magnetic semiconductors, magnetism, the thermal properties of amorphous and crystalline solids, and the fabrication and characterization of magnetic nanoparticles. His accomplishments include the conceptual development and experimental observations of magnetic polarons and the demonstration of the magnetically driven insulator/metal transition. Professor von Molnár has received an outstanding contribution award for research while at IBM. He has been a Senior Research Fellow of the Semiconductor Research Corporation, and is an Alexander von Humboldt Senior U.S. Scientist awardee and a Fellow of the American Physical Society.

His materials expertise centers on rare earth metals and alloys, transition metal based diluted magnetic semiconductors, and the perovskite type  $\text{HiT}_c$  and CMR compounds. As part of his research on the magnetic nanoparticles, he has collaborated in the development of a novel Hall gradiometer for their magnetic characterization. His interest in these subjects was motivated in large part by their potential for application in such areas as storage technologies and magnetic sensing devices.

During his tenure at IBM from 1965-1993, he continuously remained an active researcher while taking on various management positions. In his work at MARTECH he is focusing his attention on the integration of nanoparticles with semiconductor device geometries and the development of thin film magnetic semiconductor structures for fundamental study and possible technological applications in spintronics.

##### **David D. Awschalom**

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David D. Awschalom received his undergraduate degree in physics from the University of Illinois at Urbana-Champaign, and his Ph.D. in experimental physics from Cornell University. He was a Research Staff member and Manager of the Nonequilibrium Physics Department at the IBM Watson Research Center in Yorktown Heights, NY. In 1991 he joined the University of California – Santa Barbara as a Professor of Physics, and is presently Director of the UC Center for Spintronics and Quantum Computation.

His group has active research activities in optical and magnetic interactions in semiconductor quantum structures, spin dynamics and coherence in condensed matter systems, macroscopic quantum phenomena in nanometer scale magnets, and implementations of quantum computation in the solid state. He has developed a variety of low temperature femtosecond-resolved magneto-optical spatiotemporal spectroscopies aimed at exploring charge and spin motion in the quantum domain. He has presented over 300 invited lectures and is the author of nearly 200 scientific publications.

Professor Awschalom received an IBM Outstanding Innovation Award, the Outstanding Investigator Prize from the Materials Research Society, and was the Wohlfarth Prize Lecturer. Dr. Awschalom is a member of the American Association for the Advancement of Science, the Materials Research Society, and is a Fellow of the American Physical Society.

**Robert A. Buhrman**

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Robert A. Buhrman received his undergraduate degree in Engineering Physics from Johns Hopkins University in 1967 and his Ph.D. degree in Applied Physics from Cornell University in 1973. That year he joined the faculty of Applied and Engineering Physics at Cornell. He was promoted to the rank of Professor in 1982 and served a ten-year term as Director of the School of Applied and Engineering Physics from 1988-1998. Currently he is the John Edson Sweet Professor of Engineering at Cornell University. In 1977 Buhrman was a member of the Cornell team that organized the proposal that resulted in the establishment at Cornell of the National Research and Resource Facility for Submicron Structures University by the National Science Foundation. This research facility has evolved over the years into what is now known as the Cornell Nanofabrication Facility, which is one of the two major nodes of the NSF supported National Nanofabrication Users Network. This is the premier academic resource in the United States for nanofabrication and nanoscale research. Buhrman currently serves as Chair of the Faculty Executive Committee of the Cornell Nanofabrication Facility.

Buhrman's research interests are in fundamental and applied condensed matter physics, with emphasis on electronic thin film systems. Current research activities include studies of spin dependent transport in magnetic multilayers and magnetic nanostructures. Currently Buhrman is leader of an interdisciplinary team of Cornell faculty who are pursuing research in the area of the electronic and spin transport properties of nanostructure materials, which is supported by the NSF through the Cornell Center for Materials Research. Other research interests of Buhrman's include efforts in high temperature superconductivity, particularly thin film and Josephson device research, and the study of quantum transport and individual, quantum defects in metallic nanostructures. A major over-arching theme of Buhrman's research activities is the use of both electronic nanostructures and tools based on scanning tunneling microscopy to probe the electronic structure and transport properties of thin film interfaces and electronic systems at the nano-scale.

Buhrman is a Fellow of the American Physical Society, a member of the Materials Research Society and an editor of *Physica C*.



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Dr. James Daughton's expertise is in device and materials physics and in technology management. He is currently the chief technology officer of NVE, which he founded in 1989, and until recently he was president, CEO, and board chairman. Before founding NVE, Dr. Daughton spent over 15 years at Honeywell Inc. where he was a vice president managing solid state research and development. Before that, he spent 10 years at IBM in Yorktown Heights and Burlington working on magnetic and semiconductor memory devices. He received his B.S., M.S., and Ph.D. degrees in EE in 1959, 1961, and 1963, respectively, from Iowa State University. He is a fellow of the IEEE, a member of the Magnetics Society, and an adjunct professor of physics at the University of Minnesota. He has published over 60 papers and has 20 issued and 6 pending patents, primarily dealing with thin magnetic films and devices. In 1994 Dr. Daughton was a Distinguished Lecturer for the Magnetics Society of the IEEE speaking on GMR materials and applications.

**Michael L. Roukes**

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Michael L. Roukes received his undergraduate degrees in Physics and Chemistry from the University of California, Santa Cruz in 1978. He received a Ph.D. in Physics from Cornell University in 1985, focusing upon experimental research at ultralow temperatures under Professor Robert C. Richardson. That year he joined Bell Communications Research as a Member of Technical Staff/Principal Investigator in the Quantum Structures Research Group where he established an ultralow temperature laboratory and carried out research in low dimensional electron transport in semiconductors. In 1992 he joined the faculty of the California Institute of Technology where he is currently a Professor of Physics. In 1996 he co-founded Caltech's "Initiative in Computational Molecular Biology," which he currently co-directs. In 2001, in collaboration with Caltech professor Axel Scherer, Roukes has founded Caltech's "Laboratory for Large Scale Integration of Nanostructures."

Roukes' research interests range from fundamental to applied condensed matter physics, electrical engineering, and biophysics — with a unifying theme centered upon development and application of complex nanostructures. His current research activities in spin electronics focus upon investigations of spin polarized transport in semiconductor nanostructures and magnetic multilayers. Together with Dr. P. Chris Hammel at Los Alamos, Roukes co-directs a major collaborative research effort funded by the DOE/BES and the NSF in magnetic resonance force microscopy, with special focus upon imaging magnetic micro/nanostructures. Roukes is also currently the leader of an interdisciplinary team of theoretical and experimental faculty at Caltech, Harvard University and the Los Alamos National Laboratory pursuing research on the injection, manipulation, and transport of spin in ballistic semiconductor nanodevices, an effort supported by DARPA.

Roukes' other active research efforts include development of nanomechanical systems from both "top down" (nanofabrication) and "bottom up" (self-assembly) approaches, long-term research to enable observation and control of individual quanta in nanocalorimetric and nanomechanical systems, development of nanomechanical arrays for solution-based force assays with single-biomolecule sensitivity, and development of micro/nanomechanical systems for novel multichannel probes of neural tissue.

Roukes is a Fellow of the American Physical Society, and is a member of the American Association for the Advancement of Science and the Materials Research Society.

## **OTHER TEAM MEMBERS**

### **Usha Varshney**

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Dr. Usha Varshney received her Ph.D. degree in Physics from the Indian Institute of Technology, New Delhi, in 1983. She joined the National Science Foundation in 1997 as Program Director of Electronics, Photonics, and Device Technologies and Integrative Systems in the Division of Electrical and Communications Systems. Dr. Varshney manages interdisciplinary science and engineering research programs at the National Science Foundation in enabling device technologies relating to processing, simulation and modeling, fabrication and characterization of smart materials, thin films and devices for next-generation microelectronics and nanoelectronics, molecular electronics, organic electronics, spin electronics, quantum devices, integrated solid state devices and circuits, micromagnetics, wide band gap semiconductors, metrology, and integrative systems.

Prior to joining the National Science Foundation, Dr. Varshney was Senior Research Scientist and Director of Research at American Research Corporation of Virginia, where she was involved in a broad range of science and technology programs of national interest. Research areas included fabrication and characterization of materials, thin films and devices for monolithic magnetics, nonvolatile random access memories, uncooled focal plane arrays, radiation resistant solar cells and photovoltaic devices, and wide band gap semiconductors. She has also held professional appointments at Virginia Polytechnic Institute and State University, where she worked on phosphors for advanced cathode ray display systems, at Chronar Corporation on amorphous silicon solar cells, and at Merrimac Magnetics on design of high frequency transformers.

Dr. Varshney has authored over 80 refereed papers, trade journal articles, conference papers, technical reports and books. She is an inventor on seven patents, and has been the recipient of several awards and recognitions in industry and at National Science Foundation. She is a member of the Institute of Electrical and Electronics Engineers, IEEE Electron Devices Society, IEEE Magnetics Society, Materials Research Society, and American Ceramic Society.

### **Stuart A. Wolf**

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Stu Wolf is currently both a Program Manager in the Defense Sciences Office at the Defense Advanced Research Projects Agency (DARPA) and a Senior Scientist for Materials Physics at the Naval Research Laboratory. At DARPA he has conceived and initiated several projects on functional materials that have the goal of pushing the frontiers of materials science for electronics. These programs include: 1) "Spintronics" whose near term goal is the development of nonvolatile, high density, high speed magnetic memory, and now has expanded to include Spins IN Semiconductors (SPINS) which hopes to develop a new paradigm in semiconductor electronics based on the spin degree of freedom of the electron in addition to or in place of the

charge; 2) Frequency Agile Materials for Electronics (FAME), which is aimed at significantly improving the performance of tuned filters, antennas and oscillators using the properties of ferroelectrics, ferrites and MEMS capacitors; 3) Advanced Thermoelectric Materials (ATM) targeted at improving the thermoelectric figure of merit,  $ZT$ , from 1, where it has been for the last thirty years, to over 3, in which case thermoelectrics will be competitive with phase change devices; 4) Advanced Magnets for Power Systems (AMPS), geared to develop high performance permanent magnets, both hard and soft for various DOD and commercial power applications; and finally 5) Quantum Information Science and Technology (QUIST) which aims to develop communication and computing systems and architectures based on the principles of quantum mechanics.

At NRL, he is a principal consultant to the Materials Science and Technology Division and is responsible for initiating new programs and managing several of the projects that are supported by outside agencies. Until January of this year, he was the head of the Materials Physics Branch, which had vigorous programs in superconductivity, magnetism, nonlinear properties of materials and electronic transport.

He has an A.B. from Columbia College (1964) and an M.S. (1966) and Ph.D. (1969) from Rutgers University. He was a Research Associate at Case Western Reserve University (1970-73) and a Visiting Scholar at UCLA (1981-82). He is a Fellow of the APS (1984), and was a Divisional Councilor for the Condensed Matter Division (1990-91) and is currently the Divisional Councilor for the Forum on Industrial and Applied Physics. He has authored or co-authored two books and over 250 articles and has edited numerous conference proceedings.

**APPENDIX B. SITE REPORTS — EUROPE**

**Site:** CNRS Laboratoire Louis Néel  
25 Avenue des Martyrs  
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(International telephone interview pursuant to questionnaire sent earlier)

**Date:** July 16, 2001

**WTEC:** S. von Molnár (report author)

**Interviewee:** Dr. Bernard Barbara  
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**GROUP SIZE**

Dr. Barbara's group consists of the following:

- 2 permanent staff members (B. Barbara and W. Wernsdorfer)
- 2 Ph.D. graduate students

A third staff member and post-doctorate will be added shortly.

**SUPPORT**

- Current total support for the group is very modest other than the salaries for permanent staff, existing facilities, and approximately \$10,000 per year for capital investment. These funds are provided by the CNRS.
- The European Community ~ \$15,000 per year, mainly for salaries and fees for postdocs.
- CNRS ~ \$20,000 per year, mainly for equipment.
- Other French organizations (Rhone-Alpes Region, Army,...) ~ \$10,000 per year, mainly for equipment.

The latter three items are subject to the acceptance of proposals, in a way similar to the NSF. Any investment in new equipment is rare and requires additional funding.

**INFRASTRUCTURE**

- The Laboratory Louis Néel, to which Dr. Barbara belongs, has long been a leading research group in the study of magnetism in France and provides technological help and facilities to do a large variety of magnetic measurements.
- Thin film preparation techniques including thermal evaporation and laser ablation exist, but Dr. Barbara's samples come through close collaboration with a number of inorganic and organic chemists in Europe and the United States or Japan, as well from the Laboratoire de Physique des Matériaux de Nancy.
- Transport and magnetotransport facilities are available within Dr. Barbara's laboratory. For extreme temperatures in large magnetic fields, there is a long standing collaboration with the CNRS Low Temperature Lab, the Laboratory of High Magnetic Fields (LCMI), and the Nuclear Center (CENG), both of which are located at the same site in Grenoble.

## IMPRESSIONS

The emphasis of the group is not directly related to spintronics. Rather the focus is on the boundary between classical and mesoscopic magnetism. Parenthetically, these studies may have important implications for spintronics and spintronics devices as these are reduced in size to the nanoscale.

Currently these studies include, among others, the physical behavior of single crystals of molecules containing magnetic ions. These are model materials for the study of quantum reversal of large magnetic moments. The local magnetic environment, even if it is weak, strongly affects quantum magnetism of the whole (see also Prokof'ev and Stamp, for the theory). Nuclear spins, through hyperfine coupling may have profound implications for the ground state of the system. This also has important implications for switching dynamics leading in many instances to the quantum tunneling behavior of large spins. Other molecules, through long-range dipole-dipole interactions, also have a crucial influence on tunneling. Magnetic environment makes observation of tunneling much easier, but at the same time strongly reduces the coherence time. Experiments in the GHz range are in progress to observe the quantum oscillations associated with coherent tunneling in magnetic molecules.

The second subject is the dynamics of individual nanomagnets. This work is largely confined to low temperatures and employs microSQUIDs to study the static and dynamic magnetic properties of individual nanoparticles in the presence of magnetic fields especially near the switching field over a limited low temperature range. The present record is a nanoparticle of Co of 3 nm in diameter. Strong indications, obtained in this group, for macroscopic quantum tunneling of a nanoparticle, should be confirmed in the future. The help of A. Benoit and D. Mailly in setting the microSQUID technique was determinant.

There are, however, several important new initiatives directly related to spintronics at Grenoble. Among these are the following:

- Barbara's project on spintronics using molecules. This work focuses on the coherent transport of spin information within and between magnetic molecular crystals.
- The Low Temperature Laboratory's investigation of nanomagnetism. This work, which involves 5-10 researchers and technicians, is focusing on the problems of electron coherence in mesoscopic conductors, proximity effect between ferromagnets and superconductors, and the effects of spin injection on the physical properties of the superconductors.
- Useful lithography and microfabrication facilities, with the name of Nanofab, located at the Low Temperature Lab, are also available for the Magnetism Lab.
- A two staff member effort by the CNRS-magnetism lab is studying the properties of mixed valent perovskites, manganites, and various Heusler alloys as possible spin-polarized sources.
- A sizeable effort at the CENG under the direction of Dr. B. Dieny, former student of Barbara's, on thin film GMR devices.

## FUTURE PLANS

- A new laboratory has been funded and was expected to start within six months of this WTEC visit under the auspices of the CNRS and the CEA (Atomic Energy Commission). The effort, which will include 10 permanent and 15 nonpermanent employees, will be led by J.P. Nozieres and B. Dieny. The program is called Spintech. Its mission is to be an interface between fundamental and applied research. It will be analogous to the data storage center at Carnegie Mellon and will focus on the conception, design, fabrication, and tests of magnetic random access memories (MRAM) and data storage systems. Spin injection and detection into various carrier media will also be carried out by means of dynamic measurements in the 10 to 100 picoseconds (ps) range.
- A second program, which will come to fruition within one to two years, has the name, Minatech. This is also funded by the CEA and will be a large national facility for microfabrication located at Grenoble.

It is apparent that spintronics including GMR, TMR, and the more recent magnetic metal semiconductor heterostructures will play an important role in the research activities of Grenoble in the future. The French government through its CNRS and CEA will be investing considerable monies to fund at least two new major programs.

Site: **Johannes Kepler University  
Institut für Halbleiterphysik und Festkörperphysik  
Altenbergerstr. 69  
A-4040 Linz  
Austria**

Date: August 9, 2001

WTEC: D.D. Awschalom (report author, with S. von Molnár)

Interviewee: Dr. Günther Bauer  
G.Bauer@hlphys.uni-linz.ac.at

### GROUP SIZE

- 2 full professors
- 2 associate professors
- 2 postdocs
- 3 graduate students

The activities of the group are split between materials growth and characterization in physical measurements.

### SUPPORT

- Austrian Science Fund: 1 post-doctorate, 1 Ph.D. student
- All other salaries are funded by the university. It is not apparent where the funding for infrastructure and operational research expenses comes from.
- New grant applications for specific work related to Si/SiGe are pending.

### INFRASTRUCTURE

- Materials Fabrication
  - Semiconductor MBE (2 systems)
  - Semiconductor MOCVD (GaN, GaMnN)
- Nanofabrication
  - Holographic and e-beam lithography
  - AFM
- Spectroscopic Characterization
  - In Situ
  - RHEED
  - Ex Situ
  - TEM
  - Grazing Incidence Small Angle X-ray Scattering (GISAXS) and Grazing Incidence Diffraction (GID)
  - X-ray reflectivity and x-ray magnetic circular dichroism (XMCD)
  - Electron spin resonance
  - Neutron diffraction
- Other characterization include SQUID magnetometry as well as electron transport

**IMPRESSIONS**

At the moment there are no national funds specifically earmarked for spintronics research. Funding occurs through individual research grants, and the competition is with proposals from all other sub-disciplines. However, this group, under Professor Bauer's leadership, is focusing on MBE-growth Eu-based magnetic nanostructures with an eye towards utility in quantum magnetoelectronics. They are producing quantum wells and dots, among other structures. The group also is producing Si/SiGe heterostructures since these offer extra long coherence times of order 1 ms and have the advantage of being the most utilized semiconductor technology (in contrast to GaAs). Although this effort is only starting, the research is extremely well focused and is being carried out by one of the premiere semiconductor specialists in Europe with a long track record of innovative research in static and time-resolved optical spectroscopies and magnetism. Although there is no national focus on spintronics, nor is there, at this time, substantial industrial involvement, Professor Bauer sees this subdiscipline as potentially extremely important for future generations of electronic technologies. There are no formal programs for educational programs in spintronics; however, there are some strategies for encouraging cross-discipline research and for promoting partnerships on international academic levels, as well as university-industry partnerships through the Austrian Science Fund. Generally speaking, however, the activities in Austria at this time are small compared to such other European nations as Germany, France, and the Netherlands.



Site: **Unité Mixte de Physique CNRS/THALES**  
**CNRS-UMR137**  
**Domaine de Corbeville**  
**91404 Orsay, France**  
<http://www.lcr.thomson-csf.com/cnrs/umr137.html>  
(email interview)

Date: October 26, 2001

WTEC: S. von Molnár (report author)

Interviewee: Albert Fert, Professeur à l'Université Paris-Sud  
albert.fert@thalesgroup.com  
Tel: +33 (0)1 69 33 91 05; Fax: +33 (0)1 69 33 07 40

### GROUP SIZE

- 5 research assistants
- 2 post-doctorates
- 5 Ph.D. graduate students
- 3 technicians

Approximately 80% of the group's efforts are devoted to spintronics research of which about one-fifth is in theory.

### SUPPORT

- Salaries, Université Paris SUD
- CNRS — \$10,000 per year plus 3 Ph.D. students
- Thales — \$10,000 per year plus 2 Ph.D. students
- European Community — \$10,000 per year plus 2 postdocs

The university does not provide any funds other than salary support for professors, research assistants, and technicians.

### INFRASTRUCTURE

- Materials Fabrication
  - Metal MBE
  - Sputtering
  - Pulsed laser ablation (PLA)
- Nanofabrication
  - Lithography
  - Photo
  - Electron beam
  - FIB
  - Nanoindentation
- Characterization
  - In Situ

- RHEED
  - Ex Situ
  - TEM
  - EELS
  - SEM
  - XRD
  - Other Spectroscopies
  - XFS
  - EXAFS
  - XMCD in collaboration with other laboratories
- Other Characterization includes SQUID magnetometry, magnetotransport, and Hall magnetometry

### **IMPRESSIONS**

Professor Fert has been a leader in magnetic metals and multilayers for spintronics devices and is one of the discoverers of the GMR effect. The laboratory's work also has made major advances in magnetic tunneling devices, the theory of magnetic tunneling, and most recently, the theory of spin injection into semiconductors. Over the past year or so, Professor Fert's group has also been working on the integration of spin injectors into nonmagnetic semiconductors and is developing capabilities for the preparation and characterization of spin-polarized electrodes. In the past the French activity in spintronics has been limited to only a few laboratories, particularly Orsay and Grenoble. There is need of far more concerted support. A joint venture of the CNRS with the Atomic Energy Commission (CEA), expects to create a new laboratory for "science and technology for information and communications" at Grenoble, which will have a sizeable component devoted to spintronics research and development. There is very little involvement in these efforts by French industry, and interdisciplinary work has been primarily the responsibility of the researchers who foster such activity through lecture series, various academic and academic/industrial partnerships (Professor Fert's laboratory, which is located on the site of the semiconductor company J.J. Thomson, is a good example). This laboratory also stands out in that it has a number of important collaborators supported by the European Community with laboratories in Germany (Halle, Siemens, Kaiserlauter), England (Cambridge, Oxford), Ireland (Dublin), Spain (Barcelona, Zaragoza).

Site: **INESC**  
**Rua Alves Redol 9**  
**1000 Lisboa, Portugal**  
**<http://www.inesc-mn.pt>**  
(interview conducted at JEMS '01 conference, Grenoble, France)

Date: August 30, 2001

WTEC: S. von Molnár (report author)

Interviewee: Paolo Freitas  
pfreitas@inesc-mn.pt

### **GROUP SIZE**

- 4 permanent researchers (including P. Freitas)
- 5 postdocs
- 9 Ph.D. graduate students
- 3 permanent staff (processing engineers)

The group is international in character and includes American, Chinese, and English, participants. With the exception of a recent new initiative in biological applications, all the research effort is directly involved with spin electronics.

### **SUPPORT**

Current funding is ~ \$600,000 per year.

- 60% from Portuguese government
  - 40% funding from a center of excellence evaluated yearly by a panel of experts
  - 20% comes from specific projects
- 40% from other sources
  - 20% from companies
  - 20% from the European community through several programs including: (1) IST, which supports long term nanoelectronic research projects including biochips using magnetoresistive sensors and (2) growth geared to the development of nanotechnologies. The latter requires renewal during 2002.

These funds pay primarily for infrastructure, which does not include graduate students or postdocs unless these are associated with the European projects (1 post-doctorate).

### **INFRASTRUCTURE**

- Facilities
  - One 250 m<sup>2</sup> (class 10) clean room
  - 6 inch wafer back end line
  - CVD reactors (2)
  - Maskless lithography including direct write laser system with 0.8 m resolution
  - 4 normal sputtering systems with base pressure of 5x10<sup>-8</sup> torr
  - One ion beam sputtering system operating at 10<sup>-5</sup> torr
- Characterization

- Tools include automated and manual electronic testing, magnetization switching up to 1 GHz, several vibrating magnetometer and transport stations, as well as magneto-optical Kerr effect. None of this work is done at low temperatures. The group may also avail itself of facilities at a joint laboratory for spectroscopies that include magnetic force microscopy (MFM), atomic force microscopy (AFM), and scanning tunneling microscopy (STM). Parenthetically, there is also easy and continuous access to nuclear scattering facilities.

