Scanning the Issue

Special Issue on Spintronics

Conventional electronics are based on the charge of the electron. Attempts to use an electron's other fundamental property, spin, gave rise to a new, rapidly evolving field, known as spintronics. Spintronics is an acronym for spin transport electronics and was first introduced in 1994 as a name for the Defense Advanced Research Projects Agency (DARPA) program by the editors of this Special Issue. The initial Spintronics program involved the overseeing of the development of advanced magnetic memory and sensors based on spin transport electronics. Now the original program has expanded to include Spins IN Semiconductors (SPINS), hoping 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.

This Special Issue on Spintronics supplements a few recently published books [1]–[3], reviews [4]–[6], and studies [7]. Leading researchers from academia and industry contributed papers in this issue reviewing the state of technology, theoretical, and experimental research, and providing insights into the emergence of the new concepts, devices, and applications. The beginning of spintronics was the discovery of the giant magnetoresistive effect (GMR) in 1988, when two research groups performed magnetoresistivity studies [8], [9] of heterostructures composed of alternating thin (10–100 Å) metallic layers of magnetic and nonmagnetic metals in the presence of high magnetic fields (2 T) at low temperatures (4.2 K). They saw resistance changes up to 50% between the resistivities at zero field and in the saturated state. At room temperature, the GMR effect was smaller, but still significant. The GMR effect is measured as the change in resistivity divided by the resistivity at large fields. GMR is observed when the current is in the plane of the layers (CIP) and perpendicular to the plane of the layers (CPP). GMR is attributed to spin-dependent scattering at the interfaces and spin-dependent conductivity.

At the beginning, spintronics was primarily aimed at exploiting all-metal passive devices using GMR [10], [11], such as magnetoresistive random access memory (MRAM), sensors, isolators, switches, etc. Today, these products are commercially available or very close to being commercially offered.

A. Paper Descriptions

The issue starts with the review article, "Overview of Spin Transport Electronics in Metals," by M. Johnson from the Naval Research Laboratory. The paper introduces the reader to the basic principles of spin-polarized transport and spin transport electronics in metals. Dr. Johnson is very well known in the condensed matter community for his groundbreaking research in electrical spin injection and detection in metals and semiconductors. His original spin injection experiment in 1985 was the first empirical demonstration of the penetration of spin-polarized currents into a nonmagnetic material, the first demonstration of resistance modulation in a ferromagnet/nonmagnetic metal/ferromagnet structure, and the first direct measurement of electron spin diffusion lengths. In 1993, he developed a lithographically patterned thin-film device that became known as a "spin transistor." Using this device, he was among the first to suggest integrated digital electronic applications for device structures that incorporate a ferromagnetic element.

IBM was the first company to use the GMR effect in read head sensors in 1994 [12], which led to the introduction of high-density hard drives with areal density 2.69 $\mathrm{Gb/in}^2$ in 1998. Commercially available areal density currently is 40 $\mathrm{Gb/in}^2$, and 110 $\mathrm{Gb/in}^2$ is under investigation. GMR read heads are composed of "spin valves," namely, metallic sandwiches of at least two ultrathin ferromagnetic layers separated by a very thin nonmagnetic spacer layer. The resistance of such a sandwich depends on the orientation of the magnetic moments of the ferromagnetic layers and is typically about 10%–20% higher when the moments are antiparallel than when the moments are aligned parallel.

The next paper is "Magnetically Engineered Spintronic Sensors and Memory," by Parkin *et al.* This review article by Dr. Parkin, who is the magnetoelectronics team leader at IBM's Almaden Research Center and an IBM Fellow, addresses recent advances made in IBM in magnetic recording read heads based on GMR and magnetic tunneling. Parkin's work on magnetic multilayers led him to the discovery of the oscillatory exchange coupling [13] phenomena critical to the development of the data-reading element in all of IBM's magnetic high-density hard-disk drives. For the past ten years, Dr. Parkin has explored magnetic nanostructured magnetic thin-film materials, especially giant magnetoresistance (GMR) and more recently magnetic tunnel junctions

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(MTJ) and the magnetic tunneling transistor (MTT). Dr. Parkin was recently elected to the Royal Society.

The review article “Spin Dependent Sensors” was written by J. Daughton, the founder of NVE Corporation, which was one of the first companies to offer low-cost devices based on GMR. In 1994, NVE introduced the world’s first spintronic sensors for factory automation and automotive markets [14]. These sensors outperform competing devices in precision and miniaturization. In 2001, NVE announced the world’s first spintronic data couplers (also called “isolators” because they transmit data while maintaining electrical isolation), which are five times faster and much smaller than conventional devices. Dr. Daughton previously worked at IBM in Yorktown Heights, NY, and Burlington, VT, on magnetic and semiconductor memories, and was a Vice President at Honeywell managing R&D of solid-state devices. He has 20 issued U.S. patents and over 60 published papers on magnetic memory and sensors. He is a Life Fellow of the IEEE.

