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.

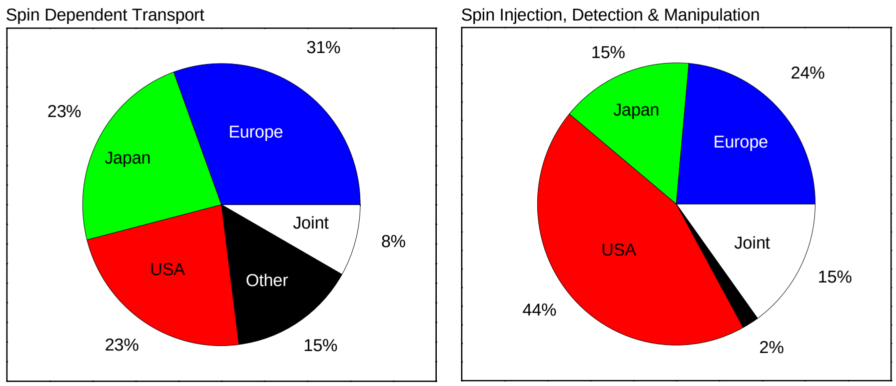

Figure 1.1. Percentages of papers written on spin-dependent transport from 1996 through 2001.

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[7]. 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.

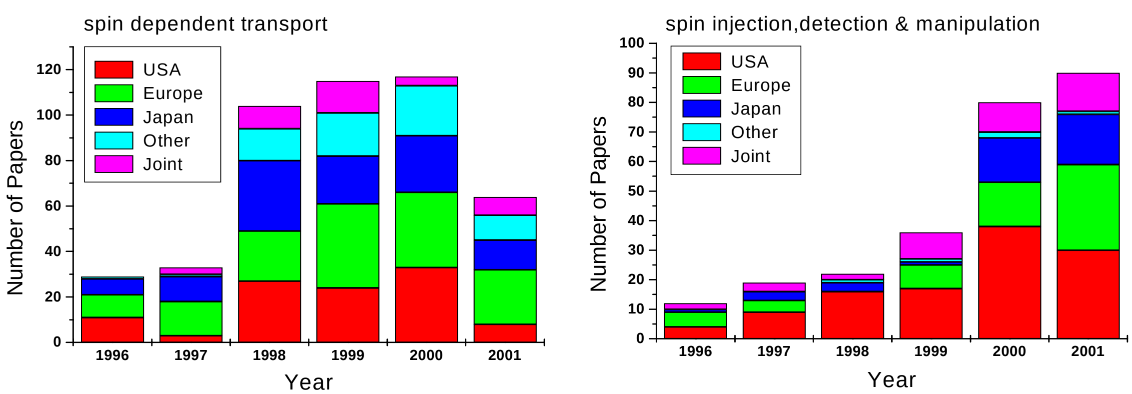

Figure 1.2. Publication activity for spin-dependent transport (left) and spin injection, detection and manipulation (right), 1996-2001.

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.

[7] 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.

REFERENCES

Awschalom, D.D. and J.M. Kikkawa. 1999. *Physics Today*. 52, 33.

Baibich, M., J. M. Broto, A. Fert, F. Nguyen Van Dau, F. Petroff, P. Eitenne, A. Friederich, and J. Chazelas. 1988. *Phys. Rev. Lett.* 61, 2472.

Barnas, J., A. Fuss, R. Camley, P. Grünberg, and W. Zinn. 1990. *Phys. Rev. B*. 42, 8110.

Daughton, J. 2000a. Advanced MRAM concepts. Paper presented at Nonvolatile Memory Symposium. Washington, D.C., November 16. (Also available at www.nve.com.)

Daughton, J. 2000b. *IEEE Trans. Magn.* 36, No. 5, 2773-2778.

Katine, J.A., F.J. Albert, R.A. Buhrman, E.D. Myers, and D.C. Ralph. 2000. *Phys. Rev. Lett*. 84, 3149-3152.

Monzon F.G. 1999. PhD. Thesis. California Institute of Technology.

Monzon, F.G. and M.L. Roukes. 1999. Spin injection and the local Hall effect in InAs quantum wells. *J. Magn. Magn. Mater.* 632.

Ohno, H., A. Shen, F. Matsukura, A. Oiwa, A. Endo, S. Katsumoto, and Y. Iye. 1996. *Appl. Phys. Lett*. 69, 363.

Rippard, W.H. and R.A. Buhrman. 1999. *Appl. Phys. Lett.* 75, 1001-1003.

Roukes, M. 2001. Plenty of room, indeed. *Scientific American*. September, p. 48.

Wolf, S.A., D.D. Awschalom, R.A. Buhrman, J.M. Daughton, S. von Molnár, M.L. Roukes, A.Y. Chtchelkanova, and D.M. Treger. 2001. *Science*. 294, 1488-1495.