## IMPRESSIONS

This appears to be a world class fabrication and characterization facility, with activities in the following areas:

- Recording heads
- Low resistance tunnel junctions
- “Current perpendicular to plane” (CPP) heads
- Although devices utilizing current to switch magnetization will be developed, these will require lithographies not yet available at the laboratory

In the area of MRAM research, the locally produced devices are capable of very fast switching in the presence of Oe fields. Testing stations have been developed in house for switching times. There are also materials developments to produce MRAM stabilization near 400°C. Fe<sub>3</sub>O<sub>4</sub> based devices have provided the most significant recent results. [In September 2002 review comments on the draft WTEC report, Dr. Freitas stated that MRAM current switching studies have begun.]

Biochips (EC funding) in which one of the elements is tagged with a large magnetic particle are being integrated by means of standard spin valve technology, which, according to Freitas, is capable of sensitivities approaching 10<sup>-12</sup> emu yielding a signal under operating conditions of 100 microvolts per particle. The effort also includes the use of electronic fields to direct and capture biomolecules at specific locations on the chip. This is a nascent effort, but my impression is that the advances are comparable to those presently pursued in the United States.

A new thrust to integrate magnetic elements onto microelectromechanical systems (MEMS) is just beginning.

In summary, Professor Freitas has developed an enviable center of excellence for microfabrication and characterization of devices. The emphasis is totally on metallic systems. No semiconductor spin electronics or device development is in evidence.

Site: **RWTH Aachen**  
**Physikal. Institut (IIA)**  
**52056 Aachen**  
**Germany**  
**<http://www.rwth-aachen.de/>**  
(email interview)

Date: October 11, 2001

WTEC: S. von Molnár (report author)

Interviewee: Professor Gernot Güntherodt  
gunther@physik.rwth-aachen.de  
Tel: +49-241-80-27055; Fax: +49-241-80-22306

### GROUP SIZE

- 2 research assistants
- 1 postdoc
- 8 graduate students
- 6 undergraduate students

The above numbers reflect only that fraction of the group's effort that is spin-based. The group's efforts are primarily experimental with approximately 20% of the activity devoted to cooperation with theoreticians.

### SUPPORT

- Federal Ministry of Education and Research (BMBF) — \$460,000 per year for the next three years
- European Commission Research Network (TMR) — \$60,000 per year. New applications for next three years are approved.

These funds support infrastructure as well as graduate students. Salaries for postdocs and staff are provided by the university.

### INFRASTRUCTURE

- Materials fabrication
  - Metal MBE
  - Metal oxide MBE
  - CVD
  - AC magnetron sputtering
- Nanofabrication
  - E-beam lithography
  - Milling
  - Reactive ion etching (RIE)
  - Self-assembly, specifically for magnetic nanoparticles within an organic molecular matrix on functionalized wetting substrates
- *In Situ* Spectroscopies and characterization
  - RHEED combined with STM
  - In Situ XPS

- MFM
- UHV Kerr magnetometry
- Brillouin light scattering
- Spin-polarized photoemission, using also synchrotron radiation
- Ex Situ
  - Kerr spectroscopy
  - Magneto-optical scanning near field optical microscopy (MO-SNOM; Faraday or Kerr mode)
  - Time-resolved linear magneto-optics using fsec and psec laser pulses
  - Nonlinear second harmonic generation (SHG) magneto-optics
  - Brillouin light scattering
  - Magnetic force microscopy (MFM)
  - SQUID magnetometry
  - Magnetotransport

The nonlinear magneto-optics through second harmonic generation, as well as MO-SNOM and Brillouin scattering, are particularly powerful to address thin film layers and interfaces.

## IMPRESSIONS

This is a premier laboratory in Germany in the area of metal spintronics, having been active in the study of both GMR and TMR devices. One particular area of expertise is exchange bias and tunneling magnetoresistance. There exists also a relatively mature effort in such half-metallic ferromagnets as  $\text{Fe}_3\text{O}_4$  and  $\text{CrO}_2$ . The laboratory is beginning work on optical as well as electrical spin injection into semiconductors (in cooperation with K. Ploog, PDF Berlin) and thus their extraordinary facilities to look at interfaces and thin films with remarkable resolution will be a great advantage. In terms of the present and future activities in spin electronics technology in Germany, appended below are unedited descriptions of Professor Güntherodt's response to the panel. It is clear that Germany's activities, although comparable to other European countries, presently lag in scope and magnitude compared to those in the United States and Japan.

1) What is the vision for spin electronics technology in your country?

*A certain vision for spin electronics technology at the German Federal Ministry for Education and Research (BMBF) arose only toward the end of the year 2000, when financial support was initiated within the program "Correlated electrons and magnetism." Support before that time was rather marginal. A proposal in the area of spin electronics submitted in 1998 within the National Center of Competence in Nanotechnology, subdivision at Aachen on "Lateral nanostructures" (headed by Prof. H. Kurz) was turned down by the referees of the BMBF, because it seemed too visionary and lacked the required 50% financial support by German industrial partners.*

Besides magnetoelectronics, there is practically no active engagement in spin electronics within German industry.

The "Deutsche Forschungsgemeinschaft," the equivalent to the American National Science Foundation, supports some small individual projects and some projects within two "Sonderforschungsbereiche" ("expert research consortia") and a "Forschergruppe" ("research group").

2) What are the various government programs that sponsor spin electronics?

*Within the BMBF project division "Quantum electronics devices based on III-V semiconductors" there is partial support for spin electronics. Individual projects are in the*

*range of \$0.5 million for three years. There is no requirement of involving either industrial partners or of presenting demonstrators.*

Within the BMBF program “Electron correlations and magnetism,” a call for projects in spin electronics was initiated toward the end of 2000. The total budget for three years amounts to about \$7.5 million. The financial involvement of industrial partners was adjusted to about 15% to 20% in form of supporting Ph.D. students only. The approval of the proposals has meanwhile been given.

Site: **University of Hamburg**  
**Institute for Applied Physics**  
**Jungiusstrasse 11**  
**D-20355 Hamburg, Germany**  
**[http://www.physnet.uni-hamburg.de/iap/group\\_h](http://www.physnet.uni-hamburg.de/iap/group_h)**  
(email interview)

Date: August 2, 2001

WTEC: S. von Molnár (report author)

Interviewee: Professor Dr. Detlef Heitmann  
Heitmann@physnet.uni-hamburg.de  
Tel: +49 (0) 40 42838 5672; Fax: +49 (0) 40 42838 6332

### GROUP SIZE

- 3 full professors
- 3 permanent research staff members
- 5 Ph.D. graduate students
- 4 Diploma students

This represents approximately 20% of the Institute for Applied Physics.

### SUPPORT

- University of Hamburg — \$10,000 per year
- German Science Foundation (GFE) — \$50,000 per year plus salaries
- NEDO (Japan) — \$50,000 per year

These funds support infrastructure as well as both Ph.D. and Diploma graduate students.

### INFRASTRUCTURE

- Materials fabrication
  - Semiconductor MBE (InAs, GaAs)
  - Sputtering
  - Thermal evaporation
- Nanofabrication
  - Holographic lithography
  - E-beam writing
  - Wet and dry etching
- Ex Situ Characterization
  - Magnetic
  - Magnetic Force Microscopy (MFM)
  - SQUID
  - Microcantilevers
  - MicroHall bars



## **IMPRESSIONS**

The primary effort here is on ferromagnetic metal/semiconductor heterostructures for spin injection and detection. There is a strong focus on metal semiconductor contacts and an effort to develop new ferromagnetic materials for spin-polarized sources, including the Heusler alloys. At the moment, InAs and (In,Ga)As are the semiconductors of choice, presumably because it is well known that InAs does not produce Schottky barriers. The group is also exploring various spin filtering schemes and is using nanofabrication techniques to tailor the magnetic properties of the metal contacts for differential switching, etc. Professor Heitmann is well known for his extensive work in semiconductor nanoprocessing and various transport and low energy spectroscopic techniques. New programs within Germany to foster greater activities in the general area of spintronics are just beginning, but in the coming year, these are estimated to include funds exceeding \$15,000,000. While MRAM and GMR programs are often collaborations between industry and academia, semiconductor spintronics is presently being carried out by universities and national research laboratories. The German national government has not developed specific programs and support to address student education nor broad interactions among academic or academic/industry organizations. However, there are long-standing interactive programs that are not specifically earmarked but are available in general for any research topics. These include the Sonderforschungsbereich (SFB) and Graduiertenkolleg (GRK).

Site: **University of Twente**  
**Systems & Materials for Information Storage (SMI)**  
**MESA+ Research Institute**  
**P.O.Box 217**  
**7500 AE ENSCHEDE**  
**The Netherlands**  
(email interview)

Date: August 24, 2001

WTEC: S. von Molnár (report author)

Interviewee: Professor Cock Lodder  
j.c.lodder@el.utwente.nl  
Tel: +31-53-489 1032; Fax: +31-53-489 3343

### **GROUP SIZE**

- 4 professors and associate professors
- 4 postdocs
- 6 Ph.D. graduate students
- 1 technician

The list above includes all personnel active in spin electronics at the University of Twente, not just Professor Lodder and his own group.

### **SUPPORT**

- Total is \$1,680,000
  - University of Twente (salaries for all permanent staff and approximately 3 Ph.D. students)
  - The Dutch Technology Foundation (STW)
  - The Dutch Foundation for Research on Matter (FOM)
  - KNAW
  - Minor support from the European Commission (TMR)

Contributions coming directly from industry are minimal.

### **INFRASTRUCTURE**

All facilities connected with the multidisciplinary effort on spin electronics at Twente is centered at MESA Research Institute. Facilities include the following:

- Clean room with standard CMOS line
  - Thin film fabrication
  - MBE
  - CVD
  - Sputtering
  - Laser ablation
  - Nanofabrication

- E-beam and optical lithography
- Wet and dry etching facilities
- Spectroscopies and other characterization
- TEM
- SEM
- AUGER
- XPS

X-ray and micro-probe facilities, as well as other standard tools also exist in the facility.

- Other characterization (located within the laboratories of the various groups)
  - Magnetotransport
  - VSM and other magnetometers

## IMPRESSIONS

The University of Twente has a record of semiconductor research and has most recently developed a completely novel technique for constructing a spin transistor. Their efforts continue to be on the use of ferromagnetic metals in combination with semiconductors to produce hybrid structures having new functionality due to spin. Another aspect of their thrust is the development of new magnetic semiconducting materials, primarily as spin sources.

## GENERAL IMPRESSIONS

In addition to the specific interviews with Professors Lodder and Van Wees, the panel has been fortunate in receiving a rather more general description from Professors de Jonge and Swagten, which is appended in its entirety. It offers a concise summary of Dutch university research in the area of spintronics:

The scientific effort in the field of spintronics is concentrated mainly in four Dutch universities, viz. Eindhoven, Twente, Groningen, and Delft. In total seven research groups (experimental: Lodder, Van Wees, De Jonge, Rasing; theory: De Groot, Kelly, Bauer) have spintronics incorporated in their main research themes, although also in other groups some activities can be recognized. These groups contribute to a total effort of about 10 permanent scientific staff members (excluding the professors), 25-30 Ph.D. students, 5-15 postdocs, and 20-50 physics students (of which the population may vary from year to year).

The infrastructural facilities include various preparation and characterization tools for magnetic nanostructures and devices, as well as numerous *ex situ* instruments to address the underlying physics, which may for each research group vary strongly in character depending on the research direction. Although national centers, e.g., nanolithography and high magnetic fields, do exist and are accessible for individual researchers, they are not developed or operated specifically for spintronics-type materials.

In The Netherlands none of the main funding agencies have defined programs dedicated directly to the field of spintronics. This accounts for the Dutch Foundation for Research on Matter (FOM) as well as for STW, the Dutch Technology Foundation, both governmental funding agencies. However, individual spintronics programs (from the research groups listed above) are supported within themes or programs covering a wider field in physics. In total we estimate the government funding volume as \$300,000–\$500,000 annually. In the future, new programs are foreseen within (governmental) nanotechnology initiatives, although in this case spintronics will be one of the subthemes with limited funding volume (estimated at \$10,000,000 annually).

Although, in general, some Dutch universities have contributed considerably to the development and continuation of spintronics in the last 10-15 years, the current trend of integration with semiconductor physics (spin injection, hybrids) as well the development of alternative routes for spintronics and characterization (spin filtering, half-metals, scanning probes, dynamics), may require a more synergetic effort within The Netherlands. Financial support by larger scale initiatives specifically devoted to these new challenges is probably required!

Site: **University of Basel**  
**Department of Physics and Astronomy**  
**Klingelbergstrasse 82**  
**CH-4056, Basel, Switzerland**  
(Interview held at the 1st International Conference on Spintronics and Quantum Information Technology, Maui, Hawaii)

Date: May 17, 2001

WTEC Attendees: D. Awschalom (report author), R. Buhrman, A. Chtchelkanova, L. Cooper, J. Daughton, K. Goto, M. Roukes, D. Treger, U. Varshney, S. von Molnár, and S. Wolf

Interviewee: Professor Daniel Loss  
Daniel.Loss@unibas.ch

### **GROUP SIZE (THEORETICAL PHYSICS)**

- 1 professor, 1 associate professor, 3 post-doctorates, 11 graduate students
- Research focus areas include the following:
  - Spin-based quantum computing
  - Transport and spin in nanostructures, including
  - Semiconductors
  - Mesoscopics
  - 2DEGs
  - Coupled quantum dots
  - Exchange
  - Quantum wires
  - Coulomb blockade
  - Noise
  - Cotunneling
  - Spin correlations in normal and superconductors
  - Decoherence and Entanglement
  - Spin filters and memory
  - Molecular magnetism
  - Spin tunneling (MQC and MQT)
  - Large spin quantum computing

### **SUPPORT**

- University of Basel: 2 postdocs, 1 graduate student
- Basel Research award: 2 postdocs, 1 graduate student
- Swiss NSF: 3 graduate students
- Nanoscience Center (Basel): 3 postdocs
- EC Molecular Nanomagnets: 1 graduate student
- DARPA SPINS: 1 postdoc, 1 graduate student
- DARPA QUIST: 1 postdoc

- EC Spintronics: 1 postdoc (pending)
  - New European Commission Research Training Network on Spin-dependent Transport in Nanostructures (2002-2006 if funded)
  - Experiment and theory (50-50) of spin injection, transport in hybrid structures, and mesoscopic magnetism
  - Countries involved and number of principal investigators include France (1), Germany (3), Hungary (1), Israel (1), Italy (2), Netherlands (2), Poland (1), Switzerland (2)
  - €100K/group per year.

## IMPRESSIONS

- Basel has established one of the leading theoretical scientific groups in the area of spintronics and quantum computation both within Europe and in the world. Professor Loss has had experience working at universities in the United States, in Canada, and in industry at the IBM Watson Laboratory in Yorktown Heights, N.Y. His experience in these locations makes him well-suited to help guide the Swiss national effort in this area.
- The university is extremely well connected within Europe and within the United States. Collaborations exist within all major institutions in Switzerland (including IBM Zurich), Europe (Delft, Karlsruhe, Florence, Aachen), the United States (IBM Watson, UCSB, Harvard, Texas, Princeton, and Urbana), Japan (Tokyo), and Korea (Seoul).
- These collaborations are targeted at working with top experimental programs and aimed at developing theory that is directly relevant to experiment.
- Recently, the University of Basel became the main node of a new 10-year National Nanoscience Center: NCCR (2001-2011)
- Includes MEMS, Spintronics, Quantum Computing, Molecular Motors, Nanotubes, Bio-recognition
- Of the 10 new centers in Switzerland, this is the only one on nanoscience
- Funding level is 4-5 M SF/year (NO overhead; funds for students, postdocs, and equipment)
- Network partners include the following:
  - IBM Zurich (no funds to industry)
  - CSEM
  - ETH Lausanne
  - ETH Zurich (Klaus Ensslin)
  - Uni Neuchatel
  - Uni Zurich
  - Paul Scherer Institute (nanolab, neutron facility, synchrotron lab)
- Educational program in preparation: considering new degree in nanoscience

Overall, the Swiss effort is clearly growing and having considerable impact in this field. Their theoretical efforts have catalyzed a variety of important new experiments in quantum dot-based computing in the United States and in Europe. The effort is well organized and well funded and prepared for a long-term commitment in this area.

Site: **University of Wuerzburg**  
**Physikalisches Institut der Universitaet Wuerzburg, EPIII**  
**Am Hubland, D-97074**  
**Wuerzburg, Germany**  
(Interview held at the 1st International Conference on Spintronics and Quantum Information Technology, Maui, Hawaii)

Date: May 17, 2001

WTEC Attendees: D. Awschalom, R. Buhrman, A. Chtchelkanova, L. Cooper, J. Daughton, K. Goto, M. Roukes, D. Treger, U. Varshney, S. von Molnár (report author), and S. Wolf

Interviewee: Prof. Dr. Laurens W. Molenkamp  
laurens.molenkamp@physik.uni-wuerzburg.de

### GROUP SIZE

Professor Molenkamp's group consists of the following personnel:

- 5 permanent staff members of which 4 are at the full professor level
- 4 assistant professors
- 5 postdocs
- 20 Ph.D. graduate students
- 10 M.S. graduate students
- 4 technicians

It is estimated that on average 40% of the time of staff, assistant professors, and postdocs is spent on spintronics research. Of the Ph.D. students, 50% are presently engaged in spintronics, and the percentage is increasing.

### SUPPORT

Current funding for spintronics-related work only, which is established to be about 70% of total funding, includes the following:

- European Union support through: Feniks – 1 postdoc for 4 years starting in 2001; two additional applications submitted.
- DARPA SPINS – 2 postdocs for four years starting 2000
- The German Applied Research Council
  - EKM (correlated electrons) – 1 postdoc for four years starting 1998; renewal submitted
  - Quantum structures system – 1.6 postdocs for four years starting 2000
- German Research Association (DFG) – 4 Ph.D graduate students, 1 postdoc through a “rolling grant” whose current period is 2001-2004.
  - At an estimated rate of .8 dollars per Euro, and €50K /postdoc/year in salary, added to running costs and other expenses of ~\$20K/post-doctorate/year, the above support is an impressive \$1,500,000/year.
- In addition Wuerzburg University supports this experimental program at \$160,000 per year.
- There are also occasional opportunities for big ticket capital items valued at ~\$350K/year funded both by the state (Bavaria) and the federal government.
- Facilities include the following:

- 7 molecular beam epitaxy (MBE) chambers devoted to II-VI and III-V substrates and heterostructures. Another is devoted to Heusler alloys as possible spin-polarized sources.
- (Ultra) high vacuum deposition of magnetic metals and insulators (thermal evaporation and sputtering)
- Lithography — including optical and e-beam instruments; reactive ion as well as wet etching capabilities exist.
- Characterization
  - Structural quality
  - In situ UHV compatible XPS (x-ray photoelectron spectroscopy) and SPA-LEED
  - High resolution x-ray diffraction
  - Scanning electron microscopy (SEM) with microprobe analysis feature
  - UHV, STM and AFM
- Physical Properties
  - Low temperature magnetotransport
  - Photo luminescence (PL) and Raman spectroscopy
  - Semiconducting properties (CV, IV and noise)
  - Magnetization using a commercial SQUID
- Professor Molenkamp's group works on several research programs aimed at spin injection and spin manipulation in semiconducting structures. Among these are the following:
  - Electronic spin injection with concomitant optical detection in II-VI diluted magnetic semiconductor heterostructures
  - Electronic spin injection and detection in II-VI diluted magnetic semiconductor heterostructures
  - Spin manipulation in II-VI diluted magnetic semiconductors using field effect lateral and other vertical device structures

## IMPRESSIONS

This laboratory has outstanding facilities and research programs of direct relevance to semiconducting spintronics. The group made a major discovery in using a spin filtering geometry to inject a highly spin-polarized flux of electrons into II-VI semiconductors. This breakthrough and continuing work in the area of spin injection and detection make this lab arguably the leader among those in the European arena. Overall, this is a very impressive, focused research effort with great probability of continuing high productivity in the near future. The group is highly competitive both in materials development and the science connected with magnetic semiconductors and their applications in spintronics.



Site: **University of Hamburg**  
**Institute of Applied Physics**  
**Microstructure Advanced Research Center Hamburg (MARCH)**  
**German Center of Competence in Nano-Scale Analysis**  
**Jungiusstrasse 11**  
**D-20355 Hamburg, Germany**  
(email interview)

Date: August 2, 2001

WTEC Attendee: S. von Molnár (report author)

Interviewee: Prof. Dr. Roland Wiesendanger  
wiesendanger@physnet.uni-hamburg.de

### **GROUP SIZE**

- 3 full professors
- 2 associate professors
- 3 permanent research staff members
- 7 postdocs
- 15 Ph.D. graduate students
- 10 Diploma students

All members of the group are involved in the development and applications of high sensitivity spectroscopies with a goal towards atomic and single spin resolution.

### **SUPPORT**

- \$500,000 per year
  - National Science Foundation (DFG)
  - German Ministry for Education and Research (BMBF)
  - German-Israeli-Foundation (GIF)
  - NEDO

These funds support the infrastructure, as well as the graduate students, both diploma and Ph.D. students.

- New sources of funding are expected from the state government of Hamburg and from the federal government.

### **INFRASTRUCTURE**

- Materials Fabrication
  - Metal-MBE
  - Semiconductor-MBE (GaAs, InAs)
- Nanofabrication
  - E-beam lithography
  - Interference lithography
- Spectroscopies and other characterization

- Scanning probe spectroscopy, in particular SP-STM/SP-STs (spin polarized scanning tunneling microscopy and spectroscopy), Low-T MFM, etc.
- SEMPA
- Spin-resolved photoemission
- Magnetotransport
- Magnetometry

## **IMPRESSIONS**

This is a leading laboratory in the development and practice of a variety of high resolution spectroscopies with goals toward achieving atomic resolution and single spin sensitivity. The correlation of structural, electronic, and magnetic properties of spintronics hybrid systems, especially those at interfaces, represent a crucial challenge to fundamental understanding of this new technology. That is this laboratory's focus with respect to spin electronics.

Site: **IMEC  
Magnetoelectronics Group  
Kapeldreef 75  
B-3001 Leuven, Belgium**

Date: July 5, 2001 (with additional updated information provided by the host in September 2002)

WTEC Attendee: J. Daughton (report author)

Host: Dr. Jo De Boeck, Group Leader and Principal Researcher  
deboeck@imec.be  
Tel: +32 16 281518; Fax: +32 16 281501

### **GROUP SIZE**

13 people total

- Dr. De Boeck
- 3 postdocs
- 7 Ph.D. students (will soon grow by 2 more Ph.D. students)
- 2 M.S. students

### **SUPPORT**

Combination of European Union and Commercial Contracts and Belgian government. Average cost of staff at the time of this visit was estimated at about \$80,000 per year.

### **ADDITIONAL DETAILS SUPPLIED BY DR. DE BOECK IN SEPTEMBER 2002**

#### **Group Overview**

The magnetoelectronics group (group leader J. De Boeck) is embedded in the department of Nano-Engineered Component Science and Technology (NEXT) (department director J. De Boeck). This department has three groups using jointly the III-V processing line, a plastic electronics processing facility, an epitaxy-centre (2 MBE and 2 MOCVD), and deposition tools for magnetic thin films (MBE, sputtering and laser ablation, to name the most important ones).

