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Spintronics
– From Materials to Circuits –

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1. Introduction

Current information technology utilizes the charge of electrons in semiconductors to process information and the spin degree of freedom of electrons in magnetic materials to realize mass storage of information. Although the two degrees of freedom lay foundation of modern information technology, they have almost always been used separately to date. Spintronics is the field in which both charge and spin degrees of freedom are used to realize functions otherwise not accessible (Fig. 1). A wide variety of research efforts is now being carried out from those that are more exploratory in nature to close to real world applications, from quantum information technology based on spins through novel spin based semiconductor structures to magnetic-semiconductor hybrid structures for magnetic random access memories. In the following, I review recent results in the field of spintronics; first focusing on semiconductor spintronics and then on metal-based spintronics.

2. Semiconductor Spintronics

An approach to utilize both charge and spin degrees of freedom is to work on semiconductors itself. Semiconductors used in electronics such as Si and GaAs are non-magnetic and contain no magnetic ions. To create 1 meV of energy difference in the two possible directions of electron spin, magnetic fields of the order of 10 T are required. This insensitivity is the reason why most of the spin-dependent phenomena have been virtually ignored in semiconductor device operations. There are several ways to enhance the magnitude of spin sensitivity. One can create spin polarization by the use of circularly polarized light. Or when electrons are confined in a quantum dot, the spin-dependent exchange interaction among them becomes important even without magnetic ions. The third approach is to introduce transition metal magnetic ions, which gives rise to exchange interaction between band electrons and the electrons localized at the magnetic ions. This has been shown to lead to ferromagnetism in the case of InAs and GaAs alloyed with Mn [1].

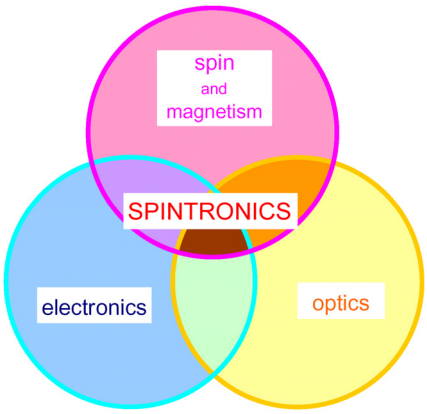

Fig. 1 Spintronics spans over three major areas that lay foundation of information technology

Hole-induced ferromagnetism in these transition metal doped III-V compounds made it possible to integrate ferromagnetism with existing nonmagnetic III-V heterostructures. These structures have allowed us to explore a new dimension of spin-dependent phenomena in semiconductors. A mean-field theory based on exchange between carrier spin and Mn spin [2] indicated that the properties of ferromagnetism in magnetic III-V's depend critically on the hole concentration. By the use of insulating-gate field-effect transistor structure to modulate carrier concentration, reversible electrical switching of the ferromagnetic phase transition as well as coercive force has been realized [3, 4]. Furthermore, current-induced magnetization reversal is shown to occur at much lower current density than the metallic counterparts, either in the form of current-induced domain wall motion [5] or in the form of magnetization rotation in nano-pillars [6]. The reduction of critical current density is believed to be related to the reduced magnetization of ferromagnetic semiconductors together with its high spin-polarization. Because these current-induced magnetization manipulation can be seamlessly integrated into semiconductor structures, we expect ferromagnetic semiconductors to be useful in developing spintronic devices that combine magnetization switching with other spin-related effects. We are thus beginning to learn and understand how to control and utilize the spin degree of freedom in semiconductor structures [7].

3. Metal-based Spintronics

Metal-based spintronics emerged from basic research on spin-dependent transport in magnetic materials (metals).

