New Materials for Spintronics

Scott A. Chambers and Young K. Yoo,
Guest Editors

Abstract

This article introduces the October 2003 issue of *MRS Bulletin* on "New Materials for Spintronics." As a result of quantum mechanics, the carriers in ferromagnetic metals such as Fe, Co, and Ni are spin-polarized due to an imbalance at the Fermi level in the number of spin-up and spin-down electrons. A carrier maintains its spin polarization as long as it does not encounter a magnetic impurity or interact with the host lattice by means of spin-orbit coupling. The discovery of optically induced, long-lived quantum coherent spin states in semiconductors has created a range of possibilities for a new class of devices that utilize spin. This discovery also points to the need for a wider range of spin-polarized materials that will be required for different device configurations. In this issue of *MRS Bulletin*, we focus on three classes of candidate spintronic materials and review the current state of our understanding of them: III–V and II–VI semiconductors, oxides, and Heusler alloys. The field of spin-polarized materials is growing very rapidly, and the search for new magnetic semiconductors and other suitable spin-injection materials with higher Curie temperatures is bringing spintronics closer to the realm of being practical.

Keywords: *ferromagnetic semiconductors, spin-polarized transport, spintronics.*

As a result of quantum mechanics, the carriers in ferromagnetic metals such as Fe, Co, and Ni are spin-polarized due to an imbalance at the Fermi level in the number of spin-up and spin-down electrons. An extreme limit of this spin imbalance is half-metallicity, which occurs when one of the spin bands is partially occupied at the Fermi level and the other spin band is either completely full or completely empty, and at an energy different from that of the Fermi level. In this case, conduction comes from carriers of one spin only.

A carrier maintains its spin polarization as long as it does not encounter a magnetic impurity or interact with the host lattice by means of spin-orbit coupling. It became clear to researchers early on that spin-polarized currents can be preserved and utilized for various device applications. Giant magnetoresistance (GMR) was discovered in thin-film structures consisting of alternating ferromagnetic and nonmagnetic metals; alignment of the ferromagnetic layers governs the scattering of spins and, consequently, the resistance of the layered structure. GMR devices quickly found large-scale commercial application as magnetic-field sensors in the read heads of magnetic recording disks. Spin-dependent tunneling, in which an insulating layer is sandwiched between two thin ferromagnetic metal films, is slowly moving toward industrial application in magnetic random-access memory (MRAM). So far, the application of spin-polarized materials has been limited primarily to ferromagnetic metals as contact electrodes in switching devices.

The discovery of optically induced, long-lived quantum coherent spin states in semiconductors has created a range of possibilities for a new class of devices that utilize spin.[1] This discovery also points to the need for a wider range of spin-polarized materials that will be required for different device configurations. The nascent field of spintronics is still in its infancy, and at the time of this writing, it is not clear what kind of device configurations will eventually be viable. It is also debatable if we will come to the point of fully utilizing both the spin and charge degrees of freedom, enabling qubit operation, as is required for quantum computing. A qubit (quantum bit) is the fundamental particle of spin-based computing. Its quantum mechanical spin state is what carries information in this new paradigm. An electron, hole, or nucleus could in principle be a qubit. The essential criterion is that the qubit maintain a well-defined spin state long enough to permit a digital operation to be carried out.

One of the major technical barriers that must be overcome to realize the practical implementation of semiconductor-based spintronic devices is the development of suitable spin-polarized materials that will effectively allow spin-polarized carriers to be injected, transported, and manipulated in semiconductor heterostructures. Also, the availability of such materials will facilitate a wider range of device configurations.

In this issue of *MRS Bulletin*, we focus on three classes of candidate spintronic materials and review the current state of our understanding: III–V and II–VI semiconductors, Heusler alloys, and various ferromagnetic oxides.

In the late 1980s, researchers at IBM succeeded in the nonequilibrium growth of a new class of diluted (doped from a few to several atomic percent) magnetic semiconductors (DMSs) based on III–V semiconductors.[2,3] This discovery paved the way for spin-injection experiments from ferromagnetic injector layers into traditional semiconductors.[4,5] Since then, other kinds of candidate materials have been investigated, including Heusler alloys and half-metallic ferromagnetic oxides.