The magnetoelectronics group totals currently an annual funding from the EC of about €450K in spintronics projects on topics such as magnetic biosensors, optical isolator, magnetic semiconductors, and spin injection devices.

The full annual cost for staff is about €95K (including overhead).

#### **Magnetic Semiconductor Research**

Work on magnetic-semiconductor hybrids was started in 1992 at IMEC with the growth of epitaxial magnetic thin films and magnetic semiconductors (InMnAs and GaMnAs). The first successful growth of GaMnAs as a magnetic semiconductor was achieved in 1995 (Van Esch 1997). Since then the work has continued in GaMnAs, and the current record T<sub>c</sub> value is 133 K and a variety of heterostructures is under investigation (in the framework of the FENIKS project). (EC support for FENIKS is €3.6 million.)

### Spin Injection Research

Subsequent to the WTEC visit, Dr. De Boeck reported results on successful spin injection from a ferromagnetic thin film through an AlO barrier into a III-V LED. The group has published these data as well as the successful room temperature SPIN-LED based on the same tunnel barrier technology. IMEC researchers believe that this is a significant result, since spin injection efficiencies over 50% at 80 K and 11% at room temperature have been assessed using a quantitative technique based on the Oblique Hanle Effect (Motsnyi et al. 2002; Van Dorpe et al. 2002). This work is embedded in the project SPINOSA, looking at spin injection, in which IMEC is a partner. (Coordination: U. Wuerzburg, other partners, U. Bologna, U. Oxford, U. Twente, U. Nijmegen). The cumulative funding for this effort is on the order of €1.2 million.

### IMPRESSIONS

- Excellent facilities. There is an operating 0.18  $\mu\text{m}$  CMOS line on site, with a GaAs development line in the same space and using some of the same equipment. De Boeck's group uses some of its own equipment and quite a bit of the GaAs equipment. Machinery of note includes two MBE systems, a sputtering tool, and a gradient field magnetometer.
- Dr. De Boeck's goal (and IMEC's) is to enhance standard semiconductor technology to get improved functionality. His group is currently working on MTJ reliability, switching speed of magneto-optic and piezo-electric films combined with ferromagnetic films and is beginning to work on GaMnAs and low dimension magnetics. The group has near term interests in spin injection and spin-polarized current switching.
- Dr. De Boeck's group is the project coordinator for FENIKS (Ferromagnetic semiconductors and Novel magnetic-semiconductor heterostructures for Improved Knowledge on Spintronics), a three-year program funding 17 different organizations, including several U.K. universities and research organizations — Nottingham, Sharp Laboratories (Oxford) Imperial College, and DERA (QinetiQ). The total program funding is €5 million for 650 person months.
- Dr. DeBoeck's group has had a rich history in magnetics research with some tendency toward applications. Topics have included magnetic semiconductors, tunnel barrier devices for optical detection of spin-polarized currents, spin valve transistors, Hall probe microscopy, and MRAM. The group worked closely with Infinion on MRAM until the tie between Infinion and IBM was established. This seems to indicate that the group can move with ease into spintronic research areas of topical interest as they arise.

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Site: **QinetiQ**  
**Sensors and Electronics Sector**  
**St Andrews Road, Malvern**  
**Worcester, WR14 3PS, United Kingdom**

Date: July 6, 2001

WTEC Attendees: J. Daughton and David E. Schindel, Head, National Science Foundation Europe Office  
(report authors)

Host: Professor J.H. Jefferson  
jhj@qinetiq.com  
Tel: (0)1684 894752; Fax: (0)1684 897275

### **GROUP SIZE**

Five to six equivalent full time people in spintronics, could grow to 10-12 with new contracts.

### **SUPPORT**

Currently, about two people receive support from FENIKS. Remainder funded by contracts, internal R&D. A new SPINS-oriented contract is anticipated this fall.

### **IMPRESSIONS**

The largest science and technology organization of its kind in Europe was the British government's Defense Research and Development Agency (DERA), which is now split into two parts, much the larger part of which is in the process of going private as QinetiQ with a staff of about 9000 people and a total revenue of about \$1.4 billion. The Malvern site has about 2000 people. John Jefferson's group is part of the optical and electronics components section, which specializes in III-V and II-VI device design, fabrication, and testing. They work on narrow gap semiconductors and have capabilities for MBE, CBE, MOCVD for III-IV semiconductors, up to 3 in wafers; optical & e-beam lithography; metal sputtering; dielectric sputtering; and wet/dry etching processes. Mercury-cadmium-telluride IR detectors and indium antimonide magnetic field sensors would represent two of this group's typical technology and product interests. John Jefferson's group works on new devices.

The group is a player in the spintronics-related FENIKS (Ferromagnetic semiconductors and Novel magnetic-semiconductor heterostructures for Improved Knowledge on Spintronics) program (contract GRD2000-30160 of the EC's GROWTH Programme). Although they have semiconductor growth equipment in close proximity, they do not intend to grow ferromagnetic semiconductor materials — they intend to leave that to others on their collaborative programs. Jefferson's group will focus on devices like spin transistors, MR sensors, and Hall structures.

Areas of future research interest include nanoscale devices with magnetic contacts/gates, molecular electronics, carbon nanotubes, quantum coherent devices, and optomagnetic devices. New projects on molecular electronics and quantum coherent devices have recently been approved and funded by the British Ministry of Defense. These projects include aspects of spintronics and quantum information processing at nano- and molecular scales.

They are bidding for spintronic optoelectronics sensor contracts and will perhaps bid on future DARPA programs.

They are also interacting with Interdisciplinary Research Centers (IRCs) in bionanotechnology and nanoelectronics at Cambridge and Oxford funded by the United Kingdom's Engineering and Physical Sciences Research Council (EPSRC).

Because of its proximity to exotic semiconductor processes and technology, this group has the potential to become a significant developer of magnetic semiconductor processes and devices if they chose to do so.

Site: **Trinity College**  
**Physics Department**  
**Dublin 2**  
**Ireland**  
<http://www.tcd.ie/Physics/Magnetism/>

Date: July 9, 2001

WTEC Attendees: J. Daughton and S. von Molnár (report authors)

Host: Professor Michael Coey  
jcoey@tcd.ie  
Tel: (353) 1 6081470/2171; Fax: (353) 1 6711759

### GROUP SIZE

- 2 permanent staff members (J.M.D. Coey and I. Shvets)
- 5 postdoctoral students
- 12 Ph.D. graduate students
- 1 technician

Professor Coey's group works in three general areas of which the spintronics-related work constitutes approximately 60%. The programs are as follows:

- Half-metallic materials for magnetoresistive devices and new permanent magnetic materials
- Spin-polarized transport, injection, and detection, especially in point contacts
- Magnetism and electrochemistry

Professor Shvets concentrates on novel probes to study surface and interface physics of magnetic materials and multilayers in UHV environments.

### SUPPORT

Professor Coey:

- Current total support for the group (3 post-doctorates, 6 Ph.D. graduate students, 1 technician) is approximately \$300,000 per year.
  - 70% from European Union programs in Ireland
  - 30% from Irish government sources
  - These funds pay for postdocs, graduate students and the technician. The composition of graduate students is about 50% Irish, 50% other European countries. Postdocs come from Ireland, China, France, and India.

Professor Shvets:

- Support and breakdown for funding is comparable to the above.

Thus the total group is supported by approximately \$600,000 per year, most of which comes from outside Ireland.

### FUTURE FUNDING

- Ireland has recently decided to invest IR£500 million (~ \$550 million) over five years to support basic research related to the following major areas:

- Biotechnology
- Information and communications technology (ICT)
- Large grants have been awarded during the first year of the cycle to 10 new principal investigators, half of them based at Trinity College, Dublin. The amounts are IR£5 million (\$5.5 million) over five years, and the intent is to structure successful research programs like the NSF's Materials Research Science and Engineering Centers (MRSECs). Professors Coey and Shvets have both received awards with a total influx of IR£2 million (\$2.2 million) per year over the next five years. Coey's program is named "Conception and Implementation of Nanoscale Spin Electronics" (CINSE) and will initially invest in nanofabrication technology including a new combination focused ion beam/electron beam fabricating tool capable of 5-7 nm resolution. There will also be a major effort to recruit expertise in electronics to integrate new spin concepts with existing electronics technology.

## **FACILITIES**

- At present these are modest. Coey's laboratory features surface characterization by Magnetic Force Microscopy (MFM), and x-ray spectroscopy, magnetometry including a commercial SQUID, vibrating sample magnetometer, and magneto-optical Kerr effect, as well as several low temperature transport stations. Room temperature facilities for bulk magnetic crystal nanocontact magnetotransport are also in place as is noise spectroscopy and Mössbauer spectroscopy. Films are prepared by pulsed laser and electrodeposition.
- Shvets's area includes at least two UHV scanning tunneling microscopes. One of the UHV systems also has metal MBE capability and surface characterization including low energy electron diffraction (LEED), reflection high energy electron diffraction (RHEED), and AUGER.

## **IMPRESSIONS**

Professor Coey is a world-renowned leader in magnetic research and has led a European network on oxide spin electronics (OXSEN), which has produced the first book on spin electronics. With the modest support he has enjoyed thus far, he has nonetheless managed to make several important discoveries, including the recent observation of room temperature low magnetic field magnetoresistance on the order of 500% using point contacts between small crystallites of magnetite ( $\text{Fe}_3\text{O}_4$ ).

The surface studies of Professor Shvets will most certainly be of critical importance to an understanding of the magnetism as structures continue to be reduced to the nanoscale. This is the goal of the new center, which has recently been funded by the Irish government and which will be led by Professor Coey in concert with his colleagues. The group is already competitive in areas of magnetic materials research and MR. The new program, CINSE, will further strengthen the group's high productivity in the areas of spintronics and its applications.

Professor Coey alerted us that there is a large effort in Jena, Germany, on magnetoelectronic applications funded from a combination of state, federal, and commercial sources.

The Dublin activities are relatively unique in that they have resulted in two spin-off companies:

- Magnetic Solutions, founded in 1994, which produces magnetic annealing tools for read heads and magnetic random access memory (MRAM)
- Allegro Technologies, founded in 1998, which specializes in small droplet jets



Site: **Imperial College of Science, Technology and Medicine**  
**Centre for Electronic Materials & Devices**  
**The Blackett Laboratory**  
**Prince Consort Road**  
**London SW7 2BZ, United Kingdom**  
(Interview conducted at the 4th Joint UK Magnetics Workshop, Cardiff, UK)

Date: July 11, 2001

WTEC Discussants: James Daughton and Stephan von Molnár

Host: Dr. Leslie Cohen  
l.cohen@ic.ac.uk  
Tel: +44 (0207) 594 7598; Fax: + 44 (0207) 594 3817

### GROUP SIZE

- 4 staff, including Dr. Cohen
- 4 postdocs (effective October 2001)
- (0.4 postdocs related issues)

### SUPPORT

\$480,000 from EU, \$560,000 from joint EPSRC, NEC, and Scientific Genetics Consortium

### IMPRESSIONS

- Dr. Cohen's group is a member of the Spintronics Network (funded for communications with other groups in the United Kingdom working in similar areas).
- Sensing applications being investigated are EMR and magnetic imaging
- Although the current emphasis is experimental, theoretical efforts will be added over the next year or so.
- Materials system emphasis is NiMnSb and CrO<sub>2</sub> electrodes on InAs and InSb because of high Curie temperatures and low deposition temperatures (although chemical vapor transport requires a substrate temperature of ~ 400°C). Potential for this system is thought to be high because of the high degree of polarization possible and the compatibility with usable semiconductors
- Materials are currently deposited by MBE, and laser ablation is being considered for the future. On site there is 0.3 μm lithography, and the London Centre for Nanotechnology can be used for smaller features in the future.
- Analytic methods include TEM and beveling. The latter process is unique in that the structure can be beveled with at an angle of a few minutes, which gives an effective magnification of the interface of several thousand, making it much easier to analyze. Magnetic analyses include VSM, MFM, Hall imaging, magnetotransport measurements up to 8T, point contact microscopy, and polarization using Andreev suppression.

Site: **University of Cambridge**  
**Department of Physics**  
**Cavendish Laboratory**  
**Madingley Rd**  
**Cambridge CB3 0HE, United Kingdom**  
**[http://homer.phy.cam.ac.uk/TFM\\_Home.html](http://homer.phy.cam.ac.uk/TFM_Home.html)**

Date: July 11, 2001

WTEC Attendees: J. Daughton and S. von Molnár (report authors)

Interviewee: Professor Tony Bland  
jacbl@phy.cam.ac.uk  
Tel: +44 (0)1223 337436; Fax: +44 (0)1223 350266

### **GROUP SIZE**

Professor Bland's group consists of the following people:

- 1 permanent staff (Bland)
- 8 postdocs
- 12 Ph.D. graduate students

It is estimated that on average 50% of the group is directly involved with spin electronics.

### **SUPPORT**

Current funding for spintronics includes £500,000 (\$700,700) for two years from various sources:

- EPSRC through the advanced magnetism programs
- The European Union
- Several companies (ABB specifically mentioned)
- The Royal Society
- Newton Trust

These funds support graduate students and postdocs both from the European community and (at a higher rate) from other countries. Cost per student per year is about £15,000 (\$21,000). Some students are obtained at no cost, and others are partially funded outside of Professor Bland's budget. Capital investment monies are more difficult to obtain.

### **INFRASTRUCTURE**

- Facilities include the following:
  - 5 home-built molecular beam epitaxy (MBE) chambers devoted to magnetic metal substrates, GMR heterostructures, tunneling magnetoresistance (TMR) devices, and magnetic metal/semiconductor structures
- Characterization
  - In Situ
    - UHV compatible low energy electron diffraction (LEED), reflection high energy electron diffraction (RHEED), scanning tunneling microscopy (STM), magneto-optical Kerr effect (MOKE), and Brillouin light scattering (BLS)

- Ex Situ
  - X-ray diffraction, atomic and magnetic force microscopy (AFM, MFM)
  - Room and low temperature magnetotransport
  - Photoluminescence (PL)
  - Noise spectroscopy
  - Current-voltage (I-V) characteristics

There is strong cooperation through European community and U.K. initiatives with external nanofabrication facilities that are crucial to Professor Bland's work.

### **IMPRESSIONS**

This group has a long history of innovative studies on magnetic thin films, multilayers, and heterostructures. The group's SPINS research efforts can be broken down into heterostructures, transport, and nanocontacts. The group addresses such issues as (a) the interface of Fe on semiconductors; (b) device applications, i.e. optically induced spin currents in spin valves; and (c) coherent spin transport between disparate materials. The group reported interesting work on spin injection using polarized light and spin detection using ferromagnetic contacts. The group is starting work on the deposition of magnetic semiconductors.

The lack of in-house nanofabrication facilities severely limits the efficient realization of new device structures. Professor Bland is working toward obtaining the sources for a local nanofabrication facility.

Site: **University of Cambridge**  
**Department of Materials Science**  
**Pembroke Street**  
**Cambridge CB2 3QZ**  
**United Kingdom**  
<http://www-dmg.msm.cam.ac.uk/dmg/>

Date: July 11, 2001

WTEC Attendees: J. Daughton and S. von Molnár (report authors)

Interviewee: Dr. Mark Blamire, Device Materials Group  
 mb52@cam.ac.uk  
 Tel: +44 (0) 1223 334359; Fax: +44 (0) 1223 334373

### GROUP SIZE

The Device Materials Group is led by Professor John Evetts and consists of 3 permanent staff members (John Evetts, Mark Blamire, and Neil Mathur).

Although the group consists of 35 individuals in its entirety, the magnetism effort accounts for approximately twelve people:

- 3 permanent staff
- 3 postdocs
- 6 students

The magnetism effort, particularly the spins-related work, is led by Dr. Blamire. The following section describes only his research activities.

### SUPPORT

Current funding for spintronics related activities includes the following:

- EPSRC — ~£1,000,000 (\$1,400,000) over three years. Of these funds one-half are devoted to spin tunnel junction research, one-fourth to magnetics, and one-fourth to new technologies
- DERA (comparable to our DARPA) — ~£40,000 (\$56,000)
- Seagate and other small industrial awards — ~£12,000 (\$17,000)

It is expected that comparable funding will be available in the future.

### INFRASTRUCTURE

- Facilities include the following:
  - 10 UHV sample preparation chambers including 3 pulsed laser deposition (PLD) and 7 sputtering systems. These are devoted to a number of thin film studies, including the superconductor MgB<sub>2</sub>, the double perovskites, GMR, TMR, etc.
  - Nanofabrication — This includes 2 mask aligners (1 contact, 1 projection), 1 focused ion beam apparatus (FIB) capable of 15 nm resolution, several wire bonders, a wafer saw and probe station
- Characterization
  - Structural quality
  - X-ray spectroscopy and surface texture of thin films

- Magnetic force microscopy
- Optical high resolution microscopy
- Transmission and scanning electron microscopy (TEM and SEM) are available externally
- Magnetic Characterization
- 1 commercial superconducting quantum interference device (SQUID)
- 2 vibrating sample magnetometers (VSM)
- Low temperature (liquid He<sup>4</sup>, He<sup>3</sup>) facilities for magnetotransport and various microwave experiments

## IMPRESSIONS

Dr. Blamire and his colleagues are U.K. leaders in the field of magnetic tunnel structures for magnetic sensing devices. They have made major contributions (also working with local industry) to integrated magnetic bridge sensors and to fundamental understanding of intergranular tunneling effects in mixed valence perovskites. They are also interested in superconductivity, i.e., to improve junction properties and to produce commercially viable superconducting wires. This research is important to spintronics because it requires the development of high quality junction and thin film interfaces. Research in thin film deposition is clearly basic to all these studies.

Dr. Blamire's research has produced tunneling devices using manganites ( $\text{La}_{0.7}\text{Ca}_{0.3}/\text{NdGaO}_3/\text{La}_{0.7}\text{Ca}_{0.3}$ ) with an on/off ratio of more than 7:1 at 77K. To the WTEC panel's knowledge, that is the highest value of magnetoresistance obtained in tunneling devices; and it demonstrates a nearly ideal "half-metal" characteristic.

The general philosophy appears to be that spin devices will produce new functionality for electronics and that even such sophisticated geometries as magnetic/superconducting multilayers may afford viable methods for transporting spins and for modifying the properties of superconductors. Dr. Blamire's future desires include *in situ* characterization during the film growth process. At the moment all characterization in this laboratory is conducted *ex situ*. Dr. Blamire also expects to move further toward the nanoscale where the possibility of new physics and very large magnetosensitivities hold promise for new device geometries.

Site: **University of Glasgow**  
**Department of Physics and Astronomy**  
**Glasgow G12 8QQ, United Kingdom**  
(email interview)

Date: July 30, 2001

WTEC Attendee: J. Daughton

Interviewee: Professor John Chapman  
j.chapman@physics.gla.ac.uk  
Tel: +44 141 330 4462; Fax: +44 141 330 4464

#### **GROUP SIZE (SPINS RELATED WORK ONLY)**

- 2 postdocs
- 1 graduate student
- 0.5 staff member

#### **SUPPORT**

Mainly EPSRC and some industry. About £180,000 per annum total.

#### **IMPRESSIONS**

Professor Chapman's group is a world leader in E-beam analysis of thin magnetic films, and the SPINS work represents only a fraction of his work. The main SPINS efforts in the group (all in collaboration with Professor Wilkinson's group in the Department of Electronics and Electrical Engineering) are (1) fabrication of a ferromagnetic single electron transistor and (2) a study of spin tunnel junctions. The latter has two aspects, one concerning the nature of the dielectric/metal interface and the other the size/shape dependence of the magnetic properties of STJ elements. In the near future the groups hope to start analyzing nano-constrictions in ferromagnetic films. Laboratory facilities and major equipment available to these programs include the following:

- Magnetic imaging using Lorentz microscopy with a specially modified TEM (Philips CM20 FEG) High spatial resolution structural and chemical information with a state-of-the-art nanoanalytical TEM (Tecnai F20)
- Electron beam lithography
- Reactive ion etching
- Focused ion beam (FEI 200 TEM)

Site: **University of Nottingham**  
**School of Physics and Astronomy**  
**University of Nottingham**  
**University Park**  
**Nottingham, NG7 2RD, United Kingdom**  
(Personal and e-mail correspondence)

Date: July 11, 2001 and subsequent e-mail correspondence.

WTEC Attendees: Jim Daughton and Stephan von Molnár

Interviewee: Dr. Bryan Gallagher  
Bryan.Gallagher@nottingham.ac.uk  
Tel: (+44) (0) 115 951 5139; Fax: (+44) (0) 115 951 5180

### **GROUP SIZE**

- 3 staff members
- 3 research assistants
- 3 graduate students

### **SUPPORT**

Approximately \$1.4 million, mostly funded by EPSRC with some funding from the European Union. Funding is \$700,000 for magnetic semiconductors, \$280,000 for hybrid ferromagnetic/semiconductor devices, and \$400,000 (the spintronics-related share of their core III-IV program). Also, there is \$700,000 funding for nitride growth, which may be indirectly related to SPINS. These programs are from one year to three years in duration.

### **IMPRESSIONS**

Dr. Gallagher is the coordinator of the Spins Network (please see the following pages for a summary of that group's activities). Dr. Gallagher's group has interests in MBE III-V semiconductor growth, magnetic semiconductor growth, nanofabrication, quantum transport in semiconductors, spin injection into semiconductors, magnetically modulated semiconductor structures, and nanomagnetometry. The group is interested in ferromagnetic/semiconductor fringing field devices, heterostructures, and quantum wells, with the magnetic materials primarily grown by MBE techniques. The group has available X-ray and TEM structural analysis and microprobe analysis. Also available are low temperature MFM/AFM instruments and room temperature STM analysis. They work with the University of Glasgow to make some fine lithography devices. They are investigating Schottky and tunnel injection and are starting work on magnetic semiconductors.

### **SPECIAL REPORT — THE EPSRC SPINTRONICS NETWORK (WWW.NOTTINGHAM.AC.UK/~PPZSPIN)**

Source: Dr. Bryan Gallagher, Network Coordinator, University of Nottingham

Research on a number of potential SPINS devices by members of the network is currently funded by the EPSRC. The importance of this new research area is highlighted by its inclusion in European Commission Information Society Technology "Roadmap for Nanoelectronics" as an important emerging technology.

Developments in the area of hybrid ferromagnet/semiconductor devices and spin electronics have been hampered by the traditional divide that exists between academic researchers with interests in "semiconductors" and in

“magnetism.” Furthermore research into submicron ferromagnetic devices such as, e.g., ferromagnetic single electron transistors, has been hampered by the fact that expertise in nanofabrication resides almost exclusively in U.K. semiconductor research groups. A network focusing on hybrid structures and spintronics brings together expertise in magnetism and semiconductors/nanofabrication. It would also provide a means of developing collaborations that make best use of the investments that have been made in advanced metal deposition facilities and semiconductor growth/nanofabrication facilities.