Reliable nonvolatile memories, able to save information when powered down and to withstand extreme temperatures and radiation-hard environments, are needed for some defense and aerospace applications. GMR-based MRAM uses magnetic hysteresis to store data and magnetoresistance to read data. Nonvolatile memory cells are integrated on a semiconductor chip and function as a static semiconductor RAM chip. Potential advantages of the MRAM compared with silicon Electrically Erasable Programmable Read-Only Memory (EEPROM) and Flash memory are: 1) 1000 times faster write times, no wearout with write cycling (EEPROM and Flash memories wear out with about one million write cycles) and 2) lower energy for writing. MRAM data access times are about 1/10 000 that of hard disk drives. MRAM is not yet available commercially, but production of at least 4-Mb MRAM is anticipated in two to three years. According to Pathfinder Research, “…the size of the [MRAM] market opportunity—$40 billion by 2005… if the technology shapes up right… it will replace DRAM.” [15]

In this issue, we have two papers from leading research teams working on two different approaches to the commercial realization of GMR-based MRAMs. The first is “Giant Magneto-Resistive Random-Access Memories Based on Current-in-Plane Devices,” by R. R. Katti, of Honeywell International, Inc. This paper describes nonvolatile random access memory (GMRAMs) based on spin-valve and pseudo-spin-valve devices, consisting of metallic magnetic and nonmagnetic multilayers where current flows primarily in the plane of the layer. Dr. Katti currently leads the GMRAM devices group at the Solid State Electronics Center. He has more than 20 technical publications and ten patents.

In the next paper, “Magnetoresistive Random Access Memory Using Magnetic Tunnel Junctions,” by Tehrani *et al.*, a team of authors from Motorola discusses MRAM based on magnetic tunneling junctions. Motorola’s MRAM research program started in 1995 and received a five-year funding contract from DARPA in 1996. In 2001, the effort expanded significantly as the company’s Semiconductor Products Sector began a development program, and in 2002, Motorola demonstrated the first 1-Mb MRAM circuit. The combined research and development team has accumulated over 70 MRAM-related patents and numerous technical publications during this period. The authors represent an interdisciplinary group of experts in memories, magnetic devices and materials, semiconductor processing, and testing.

In recent years, spintronics shifted its focus toward the development of active devices. To utilize spin in semiconductor devices, one needs to be able to polarize, inject, transport, manipulate, store, and detect spins. Studies of spin-polarized transport in bulk and low-dimensional semiconductor structures show promise of someday creating a gain device such as the spin analog of a field effect transistor, a light-emitting diode, a resonant tunneling diode, etc. So far, a serious obstacle has prevented the development of practical devices. The conductivity of ferromagnetic metals (electrodes) is significantly higher than in the semiconductors. As a result, only a small fraction of spin-aligned mobile electrons can get into the semiconductor. For the efficient transfer of spin-aligned carriers, the contacts must be semiconducting. The early diluted magnetic semiconductors (DMS)—alloys in which some atoms were randomly replaced by magnetic atoms—had to be cooled significantly below 60 K to exhibit ferromagnetic behavior. The discovery of the ferromagnetic behavior of GaMnAs at 130 K in 1998 [16] and above-room-temperature ferromagnetism in $\mathrm{TiCoO_2}$ in 2000 [17] stimulated the search for new materials. The progress in new materials engineering is enabled by developments in fabrication and characterization instrumentation. The use of molecular beam epitaxy (MBE) allows one to grow materials and heterostructures with magnetic and semiconducting properties at the same time, by introducing a significant concentration of magnetic ions into nonmagnetic semiconductors.

The status of materials research is addressed in the review article “New Materials for Semiconductor Spin-Electronics” by von Molnár and Read. Professor von Molnár is the director of the Center for Materials Research and Technology (MARTECH) at Florida State University. He is an experimental condensed matter physicist whose lifelong interest has been the study of correlation effects in electronic systems. His expertise includes transport and magnetotransport properties of magnetic semiconductors, the thermal properties (specific heat) of amorphous and crystalline solids, and magnetism at the nanoscale. His accomplishments include the conceptual development and experimental observation of magnetic polarons and the demonstration of the magnetically driven insulator-metal transition. Dr. Read is working at MARTECH developing submicrometer to nanoscale devices for measurements related to spintronic transport effects.