After the discovery of Giant Magnetoresistance (GMR) in magnetic multilayers at room temperature in 1988, which became quickly the standard technology for read-heads of current hard disk drives, a large Tunnel Magnetoresistance (TMR) between two magnetic metals separated by a thin insulator was demonstrated at room temperature in 1994 [8]. This Magnetic Tunnel Junction (MTJ) device is currently the preferred device for a magnetic random access memory (MRAM) cell of one MTJ/one transistor architecture. Typical MTJ can provide a TMR ratio of 50% defined by $(R_{high}-R_{low})/R_{low}$, where R_{high} and R_{low} are resistances at high resistant state and low resistant state, respectively. Because MRAM can deliver, 1) non-volatility with unlimited read-write, 2) ns speed, 3) high-density, and 4) low-power, it may become a universal memory that can satisfy requirements that are currently fulfilled by combination of memories such as DRAM, SRAM, and Flash. There are challenging device level issues to be solved, however, when MRAM technology is to be pushed beyond the Gbit scale. First, as the dimension reduces the magnetic field to reverse the magnetization of a magnetic bit (write) increases *i.e.* more current is required. Second, although TMR ratio is high, it is still not high enough as TMR ratio reduces with bias voltage and the maximum output voltage is currently limited to 50 mV as opposed to 100 mV of a DRAM cell. Third, it is necessary to develop processing technologies that allow uniform etching of more than 10^9 magnetic nano-elements, which are not readily available as reactive-ion etching has to deal with different set of reaction products many of which have low vapor pressures. The first one can be overcome by introduction of synthetic antiferromagnetic structure and later by introduction of current-driven magnetization reversal scheme, where magnetization reversal is done by spin-polarized current. Here, the reduction of critical current density is critical. Recently, efficient use of spin polarization in a layered structure is shown to lead to considerable decrease in required current density [9]. The use of half-metals, in which spin polarization P is 100% at Fermi-energy, can overcome the second issue as TMR ratio is equal to $2P/(1-P^2)$ [10]. Finally, reactive ion etching of permalloy (NiFe) is now being pursued by mixture of CO and NH_3, which appears to be successful when appropriate conditions are established [11].

MRAM will be the technology driver of spintronics devices for the coming years. Beyond MRAM, there are schemes to utilize MRAM not only as a memory but a part of reconfigurable logic-in-memory, which may solve the logic-memory bandwidth bottleneck we are facing today [12].

4. Summary

A review of selected recent developments in spintronics is presented. It is worth noting that there is another direction to go other than those topics covered here, which is spin-based (semiconductor) quantum information technology. For this, effective single spin manipulation and detection are required and considerable research efforts are being directed in this direction.

Spintronics bridges two major fields that lay foundation of present day information technology; semiconductor devices/integrated circuits and magnetic information storage. It brings nonvolatility to semiconductor based circuits that is essential for the reduction of power for many applications, and in turn it introduces the concept of "circuit" to magnetic storage field; nonvolatile magnetic circuits are now being pursued. This may result in a merger of the two gigantic fields (markets) in the future. It is also shown that by utilizing spin-degree of freedom, especially magnetic cooperative phenomena, semiconductors can even be more versatile and may be used in realizing new functions.

Acknowledgements

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References

[1] H. Ohno, Science **281** (1998) 951.
[2] T. Dietl, H. Ohno, F. Matsukura, J. Cibert, D. Ferrand, Science **287** (2000) 1019.
[3] H. Ohno, D. Chiba, F. Matsukura, T. Omiya, E. Abe, T. Dietl, Y. Ohno, K. Ohtani, Nature **408** (2000) 944.
[4] D. Chiba, M. Yamanouchi, F. Matsukura, and H. Ohno, Science **301** (2003) 943.
[5] M. Yamanouchi, D. Chiba, F. Matsukura, and H. Ohno, Nature **428** (2004) 539.
[6] D. Chiba, Y. Sato, T. Kita, F. Matsukura, and H. Ohno, cond-mat/0403500 (2004).
[7] H. Ohno, F. Matsukura, and Y. Ohno, *JSAP International* **5**, (2002) 4 (available at http://www.jsapi.jsap.or.jp/).
[8] T. Miyazaki and N. Tezuka, J. Magn. Magn. Mater. **139** (1995) L231.
[9] Y. Jiang, T. Nozaki, S. Abe, T. Ochiai, A. Hirohata, N. Tezuka, and K. Inomata, Nature Materials **3** (2004) 361.
[10] H. Kubota, J. Nakata, M. Oogane, Y. Ando, A. Sakuma and T. Miyazaki, Jpn. J. Appl. Phys. **43** (2004) L984.
[11] H. Kubota, Y. Ando, and T. Miyazaki, J. Magn. Magn. Mater. **272-276** (2004) e1421.
[12] H. Kimura, M. Ibuki, and T. Hanyu, Paper No. 8C3L-3-1/8C3L-3, Int. Tech. Conf. on Circuits/Systems, Computers and Communications, Matsushima, Japan, July 5-8, 2004.