The principal objectives of the network are as follows:

- To enhance collaboration between leading U.K. magnetism and semiconductor research groups and to promote the free exchange of ideas and new results
- To encourage interdisciplinary collaborations between scientists in materials, physics, and electrical engineering departments
- To allow the exchange of personnel between laboratories to aid collaboration and to help train postgraduate research students and postdoctoral research assistants
- To accelerate the development of the subject area in the United Kingdom and to raise the international profile of U.K. research in this area
- To aid access to the facilities and equipment of members’ laboratories
- To encourage collaboration between network members and industry
- To help develop future joint applications for U.K. and European funding
- To provide access to leading international experts and to ensure that these experts are fully aware of U.K. research work in the subject area.
- To focus the efforts of network members on topics of key importance and industrial relevance

A principal aim of the network is to establish collaborations between leading magnetism and semiconductor/nanofabrication groups. Major areas of collaboration will include the following:

- Spin injection transistors — analogues of established ferromagnet/paramagnet GMR structures in which a spin-polarized current is injected from ferromagnetic contacts into semiconductors or carbon nanotubes
- Hybrid magnetic/semiconductor structures in which the magnetic fringing field of integral micron or submicron ferromagnetic structures directly modifies the longitudinal or Hall resistance of the semiconductor device
- The use of submicron semiconductor Hall sensors as scanning probe nanomagnetometers
- Novel ferromagnetic analogues of established nanoscale semiconductor devices. These include ferromagnetic single electron transistors, quantum wires, quantum dots, quantum point contacts, and electron transport through single domain walls in submicron constrictions.
- Growth and characterization of magnetic semiconductors leading to spin injection and spin tunneling devices based on magnetic semiconductors

Participants in the proposed network come equally from magnetic and semiconductor/microfabrication backgrounds. The participating groups have existing, funded research programs in areas covered by the network. However it is intended that the network will have an open door policy and will positively encourage participation from all individual researchers and/or teams who have an interest in the subject areas. The initial network members are given below.

- **Nottingham, Physics (Gallagher, B.L., P.C. Main, L. Eaves, M. Henini)** MBE semiconductor growth. Nanofabrication. Quantum transport in semiconductors. Spin injection into semiconductors. Magnetically modulated semiconductor structures. Nanomagnetometry.
- **Leeds, Physics (Hickey, B.J., C. Marrows)** Magnetic multilayer growth and characterization. Magnetometry. GMR. Current perpendicular-to-plane GMR submicron dot structures, ferromagnetic quantum wires, dots, and point contacts structures.
- **Glasgow, Physics (Chapman, J.N., and A.R. Long) and Electrical Engineering (Wilkinson, C.D.W., J.H. Davies, and J.M.R. Weaver)** MBE semiconductor growth. Nanofabrication. Characterization of



micron scale ferromagnetic single layer and multilayer elements. Scanning Hall nanomagnetometry. Magnetically modulated semiconductor structures. Ferromagnetic single electron transistors.

- **Cambridge, Physics (Bland, J.A.C.)** Ultra thin film magnetism. Scanning magneto-optics. Characterization of micron scale ferromagnets. Optical and electrical detection of spin injection into semiconductors from ohmic and Schottky contacts. Interface magnetism and spin-polarized electron transport at hybrid interfaces.
- **Cambridge, Physics (Smith, C.G.)** MBE semiconductor growth. Nanofabrication. Electrical detection of spin injection into semiconductors. Single electron transistors. Scanning probe techniques.
- **Oxford, Physics (Gregg, J.F.)** Spin electronics. Spin tunneling. Spin-polarized injected current emitter transistor. Ferromagnetic single electron transistors.
- Imperial College, Physics (Cohen, L.F., R.A. Stradling, and A.D. Caplin), Materials (MacManus, Driscoll J.) and Electrical Engineering (Green, M., and K. Forelets) MBE semiconductor growth. Optimization of highly spin-polarized rare earth oxides. Spin lifetimes in semiconductors. Spin injection electrodes based on NiMnSb and CrO<sub>2</sub>. Spin-dependent transport in InAs and InSb and spin orbit-related effects. Hybrid magnetite-semiconductor composite structures.
- **York, Physics (Thompson, S.M.)** MBE-grown magnetic thin films. GMR. Spin-polarized injected current emitter transistor. Ferromagnetic single electron transistors.
- **Bath, Physics (Bending, S.J., A. Nogaret, and S.R. Andrews)** Scanning Hall magnetometry. Magnetically modulated semiconductor structures. Magnetic edge states.
- **Hitachi Cambridge Research Laboratories (Alphenaar, B.)** Magnetic memories. Spin injection and GMR in ferromagnet/Carbon nanotube/ferromagnet structures.
- **Loughborough University, Physics (Ziebeck, K.A.R., and K.U. Neumann)** Magnetic semiconductors. Magnetic and transport properties of epitaxial MnAs layers grown on GaAs. Half-metallic ferromagnets for spin-polarized current injection.

The principal activities of the network are as follows:

- The development of a website as a central resource for network members and as the primary means for publicizing the activities of the network. All members of the network will be encouraged to post their latest results and papers on the website. The website will give up-to-date details of relevant conferences and meetings. The site will also provide an expansive set of links to the pages of other related networks and international groups.
- A major two-day workshop each year. This will allow all network members and those interested in the network research areas to present their latest work and to hear invited review presentations from leading international experts.
- One-day meetings of network subgroups on specific topics.
- A series of bilateral exchanges among laboratories. This will allow staff (including postdoctoral staff) and postgraduate students to learn new techniques and to use equipment in the laboratories of other network members.

**Site:**                    **University of Regensburg**  
**Experimentelle und Angewandte Physik**  
**Universitätsstr. 31**  
**D-93040 Regensburg, Germany**

**Date:**                    June 13, 2001 (reflects updated information provided by host in April 2002)

**WTEC Attendees:** M. Roukes (report author)

**Interviewee:**        Professor Dr. Dieter Weiss  
    dieter.weiss@physik.uni-regensburg.de  
    Tel: +49 941 943 3197; Fax: +49 941 943 3196

### **GROUP SIZE**

- 3 permanent staff members (level: technician)
- 1 assistant professor
- 0 (currently) postdoctoral researchers
- 14 graduate students: Ph.D. candidates
- 5 graduate students (Masters degree candidates)

### **PERCENTAGE EFFORT IN SPINTRONICS**

It is estimated that on average 30% of the time of staff, the assistant professor, and the postdocs is spent on spintronics research. Of the Ph.D. students, six are presently engaged in spintronics, and the percentage is increasing.

### **SUPPORT**

Current funding for spintronics includes the following:

- European Union support – (COMPLETED):
  - Grant: SPIDER program on magnetoelectronics
  - Level: \$110,000 over three years
  - Period of support: 1997 – 2000
- Bundesministerium für Bildung und Forschung (BMBF)
  - Grant: “Scanning Hall Microscope”
  - Participants: Profs. Weiss and Bayreuther at the University of Regensburg
  - Level: ~\$150,000 per group over three years
  - Period of support: 1998-2001
- Bundesministerium für Bildung und Forschung (BMBF) – (PROPOSED)
  - Grant: “Joint Project: Spin Electronics and Spin Optoelectronics in Semiconductors”
  - Participants: Multiple investigators at the Universities of Regensburg, Wurzburg, Hamburg, Hanover, at TU Munich, and at MPI Halle.
  - Level (requested): ~\$750,000 per group over three years
  - Period of support (requested): 2002-2005
- German Research Association (DFG)
  - Grant: “Forschergruppe (Researcher Group): Ferromagnet/Semiconductor Nanostructures.”

- Participants: At Univ. Regensburg – Profs. Weiss, Bayreuther, Ebert, Zweck, Prettl, & Rossler.
- Level: \$1.5 million for total working group over three years
- Period of support: 2000 – 2002
- University-provided support:
  - Monetary Support: ~\$20,000 of research stipend used for spintronics efforts
  - Staff Support: six Ph.D. students supported, three technicians supported (~30% on spintronics)
  - Period of support: continuous

### **FACILITIES**

- Materials Growth: collaboration with Profs. Wegscheider and Bayreuther at Regensburg.
- Clean room: Weiss Group runs its own clean room for micro- and nanofabrication. There is some outside usage by immediate collaborators.
- Fabrication/Materials Deposition: E-beam and thermal deposition, RIE and CAIBE etching
- Lithography: Optical and Electron Beam Lithography (25kV).
- Characterization: Micro Hall Magnetometry (research topic and used for characterization), Scanning Hall Magnetometry, MFM, AFM, Lorentz Microscopy (in collaboration with Prof. Zweck).

### **RESEARCH TOPICS**

- Micro Hall Magnetometry
- Scanning Hall Magnetometry
- MFM of Ferromagnetic Nanostructures
- Spin tunneling across high quality semiconductor barriers
- Spin LED

### **MAJOR MILESTONES**

- Perhaps the most advanced scanning Hall magnetometry probes and research worldwide.
- High quality semiconducting barriers for MTJ investigations.

### **OVERALL IMPRESSIONS**

Impressive work in magnetic devices. Collaborations with others involved in magnetics research at Regensburg should make this an important emerging European center of semiconductor spintronics.

**APPENDIX C. SITE REPORTS — JAPAN**

Site: **University of Tokyo**  
**The Institute for Solid State Physics**  
**5-1-5 Kashiwanoha, Kashiwa**  
**Chiba 227-8581, Japan**  
**<http://www.u-tokyo.ac.jp>**

Date: April 2, 2001

WTEC Attendees: B. Buhrman (report co-author), K. Goto, U. Varshney, and S. von Molnár (report co-author)

Hosts: Yashuhiro Iye, Professor  
 iye@issp.u-tokyo.ac.jp  
 Shingo Katsumoto, Associate Professor  
 kats@issp.u-tokyo.ac.jp

**GROUP SIZE**

- 2 research assistants
- 2 technicians
- 6 Ph.D. graduate students
- 4 M.S. graduate students

Approximately one half of the group is directly involved in spintronics research.

**SUPPORT**

~¥10,000,000/yr ~ \$100,000 from the Ministry of Education

**IMPRESSIONS**

The Kashiwa campus is a new graduate school campus that has recently been built on the outskirts of Tokyo. It is staffed with faculty and graduate students who formerly were located on the Ropongi campus in downtown Tokyo. This campus has been a major beneficiary of the recent commitment of the Japanese government to enhance the nation's university research infrastructure. Here Professor Iye and Professor Katsumoto have assembled a very impressive suite of laboratories, including a high quality clean room whose equipment and layout matches or exceeds any that can be found in university condensed matter physics laboratories in the United States.

Major items of equipment include two new MBE systems with UHV vacuum interchange and a 75 KeV Elionix electron-beam lithography (EBL) tool capable of producing structures with 10 nm minimum feature size. (We saw several of these Elionix EBL tools during the WTEC panel's laboratory visits. This instrument appears to be the predominant EBL tool in Japan for university research. It currently is not available for export.) In addition to these central items of equipment, the laboratory is very well equipped with a variety of processing, diagnostic, and measurement instrumentation. These include two screened rooms containing dilution refrigerators with superconducting magnets for high magnetic field (> 10T) ultra low temperature investigations. Our estimate for new equipment costs alone exceeds \$10 million.

As the panel found it to generally be the case in various visits, the predominant focus of the research in the spintronics (or spin electronics) area is on the basic physics and materials science, with fairly limited

attention being given to any potential device applications at this time. Much of the particular focus is on resolving issues regarding spin-dependent transport in mesoscopic systems and on the transport properties of magnetic semiconductors, principally (Ga,Mn)As, but also (In,Mn)As ultra thin films.

Scientific results of particular significance to spintronics include the following:

- Magnetic transition temperatures in Mn doped III-V materials may not be dominated by RKKY interaction, but rather by double exchange via hopping electrons
- The metal to insulator transition in 7% Mn doped GaAs exhibits a new, as yet unexplained, universal scaling behavior
- Photo-induced magnetism.  $\text{In}_{1-x}\text{Mn}_x\text{As}/\text{GaSb}$  heterojunctions, with  $x=0.06$ , when addressed with band gap radiation for GaSb, produce persistent photoconductivity and an increase in the ferromagnetic  $T_C$  up to  $\sim 35\text{K}$ .

One device-oriented thrust that Professor Katsumoto is pursuing is the fabrication of semiconductor tunnel junctions using InMnAs electrodes with InAs tunnel barriers. An objective here is to take advantage of the low barrier height that InAs should provide to develop a low resistance magnetic tunnel junction system. Low resistance, very small cross-sectional area magnetic tunnel barriers are a major requirement for future magnetic hard disk read head applications and, some think, may be difficult to realize with conventional ferromagnetic metal/aluminum oxide tunnel junction technologies.

Professors Iye and Katsumoto have an impressive program in the effects of magnetic nanopatterning (spatially modulated magnetic fields) on the physics of 2D electron systems (2DES) and superconductors, which are only marginally associated with spintronics.

Site: **Tokyo Institute of Technology  
Physics Department, Junji Yoshino Group  
O-okayama, Meguro-ku  
Tokyo 152-8551, Japan**

Date: April 2, 2001

WTEC Attendees: R. Buhrman (report co-author), K. Goto, U. Varshney, S. von Molnár (report co-author)

Host: Junji Yoshino, Professor  
jyoshino@emmy.phys.titech.ac.jp

### GROUP SIZE

- 1 research assistant
- 7 graduate students
- 2 undergraduate students

### SUPPORT

- ~\$100,000 per year from the Ministry of Education

### IMPRESSIONS

Professor Yoshino's laboratories are spread over three rooms in disparate areas of an older interconnected building. We saw a used (IBM) MBE machine dedicated to (Ga,Mn)As growth, a UHV e-beam evaporator for producing transition metal silicides, and a magneto-optical system for the study of surface states and surface anisotropies. Furthermore an elegant homemade MBE for the production of GaMnAs to be used in concert with an *in situ* UHV BEEM system was under development.

Professor Yoshino is testing theoretical predictions by Professor Katayama-Yoshida (Osaka) for ferromagnetism in (Ga, transition metal)As, including vanadium. Thus far the only dopant that shows any promise is Cr. (Ga,Cr)As is superparamagnetic. Vanadium doped materials exhibit unusual hopping transport. Two students are associated with this work. Another project is an attempt to make Fe<sub>3</sub>Si, predicted to be a half-metallic ferromagnet, and, therefore, a source of spin-polarized carriers (2 students). A third area is the development of BEEM techniques for the measurement of spin polarization.

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Site: **Tokyo Institute of Technology**  
**Department of Chemistry and Materials Science, Shin-ya Koshihara Group**  
**O-okayama, Meguro-ku**  
**Tokyo 152-8551, Japan**

Date: April 2, 2001

Host: Shin-ya Koshihara, Professor  
skoshi@net.ksp.or.jp

### GROUP SIZE

- 1 research assistant
- 2 postdoctoral fellows
- 2 Ph.D. graduate students
- 2 M.S. graduate students
- 1 undergraduate student

### SUPPORT

- About \$60,000 per year for five years from national and local government programs

### IMPRESSIONS

Professor Koshihara is new at TIT and is in the process of building his laboratory that will specialize in the study of “photo-induced cooperative phenomena.” He is still borrowing much of the equipment but does have a rapid data collection commercial SQUID magnetometer and employs various laser excitation and detection techniques including pump probe

Professor Koshihara is working, among other things, on the following:

- Photo-induced magnetization through persistent photoconductivity in (In,Mn)As (with Professor Munekata)
- Photo control of magnetism in (In,Mn)As/GaSb heterostructures by hole injection (with Professors Munekata, Iye, and Katsumoto)
- Photoenhancement of magnetization of Fe clusters on GaAs (with Professor Munekata)
- A novel light switch by optical transformation of ferroelectric organic molecular crystals into antiferromagnetic ionic crystals

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Site: **Waseda University**  
**Department of Applied Physics**  
**Okubo 3-4-1, Shinjuku-ku**  
**Tokyo 169-8555, Japan**

Date: April 2, 2001

WTEC Attendees: D. Awschalom (report co-author), J. Daughton (report co-author), H. Morishita, and S. Wolf

Host: Atsushi Tackeuchi, Associate Professor  
atacke@mn.waseda.ac.jp

### GROUP SIZE

- 2 Ph.D. graduate students
- 5 undergraduate students

### SUPPORT

- ¥2 million per year from the university

### IMPRESSIONS

This group is continuing work started at Fujitsu on InGaAs/IP, InGaN materials for quantum devices. They are studying interdot tunneling in high dot density arrays. Transfer times have been observed of 1.3 ns and 1.2 ns for InAlAs and InAs, respectively. Devices were fabricated at Fujitsu. Two experimental observations were that spin was conserved during relaxation from bulk material to QD levels and that spin lifetime was observed to increase with decreasing dimensionality. Electronic spin lifetimes in semiconductor nanostructures are relevant to spintronics for applications ranging from information storage to quantum computation. This group is now probing QD geometries where spin up/spin down states are analogous to binary “0” and “1”. Present studies are aimed at measuring longitudinal spin relaxation time in these systems by the decay of polarized light. Work is continuing at NTT on relaxation-based mirrors for optical switching and modulation (~1 ps), which is notably faster than present charge-based modulators. Patents were applied for and received for such devices.

There are modest experimental facilities, including home built tunable Ti:Sapphire laser system and a picosecond streak camera for time-resolved polarized light.

There are approximately 50,000 students in Waseda University, and it is a prestigious university (comparable to the University of Tokyo). The school of science & engineering has approximately 10,000 students, 25% of whom are graduate students. Research money is not used to pay students but for equipment and maintenance. Waseda as a private university is given little government funds. For example, Waseda receives only 5% of the research funding of institutions such as the University of Tokyo. Professor Tackeuchi believes that the philosophy of funding should change in Japan so that private institutions have a better chance for funding. He has difficulties getting graduate students. Industry ties are limited.

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Site: **Department of Applied Physics  
Tokyo University of Agriculture and Technology  
Faculty of Engineering  
2-24-6 Nakmachi  
Koganeishi, Japan**

Date: April 2, 2001

WTEC Attendees: D. Awschalom (report co-author), J. Daughton (report co-author), H. Morishita, and S. Wolf

Host: Katsuaki Sato, Professor  
satokats@cc.tuat.ac.jp

### GROUP SIZE

- 8 graduate students
- 12 undergraduate students
- 1 assistant professor, one visiting professor
- Professor Sato

### SUPPORT

Grants-in-Aid for Scientific Research from Ministry of Education, Science, Culture and Sports [Monbusho: now changed to Monbu-kagakusho]:

- Scientific Research (A) (general) FY 2001-2003 (total ¥42 million): Physical characterization of chalcopyrite-type magnetic semiconductors
- Scientific Research (B) (general) FY 1998-2000 (total ¥12.8 million): MBE growth of single crystalline films and superlattices of MnBi and its characterization using nonlinear magneto-optical effect
- Priority Area (nanomagnetism) FY 1997-1999 (total ¥41.1 million): Development in measuring technologies for magnetism in mesoscopic area
- Scientific Research (A) (instrumentation) FY 1995-1997 (total ¥16.4 million): Observation of nanoscale spin structures using a near-field magneto-optical microscope
- Scientific Research (B) (general) FY 1996-1997 (total ¥7.7 million): Characterization of magnetic multilayers using nonlinear magneto-optics
- FY 1997 High Priority Assistance for Research Infrastructures from Ministry of Education: (total ¥130 million): Creation of intelligent quantum sensors using mesoscopic structures

### IMPRESSIONS

Fundamental materials research includes optical, magnetic, and electron spin resonance of rare earth and transition metal impurities in chalcopyrite semiconductors. They also have worked in diluted magnetic semiconductors. These are parallel research programs in nanostructured magnetic materials and superconductor/FM hybrids for spin injection studies, including BSCCO films. Materials include chalcopyrites ( $\text{CuXS}_2$  and  $\text{CuXSe}_2$ ,  $\text{AgXS}_2$  and  $\text{AgXSe}_2$ ,  $\text{CuFeS}_2$ ,  $\text{CdYP}_2$ ,  $\text{ZnYP}_2$ ; X= Al, Ga, Y= Ge, Si), thiogallates ( $\text{CaGa}_2\text{S}_4$ ,  $\text{SrGa}_2\text{S}_4$ ), chromium spinels ( $\text{CdCr}_2\text{Se}_4$ ).

Extensive work on magneto-optical Kerr spectra has been carried out to elucidate electronic structures in the number of magnetic materials, manganese pnictides (MnSb, MnAs, MnBi), amorphous rare earth-transition metal films (GdCo, GdFe, TbFeCo), perpendicular recording materials (CoCrPt), Heusler compound (PtMnSb) and magnetic superlattices (Fe/Au, Pd/Co, Pt/Co, FePt/Pt).

Significant work includes recently reported room-temperature FM in the magnetic semiconductor CdMnGeP<sub>2</sub>. They have used Mn-deposition in MBE chamber with high temperature annealing. Optical spectra. MFM and T-dependent magnetization studies show evidence of this behavior. (This study has been extended recently to ZnGeP<sub>2</sub>-Mn, in which FM is confirmed to exist above 350K by SQUID magnetometer. High resolution XRD revealed a presence of superstructure with fairly long period along [112] direction.) An additional accomplishment includes 14%-Mn incorporation in GaMnAs by MBE.

Equipment includes dedicated MBE and sputtering tools, FIB, SEM for lithography, optical lithography, RIE and Ar-ion etching, class-1000 clean room, crystal growth chambers, femtosecond-resolved Ti:Sapphire laser system, FTIR, ESR spectrometer, scanning probe microscope, nonlinear optical spectroscopy, PL and MOKE facility, MFM, VSM, and NSOM systems.

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Site: **Kanagawa Academy of Science and Technology (KAST)**  
**KSP East 309, 3-2-1 Sakado, Takatsu**  
**Kawasaki, Kanagawa, 213-0012, Japan**

Date: April 3, 2001

WTEC Attendees: D. Awschalom (report author), K. Goto, U. Varshney, S. von Molnár

Host: Hiroo Munekata, Project Leader and Professor  
hiro@isl.titech.ac.jp

### GROUP SIZE

- At home institution (Tokyo Institute of Technology)
  - 2 Ph.D.s
  - 5 graduate students
  - 1 technician
- At KAST
  - 2 staff members (past Ph.D.)
  - 1 secretary
  - very attractive environment for students

### SUPPORT

- \$12 million basic research funds from Kanagawa prefecture
- \$40.3 million basic assets from prefecture
- Munekata specific support includes \$3 million/three years from KAST.
- Munekata specific support for Tokyo Institute of Technology includes \$0.3 million/three years from JST, \$0.6 million/three years from NEDO, and \$0.3/three years from the Ohno Spins project.

### IMPRESSIONS

Kanagawa Science Park (KSP) was established in 1989 and was the first science center to make connections with the private sector. It is essentially a real estate company established by the Kanagawa prefecture government that has two parts: KAST and general R&D. The general R&D section contains large programs of common business interests such as precision machining, software development, and a set of focused independent business units. KAST consists of flexible, variable-term research projects, typically five at any given time. Each project runs 3-5 years (~5 students/project), with a total of 100-150 people.

KAST is a foundation, also established in 1989, to promote research, technology transfer, the training of skilled researchers, and general academic activities. In addition it supports the R&D of small to medium-sized companies in the areas of advanced science and technology. Its ultimate intent is to promote research, education, and, most importantly, scientific exchange. KAST offers office and laboratory space for academic researchers and business ventures of various levels. In addition, there are established materials and characterization laboratories for shared use, as well as flexible laboratories for visiting researchers. All activities are cooperative efforts among businesses, academia, and public organizations. Thus KAST provides excellent university networking by cycling academic and business tenants through the complex.

KAST activities include the following:

- Business start-up support service: provides office space, R&D space, infrastructure support

- Education and training: helps develop business plans, strategy, and implementation schemes. Seminars and meetings held to collect information
- Financial services: Investment funds to provide capital investment for companies expecting to go public; management services to guide them on the path to public offerings

For example, there are approximately 35 R&D corporations and 65 start-up companies among the tenants.