Heusler alloys constitute a unique class of cubic materials consisting of four interpenetrating fcc sublattices. They have the general formula X_2YZ, where X and Y are transition elements, and Z is a Group III, IV, or V element.

The prediction of room-temperature ferromagnetism in Mn-doped ZnO and GaN by Dietl and co-workers in 2000,[6] along with the discovery in 2001 of ferromagnetism above room temperature in Co-doped TiO_2 anatase by Koinuma et al.,[7] triggered a worldwide search for new DMS materials among the oxides and nitrides. As this field grows, so do the ensuing debates about the origin of the observed ferromagnetic properties in these materials. Much of the discourse has been precipitated by inadequate materials characterization. Since magnetic ions typically exhibit low solubilities in their respective host semiconductors, the issues of structure, composition, and secondary-phase formation must be carefully addressed. Also, measuring spin polarization in these materials and the associated devices has not been straightforward. Spin polarization has been probed by various techniques, including transport, optical spectroscopy, and tunneling behavior (see the article in this issue by Coey and Chien). However, poor

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material quality and defects at surfaces and interfaces can cause spin-flip events of significant proportion. Spin-flip scattering randomizes the spin orientation of the carriers and reduces spin polarization in the material. Despite these difficulties, progress is being made in the detection of spin polarization.

In the first article, Dietl and Ohno review compound III–V and II–VI diluted magnetic semiconductors. The major difficulty in making III–V or II–VI semiconductors ferromagnetic is the low solubility limits for magnetic impurities such as Mn or Cr. However, when the compound is grown at low temperature by molecular-beam epitaxy (MBE), there is a narrow processing window in which single-crystal solid solutions can be grown while avoiding secondary-phase formation. In this article, challenges in the nonequilibrium growth of diluted magnetic III–V and II–VI semiconductors and progress in understanding ferromagnetism in these systems are described.

In the second article, Coey and Chien discuss progress in the area of half-metallic ferromagnetic oxides. These oxides with itinerant (i.e., unbound and available for delocalized conduction) electrons (such as CrO_2 and Sr_2FeMoO_6) or localized electrons (such as Fe_3O_4), are attractive as candidates for room-temperature spin injection. However, the structure of the interface between the oxide and the material into which spins are to be injected is critical; the terminal layer of the ferromagnetic oxide tends to be magnetically disordered. In this article, a broad classification scheme for half-metals, including oxides, is discussed. The surface topology and magnetic structure of oxides is presented, along with the implications for spin-injection efficiency into other materials.

In the article by Palmstrøm, Heusler alloys (X_2YZ) and half Heusler alloys (XYZ) are examined in light of their half-metallicity and possible spintronic applications. To date, accurately probing half-metallicity has been a formidable challenge, and the study of Heusler/III–V heterostructures has just begun. For spintronic applications, minimizing interfacial reactions and controlling the growth of Heusler alloys are the initial critical challenges. In this article, the structural, magnetic, and transport properties of systems incorporating Heusler alloys are examined.

In the following article, Chambers and Farrow continue the discussion of recent developments in ferromagnetic oxides. A few of the nontraditional magnetic semiconductors discovered by combinatorial synthesis and first-principles calculations have proven to be among the most strongly magnetic and thermally robust of all known DMS materials. Of these, Co-doped TiO_2 anatase has proven to have the strongest magnetization and highest Curie temperature. In this article, recent progress in the MBE growth of this potentially important material and other promising ferromagnetic oxides is discussed.

In the article by Matsumoto et al., the high-throughput investigation of semiconducting oxides doped with a variety of magnetic ions is discussed. Initial studies applied a combinatorial synthesis approach, doping TiO_2 and ZnO with various magnetic metals. Using this approach, Co-doped TiO_2 anatase was found to exhibit room-temperature ferromagnetism and to be optically transparent. Following this lead, several combinatorial synthesis programs aimed at discovering new magnetic semiconductors have been initiated.