In the next paper, B. Jonker from NRL focused on “Progress Toward Electrical Injection of Spin-Polarized Electrons into Semiconductors,” describing a number of semiconductor-based spintronic device concepts. Dr. Jonker is an expert in the MBE growth and fabrication of hybrid magnetic/semiconductor heterostructures and in the optical characterization of electrical spin injection. His research has addressed low-dimensional magnetism in metals, spin-dependent carrier localization in semiconductor superlattices, electrical spin injection and transport in semiconductor heterostructures, and the fabrication of prototype magnetoelectronic devices. In addition to spin injection, his recent work addresses the MBE growth and study of ferromagnetic semiconductors, a new class of materials combining both ferromagnetic and semiconducting properties with the potential for new device functionality. Dr. Jonker has authored 148 scientific publications, presented over 60 invited talks, holds five U.S. patents, and is a Fellow of the AVS Science & Technology Society.

Recent theoretical research had shown that the possible solution to electrical spin injection is a tunneling contact [18], [19]. It was also shown that in principle one can use multilayered semiconductor systems to generate, control, and detect the electron spin polarization by exploiting the spin-orbit interaction. This all-semiconductor approach has the advantage of being compatible with conventional semiconductor technology [20]. In the next paper, "Rashba Effect Resonant Tunneling Spin Filters," by Ting *et al.*, an impressive team of researchers discuss in detail the basic principle of an asymmetric resonant interband tunneling diode (a-RITD) as a spin filter and propose an implementation procedure for realizing device structure. The device exploits the Rashba effect to achieve spin polarization under zero magnetic field.

A review paper, "Optical and Electronic Manipulation of Spin Coherence in Semiconductors" by Sih *et al.*, addresses experimental optical studies of electron spin states in semiconductors, heterostructures, and quantum dots. Control over spins in the solid state forms the basis for nascent spintronics and quantum information technologies. There is a growing interest in the use of electronic and nuclear spins in semiconductor heterostructures as a medium for the manipulation and storage of both classical and quantum information. Coauthor D. D. Awschalom is the Director of the UCSB Center for Spintronics and Quantum Computation, and conducts active research 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. V. Sih and E. Johnston-Halperin are graduate researchers deeply involved with developing a variety of femtosecond-resolved spatiotemporal spectroscopies and micromagnetic sensing techniques aimed at exploring charge and spin motion in the quantum domain. This research has been presented in over 200 scientific publications and has appeared on the covers of *Nature*, *Science*, *Physics Today*, *IEEE Spectrum*, and *Scientific American*.

In "Opto-Electronic Quantum Telecommunications Based on Spins in Semiconductors," Yablonovitch *et al.*, from the University of California at Los Angeles, review the experimental status of a semiconductor-based quantum repeater, a new type of telecommunication device for quantum information transmission over long distances. This paper includes the development of spin resonance transistor logic gates, and the experimental detection of single photons in a manner that preserves their spin information. The transmission of the quantum information over long distances will allow new forms of data security based on quantum cryptography.

The study of magnetodynamics of low-dimensional magnetic structures requires nanometer-length scale spatial resolution, sensitivity to detect very small total magnetic moments, and time resolution on scales of the processes. The paper on "Ultrafast Magnetization Imaging," written by Choi *et al.*, provides a detailed description of an experimental method for imaging nonequilibrium magnetic phenomena in the picosecond temporal regime and with submicrometer spatial resolution. This method, applying ultrafast techniques to magnetooptical imaging, yields a powerful tool for the study of fundamental magnetic phenomena. From a practical point of view, understanding magnetization dynamics has become crucial both to the continued evolution of conventional magnetic data storage and for the demands of newer approaches such as MRAM. Dr. Choi is an assistant professor of physics at the University of Victoria, A. Krichevksy is a graduate student in physics at the University of Alberta, and M. Freeman is an iCORE Professor of Physics and Canada Research Chair in Condensed Matter Physics at the University of Alberta. Their group pursues the development and application of a variety of ultrafast microscopies, and has authored two patents and over 50 publications related to the article in this issue.

In "The Magnetic Resonance Force Microscope: A New Tool for High Resolution 3-D Subsurface Scanned Probe Imaging," Hammel *et al.* describe the principles, status, and some recent applications of the magnetic resonance force microscope (MRFM), a scanned probe microscope based on sensitive scanned probe detection of magnetic resonance. Magnetic resonance force microscopy uses a bulk probe capable of probing deeply buried material; by using techniques of magnetic resonance imaging, the MRFM can nondestructively study controllably defined regions buried deeply beneath the surface of the material under study. This highly flexible microscope is well suited to the study of spintronic devices because of the broad range of materials to which it can be applied—only nuclear spins or electronic moments (either in a paramagnet or in an ordered ferromagnet) are required for it to be applicable—and because of the importance of selective subsurface studies for layered multicomponent devices. P. C. Hammel is Professor of Physics and an Ohio Eminent Scholar, D. Pelekhov a Research Professor and P. Wigen a Professor Emeritus at the Ohio State University; T. Gosnell is a Physicist at Pixon LLC and a Staff Member at Los Alamos National Laboratory; M. Midzor completed her Ph.D. degree at Caltech where M. Roukes is a Professor of Physics, Applied Physics, and Bioengineering.