Professor Munekata is a project leader for a three year project in the “Pursuit of Novel Electronic Materials: Photomagnetic Semiconductors” (4/1999–3/2002). His seminal discovery of homogeneous diluted magnetic III-V semiconductors provided the impetus for much of that activity worldwide. Much of his present effort focuses on MBE fabrication and characterization of InMnAs, InMnSb, GaFeAs, and GaMnAs in order to optically induce ferromagnetism on demand. The work at KAST is carried out in parallel to his existing research program at Tokyo Institute of Technology, where he is professor of Imaging Science and Engineering.

Local facilities at KAST are extremely impressive and exist within industrial class research environments. Professor Munekata’s specific facilities include an MBE machine, SQUID magnetometer, low-temperature magnetotransport system, and optical spectroscopy laboratory. Collaborative facilities add a second SQUID magnetometer and femtosecond-resolved spectroscopies when and if necessary.

Spintronic applications of interest to Professor Munekata include magneto-optical storage, photonic-based MEMS actuators, magnetic toners for copying, and photo-induced MRAM. His efforts have already led to significant research accomplishments including optically-induced FM in InMnAs, InMnSb, and GaFeAs. In particular, in the latter material, the  $T_c$  of this effect appears to have been raised above 100K. The potential exists for new classes of magneto-optical devices with short- and long-term applications when the materials become more robust and the transition temperatures approach 300K. KAST is an ideal environment within which to exploit new discoveries in science and technology, from inception to market, especially since there are well established links to industry within this research project.

Professor Munekata has readily adopted U.S. research styles in his program. These include direct funding of Japanese graduate students, employing postdoctoral students from abroad, and developing industrial contacts to “transition” research accomplishments.



Site: **Tokyo Institute of Technology**  
**Koinuma Group**  
**4259 Nagatsutacho**  
**Midori-ku, Yokohama 226-8503, Japan**  
**<http://oxide.rlem.titech.ac.jp/kawasaki/index.html>**

Date: April 3, 2001

WTEC Attendees: D. Awschalom (report co-author), K. Goto, U. Varshney, and S. von Molnár (report co-author)

Hosts: Hideomi Koinuma, Project Leader and Professor (not present)  
Tetsuya Hasegawa, Associate Professor, Materials and Structures Laboratory, Tokyo Institute of Technology; [haseg1@rlem.titech.ac.jp](mailto:haseg1@rlem.titech.ac.jp)  
Toyohiro Chikyow, National Research Institute for Metals; [tchikyo@nrim.go.jp](mailto:tchikyo@nrim.go.jp)  
Masashi Kawasaki, Associate Professor, Department of Innovative and Engineering Materials, Tokyo Institute of Technology; [Kawasaki@oxide.rlem.titech.ac.jp](mailto:Kawasaki@oxide.rlem.titech.ac.jp) (recently moved to Tohoku University, Sendai)

### GROUP SIZE

- 6 faculty members working cooperatively on combinatorial materials exploration and technology
- Associate professors: Hasegawa, Yoshimoto, Kawasaki, Funakubo
- Professors Wakihara and Koinuma

### SUPPORT

- ¥3 billion over four years (2000-2003)
- This is one of six projects in the TIT Frontier Collaborative Research Center, which derives its funds from several agencies, including the National Institute of Research in Inorganic Materials, Science, and Technology Agency (STA); CREST; the Millennium Project (National); and the TIT Cooperative Research Program with Industry.

### IMPRESSIONS

In contrast to conventional one by one synthesis techniques, this project, named COMET (Combinatorial Materials Exploration and Technology), is aimed at designing and implementing new methods for highly efficient and cost effective fabrication of a variety of solid state materials. The basic technique involves fabricating a material or device “library” on a single substrate composed of thin film pixels defined by physical masks. The project involves close interactions with scientists and engineers in the fields of materials science, electrical engineering, chemistry, and physics. It is the focus of a strong collaboration between universities, national laboratories, and industry.

The infrastructure is extremely impressive, with two synthesis chambers designed and constructed in house. In addition, there are dedicated SEMs, a state-of-the-art FIB, a low-temperature STM, a scanning SQUID magnetometer, and a variety of materials characterization machines. Professor Hasegawa is developing innovative scanning tools, including low AC resistivity and thermoelectric power.

Spintronics-related research includes the search for new ferromagnetic semiconductors (compatible with industrial interests and applications) using laser-based MBE. In addition to synthesizing a variety of TiXO materials (X=Sc, V, Cr, Mn, Fr, Co, Ni, Cu, Zn), an effort has been made to explore substrate- based control of growth (i.e., using the substrate to control the crystal growth structure to raise the solubility limit of magnetic dopants).

Significant accomplishments include the reported discovery of a transparent, n-type, room temperature ferromagnetic semiconductor  $\text{TiO}_2$  doped with Co (<5%). These materials have been fabricated on  $\text{Al}_2\text{O}_3$  (rutile phase structures) and  $\text{SrTiO}_3$  (anatase phase structures), with the former being more stable. The combination of magnetization measurements, SQUID imaging, and low temperature STM studies have led to this claim. The  $\text{TiO}_2$  work would be more convincing, however, if they obtain magneto-optical spectra for these materials, showing an enhancement of the magnetization at the critical point. Also, EXAFS would help in confirming the dilution of magnetic moments versus possible clustering effects. Moreover, the construction of assembly line style (high throughput) processing of TEM samples is extremely impressive: the use of FIB machines for cutting, thinning, and preparing samples for TEM in a single system. Finally, parallel research projects on oxide/semiconductor interface chemistry are likely to have significant impacts on spin-related devices and technology. These are extremely important developments for spintronics research and are likely to evolve towards additional new discoveries.

Combinatorial synthesis of technologically important materials is an important development in materials research. Although modern combinatorial techniques have had their origin in the United States and were applied initially to pharmaceutical problems, this group is the world leader in this technique as applied to solid state materials and devices.

The Frontier Collaborative Center has an impressive array of technical accomplishments in terms of making transitions to industry. Examples include new surface emitting lasers for communication, ferrite- based recording media, frequency stabilized quartz oscillators, and synthetic vitamins.

Site: **Fujitsu Laboratories Ltd.  
Storage Systems Laboratories  
10-1 Morinosato-Wakamiya  
Atsugi 243-0197, Japan**

Date: April 3, 2001

WTEC Attendees: R. Buhrman (report co-author), J. Daughton (report co-author), H. Morishita, M. Roukes, and S. Wolf

Host: Dr. Kazuo Kobayashi  
kkoba@flab.fujitsu.co.jp

### **GROUP SIZE**

The size of the group working on tunnel junctions for read heads was not revealed, but by a guess is on the order of three engineers and three technicians. The research facility the WTEC panel visited had a total of 1,500 people supporting a wide range of needs for a large company. Fujitsu is one of the largest suppliers of hard drives, and thus GMR and MTJ heads are important research topics.

### **IMPRESSIONS**

Fujitsu provided a talk on MTJ read head materials development. The results were not significantly different from the results in the rest of the world. The research that was discussed has explored alternative oxidation and deposition processes for the formation of low resistance tunnel junctions with high tunneling magnetoresistance (TMR). Oxidation processes that have been examined include plasma oxidation, thermal oxidation, and oxidation with oxygen radicals. The hosts reported that a UHV deposition process ( $3 \times 10^{-7}$  Pa) and thermal oxidation can result in a TMR of 20% for junctions having a specific resistance of  $7.6 \text{ Ohm-}\mu\text{m}^2$ . This was achieved with  $0.33 \mu\text{m}^2$  junctions. Similar to results reported by other groups in the United States and Japan, the Fujitsu researchers report that for the low resistance barriers, the breakdown voltage is considerably lower, 0.3 V, than is the case for high resistance junctions ( $\sim 0.9$  V). The low resistance barriers also were found to have low barrier heights, as determined by Simmons fit to the I-V characteristics. Finally it was stated that oxidation with oxygen radicals gave results similar to those obtained with ambient (room) temperature thermal oxidation.

Fujitsu's equipment must be state-of-the-art for their MTJ work. We saw the Visitors Center, which was impressive. With respect to long range research, it was mentioned that Fujitsu was looking at research in quantum devices in semiconductors, particularly single electron switching in 2D electron gases and some theoretical explorations of quantum computing issues.

The researchers the panel saw expressed interest in MRAM but said the company is going with FeRAM.

Site: **NTT Basic Research Laboratory**  
**3-1 Morinosato Wakamiya**  
**Atsugi**  
**Kanagawa 243-0198, Japan**

Date: April 3, 2001

WTEC Attendees: R. Buhrman (report co-author), J. Daughton (report co-author), H. Morishita, M. Roukes, and S. Wolf

Hosts: Dr. Junsaku Nitta  
nitta@will.brl.ntt.co.jp  
Dr. Hiroyuki Tamura  
(presented on the theory of ferromagnetism in quantum dot arrays)  
[Shingo Katsumoto, Associate Professor, University of Tokyo  
kats@issp.u-tokyo.ac.jp, also works with this group, but was not present during the WTEC panel's visit.]

### **GROUP SIZE**

The presenters themselves seemed to be the only active researchers at present. The group has suffered significantly from departures by senior staff to universities. Compounding the problem is the lack of new hires. It does not seem that the laboratory is planning to replace staff that has departed. This makes the remaining effort rather sparse.

Subsequent to this panel's visit, a spintronics research group was organized at NTT in August 2001. The group includes three researchers and one post-doctoral researcher.

### **SUPPORT**

For the staff remaining, the support seems to be continuing at a substantial level. The equipment base is, unequivocally, world class.

### **IMPRESSIONS**

Excellent studies of spin injection into compound semiconductor heterojunctions. Very interesting work ongoing to investigate use of Rashba phenomena and Berry's phase to create spin-interferometric devices. Theoretical work ongoing on coupled ferromagnetic nanostructures; interesting predictions of ferromagnetism in Kagome and other lattice structures.

Site: **NEC Fundamental Research Laboratories (FRL)  
NEC Corporation  
34, Miyukigaoka, Tsukuba  
Ibaraki 305-8501, Japan**

Date: April 4, 2001

WTEC Attendees: D. Awschalom (report author), K. Goto, U. Varshney, S. von Molnár, S. Wolf

Hosts: Jun'ichi Sone, General Manager  
j-sone@bk.jp.nec.com  
Kazuo Nakamura, Senior Manager, Quantum Information Technology Group;  
k-nakamura@ed.jp.nec.com  
Kenji Hirose, Assistant Manager, Quantum Information Technology Group;  
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s-ishizaka@ct.jp.nec.com  
Dr. Masako Yudasaka, Principal Researcher, Nanotechnology Group;  
yudasaka@frl.cl.nec.co.jp  
Yasunobu Nakamura, Principal Researcher, Quantum Information Technology Group;  
yasunobu@ce.jp.nec.com

### GROUP SIZE

- 3 general research areas (quantum information technology and nanotechnology involve aspects of spintronics)
  - Quantum information technology
    - Photonics and cryptography
    - Quantum control of entangled states
  - Nanotechnology
  - BioInformation Technology
- Close interaction with NEC Princeton Laboratory
  - Lijun Wang, Gabe Aepli (experiment), and Ned Wingreen (theory)

### SUPPORT

- Approximately 1/4 of exploratory research is funded by the Japanese government.
- Specific funding confidential

### IMPRESSIONS

Long term research is maintained in the Fundamental Research Laboratories (FRL), although the selection and focusing of research subjects has been done intensively. Research subjects growing near market are transferred to more application oriented laboratories in NEC.

Dr. J. Sone stated that MRAM work has been moved from FRL to Silicon System Research Laboratories in NEC.

Significant research accomplishments related to spintronics include the following:

- Relevant scientific research by Dr. Y. Nakamura on the fabrication and measurement of Cooper-pair boxes and gated-control of single pairs. Elegant microwave spectroscopy confirmed coherent control of

charge states, yet pointed to limited coherence lifetimes for quantum computer applications. Dr. Y. Nakamura will be spending 2002 in Europe working with H. Mooij at Delft.

- Interesting theoretical work on orbital and spin levels in quantum dots (and quantum dot molecules) as a function of the dot shape. These efforts are aimed at developing the Loss-DiVincenzo proposals of fabricating qubits based on coupled quantum dots and controlling the spin degree of freedom by gating and carrier tunneling between spin levels. Most of the work used density functional theory to calculate the density of states in these systems (Hirose and Wingreen).
- Theoretical work on the propagation of solitons in ferromagnetic dot arrays suggested that dipolar interactions between ferromagnetic particles could be controlled to enable high-speed changes in local magnetization. It was predicted that clock speeds exceeding 100 GHz may be achievable in transmission line applications (Ishizaka).
- New collaborative work on spin phenomena in carbon nanotubes suggested that magnetic wires could be fabricated by placing magnetic materials inside nanotubes. Preliminary work on Gd in C<sub>82</sub> showed success in controlling chemistry at the nanometer scale, as well as Au in C<sub>20</sub>. This particular project named the “Nanotubelite Project,” headed by Dr. Iijima supported by JST (Japan Science and Technology Corporation) involves six Ph.D. scientists, six technicians, and no students. Applications being considered include qubit devices, spin-polarized wires, and flat panel displays. This is a very new project and appears to offer a great deal of promise in both science and technology (Yudasaka).
- More information can be seen at <http://nlpgw.jst.go.jp>.

Dr. K. Nakamura made it clear that he was extremely interested in spin-based electronics and quantum computation and that this was indeed one of the research areas targeted for growth in the future. NEC researchers believe that applications range from semiconductor-based optoelectronics for secure quantum communication to spin-based modulation for low-power systems.

Site: **Joint Research Center for Atom Technology (JRCAT)**  
**c/o National Institute for Advanced Interdisciplinary Research**  
**1-1-4 Higashi, Tsukuba**  
**Ibaraki 305-0046, Japan**  
**<http://www.jrcat.or.jp/>**

Date: April 4, 2001

WTEC Attendees: D. Awschalom (report author), K. Goto, U. Varshney, S. von Molnár, and S. Wolf

Hosts: Kazunobu Tanaka, Project Leader, JRCAT  
 tanaka@jrcat.or.jp  
 Yoshinori Tokura, Group Leader, Tokura Group  
 Kazuyuki Koike, Group Leader, Koike Group  
 Hiro Aginaka, Koike Group  
 Masashi Kawasaki, Tokura Group

### GROUP SIZE

- JRCAT supports 100 research scientists within four fields, includes 30-40 postdocs, and is comprised of industrial, governmental, and academic sectors. It is organized into four fields, one of which is spin electronics.
- The spin electronics effort consists of the following:
  - Tokura group (Correlated Electron Research Center): 13 researchers and 2 students study CMR manganites and other perovskites, related oxides, and thin films
  - Koike Group (spin measurement technology): 8 research scientists, includes Akinaga effort in magnetic nanostructures.
- Related efforts include the following:
  - Ozeki Group (growth mechanisms of III-V nanostructures)
  - Kanayama Group (formation of nanostructures via cluster manipulation)
  - Yamasaki Group (surface/interface structures)

### SUPPORT

- JRCAT, as an entity, is a 10-year project started in 1992 with a total budget of \$200 million sponsored by METI, the Ministry of Economy, Trade and Industry (formerly known as “MITI”). AIST, the National Institute of Advanced Industrial Science and Technology, and ATP, the Angstrom Technology Partnership, manage the research initiative under equal partnership.
- New support as of 4/2001: Nanotechnology Research Institute, AIST (see [www.nedo.go.jp](http://www.nedo.go.jp))
- Focus of new support:
  - Nanofunctional (intelligent) structures
  - Storage (magnetic, optical)
  - Sensing, computing (magnetic nanostructures)
  - Self-repairing devices, low energy consumption
- Professor Tokura leads the spin electronics effort. Support is derived through two major projects:
  - “Spin Superstructure” — Exploratory Research of Advanced Technology (ERATO)/Japan Science and Technology Corporation (JST) – \$15 million for five years (2001-2006). This supports the 13 research scientists and two students.
  - “Correlated Electron Research Center” — \$4 million/year for seven years (2001-2008)

- New project, this will support 35 research scientists (including 20 postdocs) organized into seven teams, as follows:
  - Phase control (Tokura-Tachibana)
  - Physics (Takagi)
  - Photonics (Okamoto)
  - Superstructure (atomic interfaces) (Kawasaki)
  - Theory (Nagaosa)
  - Devices (Akoh)
  - Spin measurement (Koike)

## IMPRESSIONS

JRCAT is a research institute funded by the national government and managed by AIST and ATP. In addition, 23 companies (as of April 2001) are involved in the institute, along with domestic and international universities.

Professor Tokura's research group works on several projects based on manipulating the electron spin degree of freedom. These include the following:

- Anomalous magnetotransport properties in CMR manganese oxides, such as spin-polarized tunneling
- New magnetoresistive materials, such as the ordered perovskites for spin electronics
- Superlattices and junctions using perovskite materials by laser MBE
- Current-induced ferromagnetic metal transitions in perovskite-type manganese oxides
- Light or current control of electronic phases in organic molecular systems, such as polythiophene conjugated polymers
- Critical state phase control of valence conversion molecular systems, where charge transfer is used to make dramatic changes in dielectric and magnetic properties

The Koike research group is aimed at driving measurement technologies for spin detection and includes the following:

- Spin-polarized SEM
- Spin-polarized STM
- Spin devices based on semiconductor/insulator/ferromagnetic structures

This laboratory has outstanding facilities and research programs of direct relevance to semiconductor spintronics. For example, the work in the Correlated Electron Research Center is aimed at controlling the electronic phase of correlated electron systems through photonic, magnetic, or electrical means.

Significant research accomplishments include the following:

- Development of highly spin-polarized materials: zinc-blende CrAs (100% polarization), with  $3\mu_B/Cr$  at 300K, equivalent to theoretical expectations. Grows epitaxially on GaAs.  $T_c > 400K$ , grown at 200C (Akinaga).
- Application interests include the development of polarized spin light converters using MIS structures; magnetic control of devices using electric fields and light at room temperature.
- Successful growth of MnSb nanoclusters on GaAs by MBE, yielding  $MR > 10000\%$  at  $V=10V$  and 1.5T, the threshold voltage  $V_{th} \sim 5 V$  at 1.5T. Also showed  $MR \sim 450\%$  at 30G ( $V=40V$ ). Short-term applications include magneto-optical isolators and sensors (Akinaga).
- Development of a spin-polarized SEM (Koike et al.) with 20 nm resolution and a future target of 5 nm. The success was based on the construction of a Mott spin detector ( $10^{-4}$  efficiency) exploiting electronic spin orbit interactions. This system uniquely detected all three axes of polarization.



- Experimental verification of quantum spin Berry phase, where the effect was exaggerated using canted frustrated-lattice single crystal magnets (Tokura).
- Future plans include ultrafast control of spin states and large magneto-optical effects in magnetic materials.

Facilities include spin-polarized STM, SEM, three distinct clean rooms (including a recently completed room), e-beam and optical lithography, and ion-etching. They also feature 15 MBE machines covering III-V materials including ferromagnetic semiconductors, metals, and hybrid structures. Characterization capabilities are state-of-the-art and broadly based.

This program is heavily integrated with external universities and industry. Academic collaborators include the University of Tokyo, Osaka University, TIT, and IMEC in Belgium.

Overall this is an extremely impressive, highly coordinated research effort that is likely to be very productive in the near future. This group is highly competitive in science, materials development, and technological applications. It is a remarkable model for a successful demonstration of a valuable national laboratory.

Site: **Japan Advanced Institute of Science and Technology  
1-1, Asahidai, Tatsunokuchi  
Ishikawa 923-1292, Japan**

Date: April 4, 2001

WTEC Attendees: R. Buhrman (report co-author), J. Daughton (report co-author), H. Morishita, and M. Roukes

Host: Shoji Yamada, Professor  
shooji@jaist.ac.jp

### **GROUP SIZE**

- 7 M.S. candidates
- 4 Ph.D. candidates
- 1 assistant professor

### **IMPRESSIONS**

The primary emphasis in this group is on InGaAs heterostructures. The primary goal is higher temperature ferromagnetic semiconductors.

Prof. Yamada and his colleagues have been able to convincingly demonstrate gate control of the Rashba field, through modulation of Shubnikov-deHaas oscillations. This is solid work, with good controls in place to separate out the gate-controlled density dependence.

Micron scale spin injection devices have been investigated. They observe different qualitative differences in the temperature dependence of local Hall signals and “spin” signals – this lends credence that spin injection phenomena may be occurring.

There is also some limited magnetic work in nanomagnetic particles (colloidal deposits).

The laboratory is very well-equipped, with extensive deposition, lithography, processing and measurement equipment.

Overall, there were 700 graduate students at this somewhat remote site. It is very believable that they will do useful work in SPINS.

Site: **University of Tokyo**  
**Department of Physics**  
**Graduate School of Science**  
**7-3-1 Hongo, Bunkyo-ku**  
**Tokyo 113-0033, Japan**

Date April 5, 2001

WTEC Attendees: D. Awschalom (report author), K. Goto, U. Varshney, S. von Molnár, and S. Wolf

Host: Seigo Tarucha, Professor  
tarucha@phys.s.u-tokyo.ac.jp

### GROUP SIZE

- 15-20 people in total
- 1 assistant professor, 2 postdocs, 8 graduate students (2 Ph.D., 6 M.S.)
- NTT collaboration involves 10 NTT people
  - NTT: 1 manager, 1 contracts person, 8 scientists
- Delft collaboration includes 1 postdoc, 1 graduate student

### SUPPORT

- Professor Tarucha's funding comes from two sources:
  - JST-CREST: This supports the University of Tokyo operation.
  - JST-ERATO: This supports the NTT and Delft collaborations. The monies are split evenly at ~50% for instrumentation and ~50% for salaries and rent.

### IMPRESSIONS

The University of Tokyo has 100 physics undergraduates, typically 90 of whom go to graduate school. Professor Tarucha expressed concern that average student quality is dropping. Of these 90, 2/3 go to a Ph.D. program. Typically 70 theses/year are produced in physics. Of these graduating students:

- 10-20 go to industry
- 10 go to academia
- Of the larger remainder, half obtain postdoctoral fellowships and the other half stay in unpaid positions

Spintronics-related research involves low temperature transport measurements of spin-dependent electron tunneling between gated quantum dots (QD). This is a collaborative effort with NTT and is producing outstanding new physics in an effort to create quantum bits via the Loss-DiVincenzo QD scheme. Samples are fabricated and processed in a joint project with NTT, where students work in the NTT clean room.

Recent measurements are aimed at exploring the longitudinal electron spin lifetime in these structures, a lifetime that presently appears to fall within the millisecond time scales; transverse spin lifetimes (the lifetimes relevant for quantum computation) have yet to be ascertained.

Very recent results have revealed that the transport measurements are capable of resolving nuclear spin dynamics, driven by individual electrons relaxing their momentum in part by hyperpolarizing the nuclei (the Overhauser effect). This is a unique method for electrically polarizing nuclei and may ultimately have an important impact on quantum computation and spin-based electronics at the atomic scale.

The relevant infrastructure was very impressive, and included low-temperature magnetotransport equipment (25 mK, 15T system) and a cryogenic STM, housed in a state-of-the-art research building with spacious new laboratories.

This research is highly connected with industry, European, and U.S. research efforts.

