EXECUTIVE SUMMARY

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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.[6] 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

[6] 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.