In the final article, Jonker et al. turn the focus toward devices, discussing the use of Schottky tunnel barriers to enhance spin-injection efficiency. The Schottky barrier is an electrostatic barrier that typically forms at the interface between a metal and a semiconductor as a result of defect formation. If sufficiently large, the Schottky barrier can act as a tunnel barrier, which in turn reduces the effect of the difference in electrochemical potential between the metal and the semiconductor on spin-polarized transport across the interface. The use of a Schottky barrier as a tunnel barrier for spin injection from Fe into AlGaAs has been explored and shown to be robust, exhibiting a 30% spin-injection efficiency at room temperature. This experimental result is consistent with theoretical predictions, which indeed show that tunnel barriers can effectively mediate the disparate electrochemical potentials of ferromagnetic metals and semiconductors, thereby improving the spin-injection efficiency. The article also gives a glimpse of interface issues to be addressed when spin-polarized materials are applied to devices.

The field of spin-polarized materials is growing very rapidly, and the search for new magnetic semiconductors and other suitable spin-injection materials with higher Curie temperatures is bringing spintronics closer to the realm of the practical.

References

1. J.M. Kikkawa and D.D. Awschalom, *Nature* **397** (1999) p. 139.
2. H. Munekata, H. Ohno, S. von Molnar, A. Segmuller, L.L. Chang, and L. Esaki, *Phys. Rev. Lett.* **63** (1989) p. 1849.
3. H. Ohno, H. Munekata, S. von Molnar, and L.L. Chang, *J. Appl. Phys.* **69** (1991) p. 6103.
4. R. Fiederling, M. Keim, G. Reuscher, W. Ossau, G. Schmidt, A. Waag, and L.W. Molenkamp, *Nature* **402** (1999) p. 787.
5. Y. Ohno, D.K. Young, B. Beschoten, F. Matsukura, H. Ohno, and D.D. Awschalom, *Nature* **402** (1999) p. 790.
6. T. Dietl, H. Ohno, F. Matsukura, J. Cibert, and D. Ferrand, *Science* **287** (2000) p. 1019.
7. Y. Matsumoto, M. Murakami, T. Shono, T. Hasegawa, T. Fukumura, M. Kawasaki, P. Ahmet, T. Chikyow, S.-Y. Koshihara, and H. Koinuma, *Science* **291** (2001) p. 854. □

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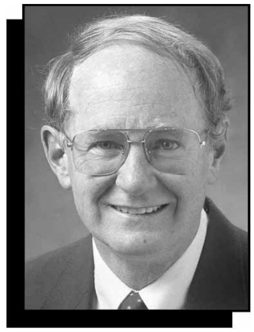

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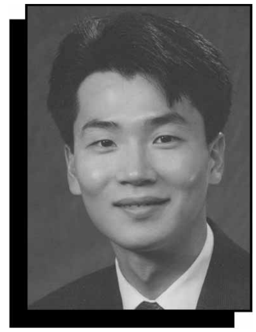

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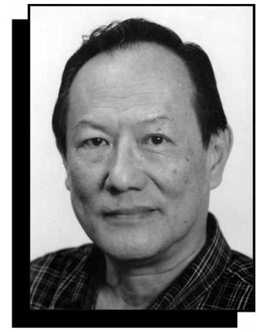

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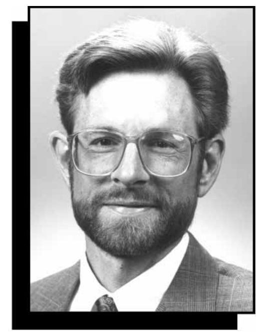

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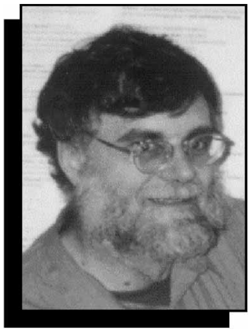

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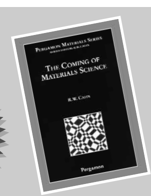

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