Site: **University of Tokyo**  
**Department of Electrical Engineering**  
**7-3-1, Hongo, Bunkyo-ku**  
**Tokyo 113, Japan**

Date: April 5, 2001

WTEC Attendees: D. Awschalom (report co-author), K. Goto, U. Varshney, S. von Molnár (report co-author), and S. Wolf

Host: Masaaki Tanaka, Associate Professor, Dept. of Electrical Engineering  
 masaaki@ee.t.u-tokyo.ac.jp

### GROUP SIZE

- 2 postdocs
- 5 graduate students

### SUPPORT (FISCAL YEAR 2000)

- ¥11 million from Monbusho
- ¥7 million from JST (CREST Project)
- ¥10 million from JSPS (Research for the Future Program)
- ¥1.5 million from University of Tokyo

### IMPRESSIONS

A major theme of Professor Tanaka's research is the fabrication and characterization of epitaxial magnetic semiconductor hybrid materials grown by MBE for magneto-optics and magnetoelectronics. These include the following:

- Ferromagnet/Semiconductor Heterostructures  
 MnGa/GaAs, MnAs/Si, MnAs/GaAs
- III-V Based Magnetic Alloy Semiconductors  
 (InMn)As, (GaMn)As, (GaMn)As/AlAs
- Ferromagnet/Semiconductor Granular System  
 MnAs nano-clusters in III-V (GaAs)

Infrastructure for research includes a dedicated MBE machine, an optical spectroscopy (PL, absorption, MCD) laboratory, and significant clean room facilities. The clean room is shared with three other faculty members; a new building is being planned with a larger clean room and advanced lithography facilities.

Spintronics-related research includes the following:

- Detailed structural studies (TEM) of GaMnAs/AlAs and MnAs/GaAs superlattices to fabricate high quality electronic interfaces between ferromagnetic and semiconductor materials
- Development of GaAs:MnAs granular structures that exhibit clear ferromagnetism. These hybrid systems are embedded in distributed Bragg reflectors (DBRs) grown on (001) GaAs substrates aimed at III competing with II-VI optical isolators. The initial results are very promising, revealing ~1 degree rotation near 1  $\mu\text{m}$ , but with transmission limited by granular scattering. This group has thoughtful means to circumvent the problem using controlled growth sequences, resulting in cluster formation

within single layers at prescribed positions in the superlattice. The successful accomplishment of this project would likely have a very significant impact on existing optoelectronics technology, as presently the optical isolator cost is equal to or exceeds the cost of the semiconductor laser. Moreover, this would be compatible with present III-V optoelectronics.

- Fabrication of bilayer and trilayer MnAs/GaAs structures at room temperature and magnetoresistance studies show clean switching in  $\sim 1$  kG in-plane fields (parallel to the current); similar studies in GaMnAs/AlAs trilayers at low temperature with single barrier  $200 \mu\text{m}$  junctions reveal a TMR  $\sim 75\%$ . Detailed investigation of effects due to barrier thickness and anisotropic TMR have also been completed.
- Professor Tanaka and co-workers have successfully grown ferromagnetic MnAs on Si substrates and modeled the experimental MCD results. This is a potentially interesting scheme for integrated III-V ferromagnetism with Si electronic devices.

Professor Tanaka has made impressive steps towards achieving practical devices exhibiting functionality by control of magnetism. In addition to magneto-optic device geometries, another goal of this group is to use ferromagnetic III-V semiconductors to build Datta-Das spin-FET devices.

## REFERENCE

- Tanaka, M., H. Shimizu, M. Miyamura. 2001. Enhancement of magneto-optical effect in a GaAs:MnAs hybrid nanostructure sandwiched by GaAs/AlAs distributed Bragg reflectors: Epitaxial semiconductor-based magneto-phonic crystal. *Journal of Crystal Growth*. 227, 839.

Site: **The Institute of Scientific and Industrial Research  
Osaka University  
8-1 Mihogaoka, Ibaraki  
Osaka, 567-0047, Japan**

Date: April 5, 2001

WTEC Attendees: R. Buhrman (report co-author), J. Daughton (report co-author), H. Morishita, and M. Roukes

Hosts: Hiroshi Katayama-Yoshida, Professor  
hiroshi@sanken.osaka-u.ac.jp  
Hitoshi Tabata, Associate Professor  
tabata@sanken.osaka-u.ac.jp

### GROUP SIZE

- 5 postdocs
- 3 graduate students
- Professors Katayama-Yoshida and Tabata

### Support

- Approximately \$83 million from the Ministry of Education

### IMPRESSIONS

Particularly since the initial discovery of the magnetic semiconductor Ga(Mn)As, there has been a burgeoning effort in Japan to understand and enhance the properties of magnetic semiconductors, to raise the maximum Curie temperature of these systems, and to discover new magnetic semiconductor systems. A major component of this latter effort is an initiative in the theoretical design of new magnetic semiconductor systems. At Osaka University, Prof. Katayama-Yoshida and his associates are pursuing such an effort that is concerned with materials design by *ab-initio* electronic structure calculations. The overriding objective is the discovery of candidate systems for experimental examination that have the strong potential of exhibiting a high Curie temperature. The approach that is being used by Prof. Katayama-Yoshida's group is based on total energy calculations using the local spin density approximation. This group has been applying this approach to the transition metal doped III-V and II-VI systems as well as to transition metal doped titanates. As result of these calculations, Prof. Katayama-Yoshida is enthusiastic about the prospects of the magnetically doped II-VIs, particularly ZnO. There is a five-year funding program for this effort for three materials design groups. Very impressive band calculations have been made for a wide variety of potential ferromagnetic semiconductors including ZnO, ZnSe, ZnTe, ZnS, GaN, GaAs, AlN doped with V, Cr, Mn, Fe, Co, and Ni. They have ready access to high power computing. They mentioned another contributor, which may have been a Prof. Akai, for providing some code of KKR-CPA. Some of their recent calculations indicate that V and Cr in p-type and Fe, Co, and Ni in n-doped ZnO should exhibit half-metallic ferromagnetism with high Curie temperatures. Currently this group is considering transition-metal doped GaN and has found that in this system, the ferromagnetic ground state should be achievable in V-, Cr- or Mn-doped GaN.

They brought up the disclosure from the University of North Carolina about room temperature ferromagnetic manganese doped gallium arsenide, and we couldn't really comment except to say there is some question about clustering of the manganese.

Guided in part by the theoretical efforts, Associate Prof. Tabata, who is a member of Prof. Kawai's experimental group, is seeking to realize some of these new magnetic semiconductor systems. Prof. Kawai is leading a very large thin film materials research effort, which is supported by a major Center of Excellence

grant, whose objective is described as “The Harmonization of Materials.” This program emphasizes the use of laser-pulse-deposition molecular beam epitaxy for the growth of oxide and semiconductor systems, particularly the cuprates and the manganites and also magnetic semiconductors. In support of this overall program, approximately 10 different LPD-MBE systems have been put into place in Prof. Kawai’s laboratory. The spin electronics portion of this materials effort is currently focused on Co doped ZnO. One graduate student and two post-doctoral students are associated with this spin electronics materials project. Recently Prof. Tabata and colleagues have found that with a Co doping level of 15%, Zn(Co)O has a Curie temperature, as determined by magnetization measurements, above 300K. Due to the problem of obtaining the required level of solubility of Co in ZnO, low deposition temperatures (~300°C) are necessary for the growth of this material, a requirement that is well matched to LPD-MBE. (Prof. Tabata mentioned that Prof. Nakayama at Osaka City University is working on Mn-GaN with which he is finding a Curie temperature of ~150°C, but at a very high concentration level, which does raise questions regarding magnetic ion clustering effects.)

Prof. Katayama-Yoshida suggests that the II-VI materials in which the transition elements have a comparably high solubility are particularly good candidates for ferromagnetic semiconductor research. He suggests that work on these systems could yield transparent ferromagnets for important magneto-optic device applications. He also pointed out the possibility of optically inducing the ferromagnetic state in a wide band semiconductor system whose minimum energy state is antiferromagnetic and then detecting this carrier-induced change optically. Prof. Katayama-Yoshida also mentioned an interest in the AlN system and indicated that the most important impact of magnetic semiconductors would be the area of the quantum computer.

The close link between processing and theoretical analysis in these efforts should be a strong asset in the development of high temperature ferromagnetic semiconductors.

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- Sato, K., and H. Katayama-Yoshida. 2000. Material design for transparent ferromagnets with ZnO-based magnetic semiconductors. *Jpn. J. Appl. Phys.* 39. L555-L558.
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- Sato, K., and H. Katayama-Yoshida. 2001. Stabilization of ferromagnetic states by electron doping in Fe-, Co- or Ni-doped ZnO, K. *Jpn. J. Appl. Phys.* 40. L334-L336.
- Ueda, K., H. Tabata, T. Kawai. 2001. Magnetic and electronic properties of transition-metal-doped ZnO films. *Appl. Phys. Lett.* 79. 988-990.



Site: **Osaka University**  
**Graduate School of Engineering Science**  
**Division of Materials Physics**  
**Department of Physical Science**  
**1-3 Machikaneyama-cho**  
**Toyanaka 560-8531, Japan**

Date: April 5, 2001

WTEC Attendees: R. Buhrman (report author), H. Morishita, and M. Roukes

Host: Masafumi Shirai, Associate Professor; shirai@mp.es.osaka-u.ac.jp  
[Subsequently moved to Tohoku University:  
Research Institute of Electrical Communication  
2-1-1 Katahira, Aoba-ku  
Sendai 980-8577 Japan  
shirai@riec.tohoku.ac.jp]

### GROUP SIZE

- 2 M.S. students

### SUPPORT

Grant-in-Aid for Scientific Research on Priority Area “Spin-Controlled Semiconductor Nanostructures,” Ministry of Education Science, Sports and Culture, and also the Japan Society for the Promotion of Science.

### IMPRESSIONS

- Major effort in *ab-initio* electronic structure calculations. The focus of Prof. Shirai’s work is electronic band structure calculations of the hypothetical zinc-blende phase of MAs, where M = Ti, V, Cr, Me, Fe, Co, and Ni. His strategy is to use such results to identify new possible ferromagnetic phases of transition metal doped III-V semiconductors. The result of these calculations is that the ferromagnetic state should be stable in zinc-blende VAs, MnAs, and CrAs with the magnetic energy gain being the largest for the CrAs case. He concludes that since the electronic band structure of (Ga,Cr)As is very similar to (Ga,Mn)As, it is a good candidate to be a ferromagnetic semiconductor with a relatively high Curie temperature. These theoretical calculations, which indicate that CrAs should be a half-metallic ferromagnet, have been supported recently by an experimental effort by Akinaga and Manago at JRCAT (Ibaraki) where a very thin layer of zinc-blende CrAs has been grown by MBE on GaAs(001), which shows ferromagnetic behavior at room temperature. The challenge of this approach is that the zinc-blende phase is only stable up to about 2 nm of thickness, but CrAs could be an effective ferromagnetic electrode in combination with (Ga,Cr)As. Currently Prof. Shirai is studying the electronic properties of superlattices of GaAs and (Ga,Mn)As, with the objective of understanding what the nature of a perfect interface between these materials would be. This is following up recent work on the interface MnAs(0001) and GaAs(111) where the electronic structure calculations indicate a layer-by-layer change in both the magnetic moment of the MnAs and the spin polarization at the Fermi level, as one moves from the interface into the bulk MnAs.

Site: **Tohoku University**  
**Research Institute of Electrical Communication (RIEC)**  
**Katahira 2-1-1, Aoba-ku**  
**Sendai 980-8577, Japan**

Date: April 6, 2001

WTEC Attendees: D. Awschalom (report co-author), R. Buhrman, J. Daughton, K. Goto, H. Morishita, M. Roukes, U. Varshney, S. von Molnár (report co-author), S. Wolf

Host: Hideo Ohno, Professor  
ohno@riec.tohoku.ac.jp

### **GROUP SIZE**

- 3 research assistants (assistant professor level, paid by government)
- 2 postdocs
- 6 graduate students (5 M.S. students, 1 Ph.D. student)

### **SUPPORT**

- Spins in Semiconductor program (1997-1999) funded by the Ministry of Education, Science, Sports and Culture provided \$5 million over three years to ~30 groups including Professor Ohno's
- All these funds are for equipment (5% overhead at Tohoku, which will rise to 30% starting FY2001)
- Professor Ohno, in addition to the minor funds through the spins program, has received \$4 million/five years from the Ministry of Education and from the Japan Society for the Promotion of Science.
- Renewals are applied for at the Ministry of Science and a new program at NEDO. The NEDO program combines existing semiconductor work with MRAM research and involves NEC, Toshiba, and other firms.

### **IMPRESSIONS**

RIEC is designed to stimulate collaborative research and consists of three research divisions: Brain Computing, Materials Science and Devices, and Coherent Wave Engineering. In addition, there is a parallel Laboratory for Electronic Intelligent Systems that consists of three programs. Professor Ohno leads one of these programs, entitled "High Speed Electronic Devices." His laboratory is also connected to the Materials Science and Devices Research Division.

The Materials Science and Devices Division also contains a program on spin electronics, led by Professor Arai. Another group (formerly headed by Professor Nakamura and now by Professor Muraoka) is working on magnetic recording. The latter group focuses on vertical magnetic recording and associated technology development including read heads and media. The former group appears to focus on metallic and nanoscale magnetic structures. Their ability to fabricate clean thin FM films has led to successful transitions of research projects including impedance-matching inductors for cell phone applications, micromagnetic actuators, and magnetic field sensors.

Professor Ohno's research focuses on the preparation, characterization, and application of semiconductor and hybrid ferromagnetic devices. This also includes quantum transport phenomena between 2D electron gases, spin-based LEDs, electrically switched magnetic FETs, and the development of large TMR materials. His development of a (Ga,Mn)As ferromagnetic ( $T_C > 100\text{K}$ ) diluted magnetic semiconductor sparked the national effort in spintronics.

In addition to his own research program, Professor Ohno has managed a large “Spins in Semiconductor” research program and is uniquely aware of ongoing work in Japan.

Existing materials research is centered around five MBE systems. These machines fabricate a variety of III-V based ferromagnetic semiconductors, including (Ga,Mn)As, (In,Mn)As, (Ga,Mn)Sb, CrAs, and new work on CrSb (ferromagnetic contacts). In addition, there are outstanding measurement capabilities including SQUID magnetometry, low-temperature magnetotransport, and a new solid state femtosecond-resolved optical spectroscopy laboratory including high pulse power capabilities (regenerative amplifiers and optical parametric amplifiers) and broad spectral range detection.

A specific near-term research goal of the group is to obtain very high TMR ratios with these materials and to construct semiconductor-based magnetic switches.

Present work includes electrical detection of spin-polarized electrons via the anomalous Hall effect and to use the results as the basis for new semiconductor spintronics.

Professor Ohno believes the following:

- While the national effort on spin electronics (broadly defined) has been funded at an estimated cost of \$50 million/five years, he would like to see significant increases over the next five years.
- The real strength in Japan is in materials sciences, less strong in devices, and quite weak in systems. One focus of the national program renewal is to increase activity in the latter two areas.

Professor Ohno expects that in 2001 all semiconductor sales will reach \$250 billion, and hard drives and other magnetic materials related sales will reach \$150 billion worldwide.

Thus the opportunity to interface these two large markets (such as in the case of MRAM) is of extreme interest, including unexplored areas such as quantum information science and the chance to more heavily integrate semiconductors and photonics. It is believed that spintronics can impact both fields (obviously).

This group is arguably the leading research group in Japan in the field of ferromagnetic semiconductors and has outstanding efforts in materials fabrication, device measurement, and fundamental physics. It is well connected with the research universities throughout Japan and with several companies. Professor Ohno organized and ran one of the first international conferences on the “Physics and Applications of Spin-related Phenomena in Semiconductors,” which was very well attended in the summer of 2000, highlighting research within his program and within Japan.

Site: **Tohoku University**  
**Department of Applied Physics**  
**Sendai, 980-8579, Japan**

Date: April 6, 2001

WTEC Attendees: D. Awschalom (report author), K. Goto, U. Varshney, S. von Molnár, and S. Wolf

Hosts: Terunobu Miyazaki, Professor  
miyazaki@mlab.apph.tohoku.ac.jp  
Hitoshi Kubota, Research Associate  
Kubota@mlab.apph.tohoku.ac.jp  
Yasuo Ando, Research Associate  
ando@mlab.apph.tohoku.ac.jp

### **GROUP SIZE<sup>1</sup>**

- 2 associate professors and one research associate
- 6 doctoral students
- 8 masters students
- 4 undergraduates

### **SUPPORT**

- Basic research funds from the university
- Grant-in-Aid for Scientific Research from Ministry of Education, Science, Sports and Culture
  - Development of Spin Tunnel Magnetoresistive Read Head (FY 1999-2001)
  - Microfabrication Process for Hybrid Magnetic Material and Fabrication of Tunnel Magnetoresistive Read Head (FY 1999-2001)
  - Nanoscale Magnetism and Transport (FY 1997-1999)
  - Study on Spin Transport Devices (FY 1996-1998)
- Ministry of Education, Science, Culture and Sports
  - IT Program (FY 2002-)
- Ministry of Economy, Trade and Industry
  - Memory Device Project (FY 2002-)
- NEDO
  - Tunnel Spin Transistor (FY 1995)
  - Ultra High Density Storage Components (FY 1998-2000)
- CREST
  - Spin-Injection as a Base of the Spin-Charge Coupled Electron Devices (2001-2005)
- Storage Research Consortium (FY 1995-)
- Private foundations

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<sup>1</sup> Information on group size and support provided by the host in September 2002.

**IMPRESSIONS**

Professor Miyazaki's activities, entitled "Spin Electronics," within the Department of Applied Physics, specialize in thin film materials and devices that provide new functionality through interplay of spin and electrical conduction processes. With an international background through personal research in Germany with Professor Gruenberg, Professor Miyazaki has developed an extremely competitive MRAM program with outstanding control of materials synthesis and characterization. He is clearly quite well connected with and knowledgeable about competitive research efforts, including work at IBM and Motorola in the United States. The laboratory has hosted several U.S. visitors, including Mark Johnson (NRL) and Stuart Parkin (IBM).

The infrastructure is state-of-the-art, including a dedicated clean room, metals fabrication, dedicated SEM, AFM, and a variety of electrical testing equipment. Laboratories were industrial-class facilities. It is to this program's credit that the best device density/resistance ratios accomplished in Professor Miyazaki's laboratory seem to be at or exceed the specifications of the published literature.

This is a very high quality research and engineering program, with ambitious goals and impressive results.

Site: **Tohoku University**  
**Department of Materials Science**  
**Graduate School of Engineering**  
**Sendai 980-8579, Japan**

Date: April 6, 2001

WTEC Attendees: D. Awschalom (report co-author), R. Buhrman (report co-author), J. Daughton, K. Goto, H. Morishita, M. Roukes, U. Varshney, S. von Molnár, and S. Wolf

Host: Yoshichika Otani, Associate Professor  
chika@material.tohoku.ac.jp

### **GROUP SIZE**

- 2 graduate students
- 1 postdoc

### **SUPPORT**

- CREST funding \$3-4 million/five years

### **IMPRESSIONS**

Professor Otani leads a small, extremely imaginative research program aimed at electrical spin injection and subsequent magnetization reversal in devices (i.e., electrical control of magnetization). Additional research projects include magnetic tunnel junction work and magnetic phase transition in metamagnetic materials with applied electric fields (via the injected polarized current). Reported and planned experiments spatially resolve the anomalous Hall effect due to injected polarized current in nonmagnetic metal thin films to record spin transport lengths and injection efficiencies.

Professor Otani has an accomplished history of research in micromagnetics, including transport studies of domain motion in submicron ferromagnetic wires and Hall studies of carrier injection into ferromagnetic/nonmagnetic wire and planar junctions.

To carry out this work, Professor Otani has put together a very nice, university-scale processing facility and a small clean room that has as its centerpiece an JEOL EBL system. (Professor Otani points out that the advantage of having his own EBL tool for his research group is counterbalanced by the effort and expense needed to maintain such a capability. This is a problem that is also encountered in the United States by those seeking to pursue leading edge research that depends on nanoscale lithography and pattern transfer processing.) Other equipment includes a resonating sample magnetometer (RSM, Toei Co. Ltd.) and magnetotransport equipment.

Professor Otani is attempting very interesting physics projects with ambitious research goals. However, the work is somewhat disconnected from other efforts in Japan, with the possible single exception of Professor Ohno. In addition, there is little connection to industrial partners or government laboratories. Professor Otani did tell us that there are plans for a new consortium; if funded, he will leave his present position and assume managerial responsibilities for nanomagnetics research in this program. [Following the WTEC panel's visit, Prof. Otani decided to move to RIKEN in April 2002, where he is organizing a "nanomagnetism" research group. The program includes above-mentioned spintronics as well as dynamic magnetic properties of nanoscale magnets.]

Site: **Tohoku University**  
**Institute of Multidisciplinary Research for Advanced Materials**  
**2-1-1, Katahira, Aoba-ku**  
**Sendai 980-8577, Japan**

Date: April 6, 2001

WTEC Attendees: R. Buhrman (report co-author), J. Daughton (report co-author), H. Morishita, and M. Roukes

Host: Yasuo Oka, Professor  
oka@tagen.tohoku.ac.jp

### **GROUP SIZE**

- Approximately 15 people in group (about six students, the remainder are postdocs and junior faculty)

### **SUPPORT**

- CREST (Japan Science and Technology Agency)
- METI, the Ministry of Economy, Trade and Industry
- Ministry of Education, Science and Culture

### **IMPRESSIONS**

Professor Oka is leading a fairly large university effort that is chiefly concerned with Mn alloyed II-VI semiconductors, particularly Cd-Mn-Te and Cd-Mn-Se. The focus is on the strong magneto-optical properties of these materials in quantum size regimes, which include a giant Zeeman splitting, a strong magnetic polaron effect, and giant Faraday rotation. The initial technological application envisioned is the use of these materials as optical isolators, an application that was mentioned regularly during our visits. There is an association of past work with a CdMnTe optical isolator product (Tokin).

The research in Professor Oka's group covers the fabrication and study of Cd-Mn-Te and Cd-Mn-Se quantum dots, quantum wires, and double quantum well structures. Quantum dots have been formed by atomic layer epitaxy of a thin magnetic layer followed by a controlled anneal to form dots in the 2.8 nm size regime. Cd-Mn-Se quantum wires have been formed by high resolution electron beam lithography and controlled chemical etching; and quantum well structures have been fabricated through the growth of CdTe – CdMnTe layers. The quantum dots have been used in optical studies of the decrease of the exchange interaction in the quantum size regime, while the quantum wire results have indicated that 1D quantum confinement can also modify the exchange interaction. The double quantum well structures, consisting of a magnetic and a non-magnetic well, have been used in studies of the polarized light emitted from the nonmagnetic well as a result of spin injection from the magnetic quantum well.

Associate Professor Murayama has recently joined Professor Oka's group. Previously he was working at Komag and had spent some considerable time with Professor Falco's group at Arizona. Professor Murayama is interested in pursuing spin injection research that utilizes ferromagnetic electrodes such as Co. A possible objective is the development of a successful spin transistor structure.

This group has good equipment and access to fabrication facilities.

**APPENDIX D. HIGHLIGHTS OF RECENT U.S. RESEARCH AND DEVELOPMENT ACTIVITIES****SPIN ELECTRONICS — IS IT THE TECHNOLOGY OF THE FUTURE? (STEPHAN VON MOLNÁR)**

The consequences implicit in the question of the title are the reasons that the WTEC panel is reviewing the status of spin electronics research and development around the world. In recent years, electronic devices have been scaled down to size regimes where quantum effects begin to interfere with their functioning. By some industry predictions, this physics impasse will be felt commercially as early as 2003. By incorporating one of the formerly undesirable quantum effects, electron spin, into device functioning, spin electronics offers a possible route to continue with the impressive gains in memory capacity and speed that Moore's Law predicts. In spintronics it is not only the electron charge but also its spin that carries information. Further, spintronics combines standard microelectronics with spin-dependent effects that arise from the interaction between electrons and a magnetic field. Thus the combination of bandgap engineering and integrated magnetics offers remarkable opportunities for a new generation of devices with completely different functionality. Furthermore, magnetic interaction lengths are small. The advantages of magnetic devices would be nonvolatility, increased data processing speed, decreased electric power consumption, and increased integration densities compared to semiconductor devices. Magnetic random access memory (MRAM) could enable nonvolatile RAM with the high speed of today's static RAM and the high density of dynamic RAM. Nonvolatile means that the memory is maintained even when power to the device is turned off. Such devices would allow for instant-on computers and extend the battery life of portable electronics. In addition to storage applications, which are being pursued in the United States by such industrial innovators as IBM, Honeywell, Motorola, and NonVolatile Electronics (NVE), spin electronic elements will result in new approaches to logic design, quantum computing, and quantum communications.

This WTEC panel was organized to evaluate the research efforts in the field within the United States and to compare them to existing international efforts. Most significant among these is the research and development activity in Europe and Japan. While research in metallic multilayer giant magnetoresistive (GMR) structures and their integration into various magnetic random access memory (MRAM) configurations continues to be a highly active area, the promise of orders of magnitude larger signal-to-noise ratio in magnetotunneling devices has resulted over the past two years in major research investment both by the private sector (e.g., IBM, NVE, Motorola) and by academic institutions.

High interest in the utility of semiconductors as both sources and carriers of spin information has been rekindled by two recent discoveries. The first of these, by Awschalom and coworkers (Awschalom and Kikkawa 1999), demonstrated that optically injected spin-polarized carriers maintain their coherence over nanosecond time scales. This means that they can be transported over distances far in excess of tens of micrometers, making the transport of coherent spin information from device to device a practical reality. The second discovery, by Ohno and coworkers in Japan (Ohno et al. 1996), resulted in the fabrication of low concentration Mn substitution in GaAs epilayers with ferromagnetic ordering temperatures in excess of 100K. Other semiconducting materials with  $T_C$  higher than room temperature and their practical potential are in the offing. Thus the natural integration of spin sensitive and normal semiconductor functionality will lead to new opportunities for integrating electronics, magnetics, and photonics into single technologies with multifunctional capabilities.

The WTEC panel's responsibility is to provide a comparative assessment of U.S., Japanese, and European research and development in this field and to make recommendations to their sponsors, the National Science Foundation (NSF), the Office of the Secretary of Defense (Research and Engineering), the Defense Advanced Research Projects Agency (DARPA), the Office of Naval Research, and the National Institute of Standards and Technology (NIST), as well as the public at large concerning planned programs. The task will



include the identification of emerging research activities and opportunities, as well as potential cross-disciplinary and international collaborations. The panel will also explore issues such as methodologies for academic/industrial collaboration, long-term graduate educational needs, and strategies for research and development funding on the national level.

The summary pages that follow were originally prepared as a handout given to researchers in Europe and Japan who hosted the panel's site visits beginning in April of 2001. They are intended to give our hosts a measure of the panel's view on the most important spintronics research issues and activities in the United States. Wherever appropriate, recent advances are outlined. Thus, all members of the panel have contributed to this summary.

The panel members express gratitude to their international hosts for allowing the panel to visit them and discuss the present and future of spintronics. It is the panelists' hope that this discussion is mutually beneficial and will lead to a deeper understanding of our joint needs and a continuing dialogue and close collaboration with our hosts.

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### FABRICATION OF MAGNETIC NANOSTRUCTURES (MICHAEL ROUKES)

Three classes of modern technological advances have greatly invigorated the investigation of magnetism:

- *nanofabrication methods* – that allow patterning ferromagnetic materials down to the dimensions of single domain magnetism and the definition of nanoelectronic devices exhibiting pronounced ballistic and quantum confinement phenomena
- *heteroepitaxy* – that enables the creation of new types of crystalline magnetic alloys and ferromagnetic semiconductors, as well as the definition of extremely high quality interfaces between materials systems
- *magnetic imaging* – new methods that are providing resolution of the local structural and magnetic properties of new materials and devices on the nanometer length scale

Concerted application of these advances is providing the capability to observe, control, and engineer magnetic phenomena at the nanoscale. This is enabling the creation of entirely new magnetic materials and magnetoelectronic device structures.

### Integration of Semiconductors and Ferromagnets

The integration of semiconductors and ferromagnets has been a long-standing goal and has proven to be elusive due to differences in crystal structure and chemical bonding (Tanaka 1999; Prinz and Hathaway 1995). Historically, the search for magnetic semiconductors was motivated by the expectation that both semiconducting and magnetic properties could be found in one and the same material. The Eu chalcogenides, the most thoroughly studied early magnetic semiconductors in which the magnetic species ( $\text{Eu}^{2+}$ ) resides on every lattice site, failed in the practical sense, since its ferromagnetic transition temperatures  $T_C$  were much lower than room temperature with little hope of great improvement (Methfessel and Mattis 1968).

Not surprisingly, the discovery of ferromagnetic order as high as 110K in III-V-based diluted magnetic semiconductors (DMS) (Ohno et al. 1996) has generated much attention, especially since there are theoretical predictions for  $T_C$ s above room temperature in several classes of these materials (Dietl et al. 2000). Although DMS materials programs in the United States, other than II-VI-based DMS, are in their nascent stages, efforts are in place at the Naval Research Laboratory (B. Jonker), Pennsylvania State University (N. Samarth), Notre Dame (J. Furdyna), and the University of California, Santa Barbara (A.C. Gossard). Other than the promise of devices such as, e.g., controlled magnetism (Ohno et al. 2000), one of the advantages of magnetic semiconductors is their potential as spin-polarized carrier sources. To effect large spin polarization, the Zeeman splitting of the conduction (valence) band must be greater than the Fermi energy of

the electrons (holes). In concentrated materials, this occurs easily because the net magnetization upon ordering is proportional to the concentration of magnetic species. In DMS, however, the Mn content is low (~5%) while the carrier concentrations are high ( $\sim 10^{20} \text{ cc}^{-1}$ ). Furthermore, the Mn content may be limited by phase separation for much higher concentration of the magnetic species, and externally applied magnetic fields may thus be necessary to produce large polarization.

Another approach is to search for new materials that exhibit large carrier spin polarization. Thus in the United States there are efforts to produce magnetic Heussler alloys (Dong et al. 1999). These materials have been predicted to be half-metallic ferromagnets (de Groot et al. 1983). Furthermore, several magnetic oxides hold promise as polarized sources. These include  $\text{CrO}_2$  (Watts et al. 2000), the only magnetic metallic oxide, various members of the mixed valence perovskites (Coey, Viret and von Molnár 1999), e.g.  $\text{La}_{0.70}\text{Sr}_{0.30}\text{MnO}_3$ , and  $\text{Fe}_3\text{O}_4$ , which, according to recent photoemission data (Ruediger ND), have completely spin-polarized electrons at the Fermi energy at room temperature. Other than the latter, all these oxides have all been investigated by Soulen and co-workers (1998) via Andreev reflection spectroscopy and yield high (above 70%) carrier spin polarization values at low temperature. Finally, MnAs, with  $T_C$  near room temperature (Beam and Rodbell 1962), is being investigated actively both in the United States and Japan to determine its spin polarization. Clearly, the development of new materials, as has recently been demonstrated by the discovery of room temperature magnetism in Co doped  $\text{TiO}_2$  (Matsumoto et al. 2001), zinc-blende CrAs, and the surprisingly high  $T_C$  in La doped  $\text{CaB}_6$  (Young et al. 1999), which contains no magnetic species, will continue to be a major part of any program on spintronics.

### Spin Transfer Electronics

Three areas that exemplify the intense current activity in magnetoelectronic device research are magnetic tunnel junctions, spin injection structures, and magnetic point contacts. These new classes of devices have become possible only through the advances in magnetic materials, nanopatterning, and characterization mentioned above. All three device classes involve the electrical transfer of spin-polarized carriers from the “source” to the “drain” of a device structure. This resultant spin current is controlled by local magnetic fields, either ones that are physically applied, or ones that are controlled or induced (e.g., by switching a magnetic domain within a nearby nanomagnet or via an electric field, by a  $\mathbf{k} \times \mathbf{E}$  Rashba mechanism).

Spin transfer electronics is founded upon the assumption that spin-polarized electrons can survive during traversal of an entire device structure. This involves two distinct and important pieces of physics. First, the transfer of spins across the interfaces between materials must be possible without wholesale loss of polarization. Second, once the “source” interface is traversed, spin polarization must be largely preserved while the spin current propagates to the “drain.” For the case of magnetic tunnel junctions, the barrier properties must be ideal to avoid magnetic scattering. In the case of spin injection devices, there must be minimal spin relaxation within the paramagnetic “propagation region,” i.e., the initially unpolarized electron gas in the semiconducting or metallic layer that separates “source” from “drain.” Understanding the physics of these two steps of device operation and using this information to engineer materials and device geometries for next generation structures will undoubtedly be the focus of much research in the next decade.

Spin injection devices have represented one of the longest standing hopes in spin transfer electronics (Prinz 1995); they illustrate many of the crucial advances required for the full potential of all types of spin transfer electronics to be realized. Spin injection phenomena were first demonstrated in macroscale metallic structures in 1985 (Johnson and Silsbee 1985). Shortly thereafter (but now more than a decade ago) this initial work inspired Datta and Das to propose the concept of a “spin transistor” (Datta and Das 1990). It is based upon electrical injection of spin-polarized carriers from a ferromagnetic conductor into an electron gas within a semiconductor. Electrons propagating in the interfacial electric field that confines them are pictured as experiencing an effective magnetic field that induces spin precession; this is called the Rashba effect. As originally proposed, the rate of spin precession would be tunable through an external gate voltage that modifies the confinement potential (Nitta, Akazaki, and Takayanagi 1997). With ferromagnetic source and

drain contacts acting as spin polarizer and analyzer, an electron device analogous to an electro-optic modulator<sup>12</sup> would result.

Despite widespread interest that the proposal attracted in the intervening period, the Datta/Das device has not been realized (Monzon and Roukes 1999; Monzon, 1999) and remains a singular challenge for the community of researchers interested in these issues. Since the initial demonstration of the spin injection phenomenon in macroscale metallic structures in 1985, there has been only very sparse confirming evidence of this effect<sup>13</sup>. What has been demonstrated has been engulfed in a shroud of controversy given the disappointingly small “signals” that have been observed. Data from these experiments allow an upper bound to be placed on the magnitude of the induced current polarization, and it appears extremely small, on the order of 1% at best. What is troublesome about signals at this level is that conventional magnetoresistance measurements (the only approach employed in all investigations to date) are plagued with a host of obfuscating, non-spin injection related magnetoelectronic phenomena (Monzon, Johnson, and Roukes 1997). Hence, correct interpretation of the signals obtained in such devices remains problematic and unclear.

Recently, very significant advances within two separate areas of spin electronics have emerged that provide new optimism that spin injection transistors can ultimately be realized. First, electrical spin transfer across interfaces has been demonstrated in spin-polarized light-emitting diodes (LEDs) (Ohno et al. 1999; Fiederling et al. 1999; Jonker et al. 2000). The emission of circularly polarized light from these devices provides rather compelling evidence that electrical injection of hot, spin-polarized carriers can indeed be achieved. What is interesting about these structures is that they all involve electrical spin injection across epitaxial interfaces — ones far more ideal than those employed, so far, in the all electrical spin injection devices that have been studied. Hence, this recent body of LED work appears to demonstrate that spin polarization, in amounts varying from very small to substantial, can be preserved in injected currents if they traverse an optimal contact interface. Second, the long lifetime for spin-polarized carriers observed in optically polarized systems (Kikkawa et al. 1997; Awschalom and Kikkawa 1999) demonstrates that carrier propagation within semiconducting electron gases need not be accompanied by significant loss of spin polarization. This work, and the body of spin injection research that has preceded it in the years intervening since the first observation 1985, serve to demonstrate how crucial new materials, ideal interfaces, and optimal device geometry are to these new classes of magnetoelectronic devices. In the face of the difficulties and ambiguities that exist in general, it is clearly very important to elucidate the underlying mechanisms controlling spin coherence during the electrical injection process.

### **Magnetic Imaging**

Imaging and metrology of magnetic structures are at the heart of efforts to systematically develop and characterize magnetoelectronic materials and devices. For work with nanometer scale magnetic systems the requirements are demanding: not only must the spatial resolution of the imaging methods employed be at, or better, than the minute structural dimensions of the samples, but the imaging technique must also have the requisite sensitivity to detect very small total magnetic moments. Modern approaches that satisfy these requirements span the scale of size and complexity from true facilities-based approaches involving synchrotron radiation (Kortright 1999) or small-angle neutron scattering (Wiedenmann 2000) to large single laboratory instruments such as used for electron holography (Mankos, Scheinfein, and Cowley 1995) to “table top” instrumentation such as is used in various forms of magnetic scanned probe microscopy (Dahlberg and Proksch 1999). The following section summarizes a few representative recent investigations using these approaches from among the wide spectrum of emerging applications:

- X-ray magnetic circular dichroism has emerged as an important technique for showing local magnetic environment of thin films and interfaces with extremely high resolution (Stohr 1995; Freeland et al. 1999; Idzerda, Chakarian, and Freeland 1999; Wende et al. 1998). Also complementing this approach is small-angle neutron scattering (Loffler, Wagner, and Kostorz 2000), which yields information about

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<sup>12</sup> An electro-optic modulator functions via crossed polarizers that sandwich an electrically-tunable birefringent material.

<sup>13</sup> A compelling new set of experiments in metallic devices has recently been carried out by the group in Groningen.

magnetic environments down to the atomic scale. These methods have provided important insights into the microscopic magnetism of nanophase materials and thin films and their interfaces. They can also be applied to investigate the average properties of arrays of nanostructures. Electron holography (Smith 2000) is unique among such high resolution approaches given its ability to provide information about the magnetic environment of individual nanostructures.

- In comparison to these facilities- and laboratory-scale approaches, an exciting new slate of compact instruments that are based upon the principles of scanned probe microscopy has been developed. The forerunner of these approaches is magnetic force microscopy (MFM) (Proksch 1999), which involves a small micro- or nanomagnet affixed to the end of a mechanical force detector. Its first realizations allowed scanning across ferromagnetic samples to provide sensing of local field gradients; significant refinements to the technique have emerged.
- The immediate successor to this technique was scanned SQUID (superconducting quantum interference device) microscopy (Kirtley and Wikswo 1999), which provides direct information about the local fields. However, the geometry of the nanoscale superconducting loop used is, of necessity, slightly larger than the dimensions the smallest nanomagnets used in MFM; hence, the SQUID approach does not provide comparable spatial resolution. On the other hand, with its high sensitivity it has enabled an exciting new class of important studies of domain reversals in individual single domain nanomagnets (Wernsdorfer, Mailly, and Benoit 2000).
- Recently it has become apparent that nanoscale semiconducting Hall probes can provide sensitivity comparable with SQUID magnetometers (Monzon, Patterson, and Roukes 1999), but without the need for low temperatures. A further advantage is the robustness and the simplicity of this approach, compared to those involving superconducting devices. The devices and technology of scanning such Hall probes have become rather sophisticated (Geim et al. 1997; Schweinböck et al. 2000) and are now providing new insights into micro- and magnetic systems, as well as into studies of vortex excitations in novel superconducting materials.
- In the past, ferromagnetic resonance has been carried out using uniform external fields both for magnetic polarization and microwave excitation. Hence the entire sample has typically contributed to the resultant signal. Recently a scanned probe technique for magnetic resonance called magnetic resonance force microscopy (MRFM) has emerged, which provides local information for the cases of EPR and NMR. This has been extended to ferromagnetically coupled spin systems (Zhang, Hammel, and P.E. Wigen 1996) in a technique called ferromagnetic resonance force microscopy (FMRFM). Resolution of layered magnetic structures (Zhang et al. 1998) and direct imaging of magnetostatic modes in ferromagnetic micro- and nanostructures (Midzor et al. 2000) has been demonstrated. With the use of nanomagnets providing very strong local gradient fields, the technique is now beginning to illustrate how local imaging can occur even in the case of long-range ferromagnetically coupled spin systems (Midzor et al. 2001).
- An alternate approach that provides local detection of ferromagnetic resonance involves coupling to the sample with a spatially confined microwave field rather than using a nanomagnet probe as in case of FMRFM. In this technique, called scanning near-field microwave microscopy (Lee et al. 2000), the spatial resolution is determined by the size of the microfabricated loop used to generate a local microwave-frequency magnetic excitation field; currently resolution slightly below the 100  $\mu\text{m}$  scale has been attained.

Most of the techniques described above have, to date, provided information only about the time-average magnetic properties, or dynamics for processes slower than roughly the microsecond scale. By contrast, powerful new optical techniques have been developed that enable tracking the evolution of fast microscopic magnetic events in real time. Among the first of these were optically pumped SQUID magnetometry (Awschalom and Warnock. 1989); its most recent successor is time-resolved Kerr microscopy (Choi et al. 2001). The application of such techniques is expected to play a very crucial role in elucidating spin relaxation processes in magnetic nanostructures, as well as unraveling the precise details of magnetization reversal processes. This information is essential to the iterative refinement of advanced magnetic materials and devices.

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## **RECENT DEVELOPMENTS IN SPIN INJECTION AND SPIN TRANSPORT STUDIES (R.A. BUHRMAN)**

### **Spin Injection and Spin Ejection**

A research effort that is rapidly developing in the United States (and elsewhere) in spin electronics is the pursuit of new approaches for successfully demonstrating and then utilizing the injection of strongly spin-polarized currents from ferromagnetic electrodes into semiconductor structures. This renewed effort follows an extended period of time during which there were a number of attempts to achieve the electrical injection of spins with the use of “ohmic” ferromagnetic metal/semiconductor contacts. The lack of clear and compelling success in these initial efforts resulted in a more serious and thorough consideration of the key issues that must be successfully dealt with before this goal can be achieved. This reconsideration included the recognition of the important point made best by the model calculation of Schulz and Molenkamp (Schmidt et al. 2000), which pointed out the important and limiting effect of the strong mismatch in the density of states of a typical ferromagnetic metal and a semiconductor at the Fermi energy. The result is that a high nonequilibrium spin population in the semiconductor is very difficult, perhaps impossible, to achieve with a diffusive electrical current flowing across an F-S interface that does not contain a potential barrier, i.e., an interface across which spin carriers can diffuse equally well in both directions.

This model calculation, which builds on a prior examination of Wyder and co-workers in the Netherlands on nonequilibrium spin populations at F-N interfaces, is now being extended to real F-Semi interfaces by several theoretical groups. For example, Flatté at Iowa and Byers at NRL are collaborating in an effort (as yet unpublished) to look at the issue of hot electron spin transport across both Schottky diode interfaces and through tunnel barriers between ferromagnetic electrodes and semiconductors. Rashba at MIT also has been examining the latter situation theoretically (Rashba 2000).

With this developing understanding of the key physics governing spin injection from a ferromagnetic electrode, at least in the ideal case, a number of experimental efforts are currently underway to explore and develop spin injection techniques that utilize either Schottky barriers or insulator tunnel barriers. Parkin and Monsma at IBM-Almaden have, for example, been studying the ballistic transport of tunnel-injected electrons across a ferromagnetic metal base layer and into an underlying Si substrate. Since the ballistic electron current that passes through the ferromagnetic layer is spin-polarized, that portion of the current that

successfully passes ballistically through the ferromagnet/Si Schottky barrier interface should also be spin-polarized. This will be the case provided that the interface is of high enough quality that there is not strong spin flip scattering during this passage, which has yet to be examined directly. As of now, the evidence for successful ballistic spin injection with this approach is indirect, but there are several efforts underway at a number of laboratories to demonstrate this in a more direct way. One approach being pursued at Cornell (and elsewhere) is to use one F/Si Schottky barrier to inject a polarized current into a thin Si layer and a second F/Si contact to extract the ballistic current. In such an experiment, the collector current amplitude is expected to be dependent on the relative magnetic orientation of the emitter and collector ferromagnetic electrodes.

In a different effort, McGill and colleagues at Caltech (Hill et al. ND) have sought to demonstrate the feasibility of tunnel junction of spin-polarized current in an STM experiment. In a preprint, they have reported results obtained with the use of Fe and Co STM tips tunneling, in air, into MBE-grown GaN layers. The spin polarization of the injected hot electrons was then determined through the measurement of the emitted light, which changed sign upon reversal of the magnetization of the tip. While the very high tunnel currents that were used, in the  $\mu\text{A}$  range and the fact that the experiment was done in air, which suggests that the magnetic tips may have been oxidized, both raising questions, the data appear to indicate a spin injection efficiency of  $\geq 25\%$ . The result is reported to be the achievement of a net spin polarization of 10% with this technique.

Perhaps the most exciting and promising experimental result recently in the spin injection area is the work of the Crowell group at the University of Minnesota. There a serious effort has been underway for some time to grow  $\text{Fe}_{1-x}\text{Co}_x$  epitaxially on GaAs surfaces, with very good results being achieved. These samples have recently been used to study the process of spin ejection from the optically excited GaAs across the Schottky barrier interface and into the ferromagnetic alloy. As was reported at the recent meeting of the American Physical Society, the magnitude of the electron (and hence spin) current that passes into the  $\text{Fe}_{1-x}\text{Co}_x$  depends strongly on its magnetic orientation. If this preliminary report is fully confirmed, it will be a very compelling demonstration that there are indeed no fundamental barriers to the successful passage of spin-polarized currents across metal/ semiconductor interfaces that include a potential barrier.

### **Spin Transport**

A topic of considerable interest recently has been the character of the spin current transport in semiconductor systems, as measured, so far, optically. Of particular interest has been the question as to whether the quasi-independent electron model can adequately account for the experimental results, or whether many-body or correlated electron processes are important. Here again Flatté and Byers have been in the forefront of this theoretical work and have concluded that an independent electron approach is quite capable of explaining the room temperature measurements of spin lifetimes. Sham and colleagues (Sham and Ostreich 2000; Sham 1999) at UC San Diego have been focusing on the low temperature case where collective electron processes may well be important in determining the spin relaxation rates and spin lifetimes, although experimental results in this regime are quite limited. Also Flatté and Vignale (Flatté and Vignale. 2001) have been looking at the possibility of constructing unipolar electronic devices by utilizing ferromagnetic semiconductor materials with variable magnetization directions. They have shown that such devices should behave very similarly to p-n diodes and bipolar transistors and suggest that they could be applicable for magnetic sensing, memory, and logic.

### **Spin Transfer**

Recently it has been definitively demonstrated that the spin-polarized current that flows from one ferromagnetic layer, through a nonmagnetic layer, to another thin film nanomagnet, can by the spin-dependent scattering of the polarized current excite or even reverse the orientation of the magnetic moment of the second layer (Katine et al. 2000). This spin transfer process opens up the possibility of new nanoscale devices for memory and other spin electronics applications. Efforts to understand, enhance, and utilize spin transfer phenomena are now being initiated at a number of research labs in the United States (and Europe). One of the possible applications that are being examined, in addition to direct current addressable magnetic

memory, is the use of spin transfer to excite a uniform spin wave in a nanomagnet and then to employ this as a precessing spin filter to inject a coherent spin pulse into a semiconductor structure.

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## RECENT DEVELOPMENTS IN THE OPTICAL MANIPULATION OF SPIN IN SEMICONDUCTORS AND NANOSTRUCTURES (D.D. AWSCHALOM)

### Creation and Manipulation of Electron Spin Coherence

There is a growing interest in the use of spin in semiconductor quantum structures as a medium for the optical manipulation and storage of classical and quantum information. During the last few years, femtosecond-resolved optical experiments by Awschalom and coworkers (UCSB) have revealed a remarkable resistance of electron spin states to environmental decoherence in a wide variety of semiconductors (Awschalom and Kikkawa 1999; Kikkawa et al. 1997; Kikkawa and Awschalom 1998; Kikkawa and Awschalom 1999; Gupta 1999). Some of these materials include GaAs, ZnSe, CdSe, GaN, and alloys with the magnetic dopant  $Mn^{2+}$ . Optical pulses are used to create a superposition of the basis spin states defined by a modest applied magnetic field and to follow the phase, amplitude, and location of the resulting electronic spin precession in bulk semiconductors, heterostructures, and quantum dots. The data show that spin lifetimes can exceed hundreds of nanoseconds and that spin packets can be transported over a hundred  $\mu m$  in some of these systems. In several instances, the dynamics persist to room temperature and thus provide practical pathways for coherent quantum magnetoelectronics.

Understanding the properties of spin transport in semiconductors is essential for the development of semiconductor-based spin electronics. Properties such as spin mobility and spin coherence time play the role of minority mobilities and lifetimes in charge-based devices. Flatté (Iowa) and Byers (NRL) have shown (1) that it is essential to consider the influence of electric fields induced by carrier motion to understand the motion of spin and (2) that the room-temperature spin coherence times in bulk and quantum well are dominated by precessional decoherence due to spin orbit coupling (Flatté and Byers 2000). They have described how the low-field mobility and diffusion of spin packets depend sensitively on the doping. They also have performed quantitatively accurate calculations of spin coherence times for bulk and quantum well systems, including the effect of quantum well growth-direction orientation on spin coherence times.

Sham and collaborators (UCSD) have recently developed a theoretical understanding of exciton spin dynamics in quantum dots, as well as potential pulse sequencing schemes for preparing and manipulating quantum information in these systems. Measurements by Steel and collaborators (Michigan) have confirmed these calculations, and reveal experimental techniques for direct quantum control of coherent wave packets in these systems (Bonadeo et al. 1998).

DiVincenzo and collaborators (IBM) have proposed novel schemes for utilizing electron spin coherence and thin ferromagnetic films to prepare coherent "spin valve" structures for quantum computation. In addition, they have proposed "spin-to-charge" converters with electron spins in coupled quantum dots for optical generation and electrical detection.



### **Spin Transport in Heterostructures and Coherent Spintronics**

Spatial imaging and dynamical magnetometry is being used by Awschalom and coworkers (UCSB) to monitor decoherence and dephasing of itinerant spin information as it flows not only through semiconductors, but also across dissimilar material interfaces in engineered structures. The interfaces appear surprisingly permeable to the flow of spin information over a broad range of temperatures, where regional boundaries may be used to control the resulting spin coherent phase (Malajovich et al. 2000). Moreover, recent measurements by this group distinguish several parallel channels of interlayer spin coherent injection within semiconductor heterostructures; they observe relative increases in spin coherent injection of up to five fold in electrically-biased structures, and 40 fold when p-n junctions are used to impose a built-in bias. The former results from a new ‘persistent’ spin conduction mode that appears upon bias, sourcing coherent spin transfer for at least 1-2 orders of magnitude longer than in unbiased structures. These experiments reveal promising new opportunities for multifunctional spintronic devices such as spin transistors that combine memory and logic functions wherein the amplitude and phase of the net spin current are controlled by either electrical or magnetic fields.

### **Role of Disorder in Spin-based Electronics**

As the majority of studies to date have been performed in high quality semiconductor systems, a deeper understanding of the effect of defects on spin coherence is clearly important for the development of spin-based electronics. In this context the III-V semiconductor GaN is intriguing in that it combines a high density of charged threading dislocations with high optical quality, allowing optical investigation of the effects of momentum scattering on coherent electronic spin states. Despite densities of charged threading dislocations of  $\sim 5 \times 10^8 \text{ cm}^{-2}$ , new measurements by Awschalom and coworkers (UCSB) reveal electron spin coherence in n-type MOCVD-grown GaN epilayers with spin lifetimes of  $\sim 20 \text{ ns}$  at  $T = 5\text{K}$  that persist to room temperature (Beschoten et al. 2001). Further investigations in the vicinity of the metal/insulator transition reveal a dependence on both magnetic field and temperature qualitatively similar to previous studies in n-type GaAs, suggesting a common origin for spin relaxation in these systems despite a difference of eight orders of magnitude in defect density.

### **Coherent Magnetoelectronics in Ferromagnetic Heterostructures**

A complementary approach to developing spintronic devices is based on generating novel magnetic materials and is exemplified in recent work involving III-V ferromagnetic semiconductors (e.g., (Ga,Mn)As and (In,Mn)As). This approach has already led to the demonstration of zero-field electrical spin injection in a hybrid structure (spin LEDs) involving both high quality semiconductor epilayers and ferromagnetic (Ga,Mn)As (Ohno et al. 1999). The integration of these two approaches — introducing coherent spins into ferromagnetic nanostructures — could lead to a new class of quantum magnetoelectronics based on the spin degree of freedom. In particular, some quantum computation schemes rely on the interaction of coherent spins with ferromagnetic materials to facilitate quantum logic operations. To investigate the nature of the carrier-mediated ferromagnetism in these materials, it is desirable to disentangle the electronic and magnetic interactions through alternative semiconductor growth techniques. (Ga,Mn)As has been grown at UCSB (Gossard, Awschalom) as a digital ferromagnetic heterostructure (i.e., digital alloy) by alternately depositing GaAs and submonolayer MnAs using low temperature molecular beam epitaxy (Kawakami et al. 2000). Magnetic measurements indicate ferromagnetism in the digital structures. Further, by varying the spacing of the MnAs layers, systematic investigations of the length scale of the ferromagnetic interaction find that the Curie temperature varies with the MnAs spacing with evidence for magnetic decoupling beyond 40 ML (11 nm) spacing. In fact, single layers of 0.5 ML MnAs embedded in a GaAs host are shown to be ferromagnetic. This growth technique therefore offers the opportunity for the separation of electronic and magnetic interactions suggested above, enabling future developments in magnetoelectronics and optoelectronics. Related work on these systems is now also being performed at SUNY-Buffalo by Luo and coworkers in GaAs/MnAs and InSb materials. Theoretical modeling of these digital structures has recently been completed by Sham and coworkers (UCSD), where the simulations indicate that interlayer diffusion appears to dominate the ferromagnetic properties.

Magnetic-semiconductor interfaces and magnetic semiconductors provide a new route to tuning properties of materials in spin electronics. Flatté and collaborators have suggested possible new device functionality with magnetic semiconductors (Flatté and Vignale 2001). For example, the domains in a unipolar magnetic semiconducting film could be configured to produce transistor-like behavior, suggesting applications in non-volatile memory and reprogrammable logic. Furthermore, he has provided a different explanation of the difficulties for spin injecting from ferromagnets into semiconductors, focusing on the low spin coherence times expected for the interface configurations.

### Optical Manipulation of Nuclear Spins

Nuclear spins have several orders of magnitude longer lifetimes and are thus favorable candidates for storing quantum bits whose entanglement proceeds via their hyperfine coupling with electron spins, as first discussed by Kane (Maryland). Hence, the dynamics of coherent electron-nuclear interactions are of considerable interest in spintronics. In addition, the inherently long spin relaxation time of nuclei (minutes to hours to days) suggest that they may also be promising candidates for classical spin-based storage. Dynamic nuclear polarization by electron spin is an incoherent thermodynamic process that has been extensively studied in bulk semiconductors, quantum wells, and quantum dots. It was recently proposed by Awschalom and coworkers (UCSB) that the hyperfine field of periodically excited electron spins could affect nuclear magnetic resonance (NMR) and may provide a foundation for coherent nuclear manipulation using optical techniques (Kikkawa and Awschalom 2000). However, optically induced resonances in bulk GaAs semiconductors occurred at unexpected magnetic fields so that a direct connection with NMR could not be established.

Now, time-resolved measurements of electron spin precession by this group provide unambiguous signatures of all-optical NMR in modulation-doped GaAs quantum wells (QW) and enable spatially selective manipulation of nuclear spin through confinement of the tipping field (Salis et al. 2001). By using QW electrons to resonantly depolarize nuclear spin, the nuclear excitation has been focused on the 7.5 nm wide QW layer. Resonances are identified from all three host nuclear isotopes, including quadrupolar splittings and nominally forbidden transitions at half the conventional resonance field. Moreover, the results show low field resonances indicating the survival of nuclear coherence on millisecond time scales. This specific project was performed as a joint venture between Awschalom in Santa Barbara and Ohno in Sendai, where the materials were developed.

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## **MAGNETOELECTRONICS AND DEVICES (JAMES DAUGHTON)**

Giant magnetoresistance (GMR) and magnetic tunneling junction (MTJ) structures have demonstrated their ability to deliver higher signals, compact device integration, and significantly higher magnetoresistance. These qualities make GMR and MTJ devices immediately important in applications in magnetic field sensors, read heads for hard drives, galvanic isolators, and magnetoresistive random access memory (MRAM) in the near term. They also promise future performance in spin electronics devices for use in semiconductors as well as completely new applications.

### **Magnetic Field Sensors**

Magnetic sensors serve a wide spectrum of applications in industrial, automotive, medical, and military markets. The long term trends (Frost and Sullivan ND) in this business area include (a) utilization of solid state rather than electromechanical sensors for improved reliability; (b) incorporation of more intelligence into sensors (which also favors use of solid state sensors); (c) miniaturization; and (d) higher operating temperatures, particularly for automotive applications. Several firms have been producing AMR sensors for more than a decade, including Philips and Honeywell, but general purpose GMR sensors have been introduced only in the past five years (NVE ND; Siemens ND), and several companies are producing GMR sensors for internal consumption. The MTJ looks very attractive for sensors due to high magnetoresistance (~40%), relatively low saturation fields, and high resistance (low power). No commercial sensors using MTJ structures are yet available, but NVE is developing an MTJ sensor.

### **Read Heads**

GMR read heads dominate applications in hard drives. Although some alternative configurations have been proposed, nearly all commercial GMR heads use the spin valve format originally proposed by IBM (Tsang et al. 1994). There has been development interest in MTJ and GMR multilayers for read head applications, but no significant products. The values of GMR in the spin valves have increased dramatically from about 4–5% in early heads to about 12–15% today. This increase is usually attributed to the use of specular reflecting layers and the stronger pinning using synthetic antiferromagnets (Koui et al. 2001; Huai et al. 2001). As hard drive storage densities approach 100 Gbits/square inch, stripe widths are approaching 0.1  $\mu\text{m}$ , and current densities are becoming very high. It is unclear how far the conventional spin valve read head can be extended.

### **Galvanic Isolators**

GMR isolators were introduced as products by NVE in 2000. They can eliminate ground noise in communications between electronics blocks in a manner similar to opto-isolators. The GMR isolator integrates well with other communications circuits or in the packaging of a large number of isolation channels on a single chip. The speed of the GMR isolator can eventually be 10 to 100 times as fast as opto-isolators, depending primarily on the switching speed of the magnetic materials and the speed of the associated electronics.

### **MRAM**

Magnetoresistive random access memory (MRAM) is not yet available commercially, but development activity is high. IBM/Infion, Honeywell, Motorola, Hewlett-Packard, Micron, and Union Semiconductor Technology Corporation (USTC) all have substantial development activities. Many developers are using MTJ cells (Tehrani 2000; Scheuerlein 1999), while some are using the pseudo-spin valve GMR cell (Katti 2001). Motorola has announced a 256K development level MRAM (Naji 2001). Common challenges in commercializing MRAM include (a) integration of the special MRAM layers in the semiconductor process, (b) high current levels, and (c) yield loss due to insufficient control and uniformity of the thresholds for switching in 2D arrays. Improvements in density have been proposed with vertical cells of cylindrical shape (Zhu, Zheng, and Prinz 2000) and Curie point writing (Beech et al. 2000). Also suggested are producibility improvements using a transistor/cell for writing, which results in a lower density, smaller capacity memory (Daughton 2000). Potential advantages of the MRAM as compared to EEPROM and flash memory include

faster write times, no wear out with write cycling, and lower energy for writing. The next several years should see the introduction of MRAM products, initially in niche applications. There is a potential for the MRAM to become a standard and very significant memory technology.

### **Spin-Dependent Transport Structures**

In just 10 years, magnetoresistance devices have developed very rapidly from AMR to GMR, spin tunneling, and now SPINS devices. Several possible new structures have suggested startling further additional improvements in magnetoresistance (Akinaga, Manago, and M. Shirai 2000; Akinaga et al. 2000; Matsumoto et al. 2001; Coey ND), from the 15% to 40% available today in GMR and MTJ structures, to hundreds of percent changes (at room temperature) with the new materials or structures. Converting these new structures into usable devices should become a very interesting field over the next several years. In addition, development of semi-metallic magnetic materials could make an almost direct conversion of conventional GMR and MTJ structures into very high magnetoresistance devices. And there may be other techniques, such as the use of specular scattering, to improve performance of GMR and MTJ structures.

The very thin barrier associated with the spin tunneling device could represent a reliability risk. Work at Motorola (Oepts 1999) and at NVE suggests that failure rates are very dependent on barrier voltages, and that if the barrier voltage is restricted to about 150 mV for aluminum oxide barriers about 15 Å thick, good reliability can be expected. This work should be extended to include alternative barrier materials and even thinner oxide barriers.

### **Some Thoughts on SPINS**

In order to use the spin of electrons in semiconductors, it will be necessary to control spin injection, spin transport, and spin detection. Researchers disagree on whether spin injection into a semiconductor from a ferromagnet is possible. Some argue that ballistic (or hot electrons) are likely to be polarized. Contentions that such injection is not possible point to the high resistivity of the semiconductor compared with the low resistivity of the ferromagnet — which is not a necessary condition. For example, it is easy to make CoFeHfO that is a ferromagnet with at least 4 milli-Ohm cm resistivity, a resistivity level obtainable with heavy doping of silicon or gallium arsenide. Use of a half-metallic ferromagnetic injector has been a well-recognized possibility for injection. Finding reliable electronic means of detecting spins may also generate controversy.

Spin current-induced switching is projected to have a much lower current requirement than etched windings. Because ferromagnetic semiconductors generally have a lower magnetic moment than ferromagnets, this could mean that lower currents may be required for switching.

Because devices using ferromagnetic semiconductors are not yet defined, it is difficult to specify desired characteristics of these materials, but intuitively, it would appear to be advantageous to have both n-doped and p-doped ferromagnetic semiconductors. It appears that p-doped materials are much easier to produce at this time than n-doped materials.

In the semiconductor business, equipment developments precede advances in the devices that can be fabricated. It is probable that new processing equipment may be required for breakthroughs in SPINS materials.

For decades, semiconductors and magnetic materials have been mated at the subsystem level, connected through wires and cables or on PC cards or in hybrid circuits. For the first time, magnetoresistive devices have enabled semiconductors and magnetic materials to be incorporated on an integrated circuit chip. Now, with ferromagnetic semiconductors, the connection is more intimate still. Applications of new technologies are always of two types: extensions to existing applications and new functions. Existing applications that SPINS will probably impact include memory, magnetic sensing, devices that absorb or emit polarized light, and logic. The all-new functions are likely to become apparent only after years of additional development.

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**APPENDIX E. GLOSSARY**

1D	One-dimensional
2D	Two-dimensional
2DEG	Two-dimensional electron gas
2DES	Two-dimensional electron system
3D	Three-dimensional
AFM	Atomic force microscopy
AIST	(Japan) National Institute of Advanced Industrial Science and Technology
AMPS	(U.S./DARPA) Advanced Magnets for Power Systems program
AMR	Anisotropic magnetoresistance
APS	American Physical Society
ATIP	Asian Technology Information Program
ATM	(U.S./DARPA program) Advanced Thermoelectric Materials
ATP	(Japan) Angstrom Technology Partnership

BEEM	Ballistic electron emission microscopy
BEMM	Ballistic electron magnetic microscopy
BLS	Brillouin light scattering
BMBF	(Germany) Federal Ministry for Education and Research
BSCCO	Superconducting material composed of Bi (or Pb), Sr., Ca, Cu, and O
CAIBE	Chemically assisted ion beam etching
CBE	Chemical beam epitaxy
CCN	(Germany, U. of Hamburg) Center of Competence in Nanoscale Analysis
CEA	(France) Atomic Energy Commission
CENG	(France, part of CNRL) Nuclear Center
CIP	Current in the plane
CMOS	Complementary metal oxide semiconductor
CMR	Colossal magnetoresistance
CNRS	(France) Centre National de la Recherche Scientifique
CPP	Current perpendicular to the plane
CREST	(Japan/JST) Core Research for Evolutional Science and Technology
CV	Capacitance-voltage
CVD	Chemical vapor deposition
DARPA	(U.S.) Defense Advance Research Projects Agency
DBR	Distributed Bragg reflector
DERA	(UK) Defense Research and Development Agency
DFG	(Germany) National Science Foundation
DMS	Diluted magnetic semiconductor
DOD	(U.S.) Department of Defense
DOE	(U.S.) Department of Energy
DOE/BES	(U.S.) Department of Energy, Office of Basic Energy Sciences.
E-beam or e-beam	Electron beam
EBL	Electron beam lithography
EC	European Commission
EELS	Electron energy loss spectrometer
EEPROM	Electrically erasable programmable read-only memory
EMR	Electron magnetic resonance (see also EPR)
EPR	Electron paramagnetic resonance (see also EMR)
EPSRC	(UK) Engineering and Physical Sciences Research Council
ERATO	(Japan, JST) Exploratory Research of Advanced Technology
ESR	Electron spin resonance
EU	European Union
EXAFS	Extended X-ray absorption fine structure
fcc	face-centered cubic (crystal structure)
FAME	(U.S./DARPA program) Frequency Agile Materials for Electronics
FEG	Field emission gun
FENIKS	(UK) Ferromagnetic semiconductors and novel magnetic-semiconductor heterostructures for improved knowledge on spintronics
FeRAM	Ferroelectric random access memory
FET	Field effect transistor
FIB	Focused ion beam
FIS	Ferromagnet/insulator/semiconductor
FM	Ferromagnet
FMD	Ferromagnetic detector
FMRFM	Ferromagnetic resonance force microscopy
FN	Ferromagnetic nonmagnetic normal metal
F-N interface	Ferromagnetic-normal interface
FNF	Ferromagnet/normal metal/ferromagnet
FOM	(Holland) Foundation for Research on Matter
F-S interface	Ferromagnetic-semiconductor interface

FTIR	Fourier transform infrared (spectrometer)
GID	Grazing incidence diffraction
GIF	German-Israeli Foundation
GISAXS	Grazing incidence small-angle X-ray scattering
GMR	Giant magnetoresistance
GS	(informal) graduate student
IEEE	Institute of Electrical and Electronics Engineers
IR	Infrared
IRC	Interdisciplinary research center
ITRS	International Technology Roadmap for Semiconductors
I-V	Current-voltage
JAIST	Japan Advanced Institute of Science and Technology
JEMS	Joint European Magnetism Symposium
JMW 01	Joint UK Magnetism Workshop (2001)
JRCAT	(Japan) Joint Research Center for Atom Technology
JSPS	Japan Society for the Promotion of Science
JST	Japan Science and Technology Corporation
KAST	(Japan) Kanagawa Academy of Science and Technology
KKR-CPA	Korringa-Kohn Rostocker (method of) coherent potential approximation
KNAW	(Holland) Royal Netherlands Academy of Arts and Sciences
LCMI	(France, CNRL) Laboratory of High Magnetic Fields
LED	Light-emitting diode
LEED	Low energy electron diffraction
LPD-MBE	Liquid phase deposition molecular beam epitaxy
MARCH	(University of Hamburg) Microstructure Advanced Research Center Hamburg
MARTECH	Center for Materials Research and Technology, Florida State University
MBE	Molecular beam epitaxy
MCD	Magnetic circular dichroism
MEMS	Microelectromechanical systems
METI	(Japan) Ministry of Economy, Trade, and Industry (formerly MITI)
MFM	Magnetic force microscopy
MIS (diode)	Metal-insulator-semiconductor
ML	Monolayer
MOCVD	Metal organic chemical vapor deposition
MOKE	Magneto-optical Kerr effect
Monbu-kagakusho	(Japan) Ministry of Education, Culture, Sports, Science, and Technology (MEXT, formerly Monbusho and STA)
MO-SNOM	Magneto-optical scanning near field optical microscopy
MQC	Macroscopic quantum coherence
MQT	Macroscopic quantum tunneling
MR	Magnetoresistance
MRAM	Magnetic random access memory
MRFM	Magnetic resonance force microscopy
MRSEC	(U.S./NSF) Materials research science and engineering center
MTJ	Magnetoresistive tunnel junctions
NCCR	(University of Basel) National Nanoscience Center
ND	No date (in references)
NEDO	(Japan) New Energy and Industrial Technology Development Organization
NIST	(U.S.) National Institute of Standards and Technology
NMR	Nuclear magnetic resonance
NOL	Nanooxide layer
NRL	(U.S.) Naval Research Laboratories
NSF	(U.S.) National Science Foundation
NSOM	Near-field scanning optical microscopy
NVE	(U.S. company) Non-Volatile Electronics Corporation

ONR	(U.S.) Office of Naval Research
PL	Photoluminescence
PLA	Pulsed laser ablation
PLD	Pulsed laser deposition
QD	Quantum dot
QUIST	(U.S./DARPA program) Quantum Information Science and Technology
RHEED	Reflection high energy electron diffraction
RIE	Reactive ion etching
RIEC	(Japan, Tohoku University) Research Institute of Electrical Communication
RIKEN	(Japan) Institute of Physical and Chemical Research
SEM	Scanning electron microscopy
SEMPA	Scanning electron microscopy with polarization analysis
SET	Single electron transistor
SHG	Second harmonic generation
SPA-LEED	Spot profile analyzing low energy electron diffraction
SPIN-LED	Spin light-emitting diode
SPINS	(U.S./DARPA program) Spins in Semiconductors
SPS	Scanning probe spectroscopy
SP-STM	Spin-polarized scanning tunneling microscopy
SP-STs	Spin-polarized scanning tunneling spectroscopy
SQUID	Superconducting quantum interference device
STA	(Japan) Science and Technology Agency
STM	Scanning tunneling microscopy
STW	(Holland) Dutch Technology Foundation
T	Tesla
$T_c$	Temperature of coherence
TEM	Transmission electron microscopy
TIT	(Japan) Tokyo Institute of Technology
TMR	Tunneling magnetoresistance
UCSB	University of California, Santa Barbara
UCSD	University of California, San Diego
UHV	Ultra high vacuum
UKRI	United Kingdom and Republic of Ireland Chapter of IEEE
VSM	Vibrating sample magnetometer
XFS	X-ray fluorescence spectroscopy
XMCD	X-ray magnetic circular dichroism
XPS	X-ray photoelectron spectroscopy
XRD	X-ray diffraction