One of the central themes of this Special Issue is that engineers and scientists are now entering into a golden age of quantum measurement theory and experiment. Today's "informatic" technologies are required to operate at maximum speed, and achieve maximum sensitivity, while consuming minimal power. As the engineering community presses against the quantum limits to speed, sensitivity, and power, they are scrutinizing the physics literature for practical guidance on how to approach these limits. The resulting cross-disciplinary fertilization is good for both physicists and engineers. As two-time Nobel Prize winner J. Bardeen put it: "[Most advances] are made in response to a need, so that it is necessary to have some sort of practical goal in mind while the basic research is being done; otherwise it may be of little value" [21]. In their contribution "The Classical and Quantum Theory of Thermal Magnetic Noise," an interdisciplinary team of physicists (authors Sidles and Dougherty) and engineers (authors Garbini and Chao) has combined fundamental physics with solid engineering sensibility. The result is a set of simple, reliable design rules that predict magnetic noise levels for a broad range of spintronic devices. This magnetic noise plays the same fundamental role in spintronic devices that Johnson noise plays in electronic devices—the spintronic community can expect to see broad application of these design rules in coming decades. Professors Sidles and Garbini proudly call themselves "quantum system engineers," and they head the Magnetic Resonance Force Microscopy Laboratory at the University of Washington. Dr. Chao and Dr. Dougherty are also members of this laboratory, where they focus respectively on advanced imaging technologies and overall system integration issues.

Discoveries in theoretical understanding of spin interactions in solid state, developments in materials science, and actual device fabrication are necessary to harness the spin degree of freedom in semiconductors. Interdisciplinary efforts including physics, chemistry, biology, electrical engineering, computer science, and mathematics have a great impact on advances in spintronics as a technology of the future.

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STUART A. WOLF, *Guest Editor*
DARPA/DSO
Arlington, VA 22203-1714 USA

DARYL M. TREGER, *Guest Editor*
Strategic Analysis, Inc.
Arlington, VA 22201 USA

REFERENCES

[1] M. Ziese and M. Thornton, Eds., *Spin Electronics*. New York: Springer-Verlag, 2001.
[2] D. Awshalom, D. Loss, and N. Samarth, Eds., *Semiconductor Spintronics and Quantum Computation*. New York: Springer-Verlag, 2002.
[3] A. Chtchelkanova, S. Wolf, and I. Idzerda, Eds., *Magnetic Interactions and Spin Transport*. Norwell, MA: Kluwer, 2002.
[4] S. Wolf, D. Awschalom, R. Buhrman, J. Daughton, S. von Molnár, M. Roukes, A. Chtchelkanova, and D. Treger, "Spintronics: a spin-based electronics vision for the future," *Science*, vol. 294, pp. 1488–1495, 2001.
[5] H. Ohno, F. Matsukura, and Y. Ohno, "Semiconductor spin electronics," *JSAP Int.*, vol. 5, pp. 4–13, 2002.
[6] S. Wolf, A. Chtchelkanova, and D. Treger, *Handbook of Nanoscience, Engineering, and Technology*, W. Goddard, III, D. Brenner, S. Lyshevski, and G. Iafrate, Eds. Boca Raton, FL: CRC, 2002, ch. 8.
[7] WTEC Study on Spintronics.
[8] M. Baibich, J. Broto, A. Fert, F. Nguyen Van Dau, and F. Petroff, "Giant magnetoresistance of (001)Fe/(001)Cr magnetic superlattices," *Phys. Rev. Lett.*, vol. 61, pp. 2472–2475, 1988.
[9] J. Barnas, A. Fuss, R. Camley, P. Gruenberg, and W. Zinn, "Novel magnetoresistance effect in layered magnetic structures: theory and experiment," *Phys. Rev. B, Condens. Matter*, vol. 42, pp. 8110–8120, 1990.
[10] G. Prinz, "Magnetoelectronics," *Science*, vol. 282, pp. 1660–1663, 1998.
[11] ——, "Magnetoelectronics applications," *J. Magn. Magn. Mater.*, vol. 200, pp. 57–68, 1999.
[12] C. Tsang *et al.*, "Design, fabrication and testing of spin-valve read heads for high density recording," *IEEE Trans. Magn.*, vol. 30, pp. 3801–3806, Nov. 1994.
[13] S. S. P. Parkin, N. More, and K. Roche, "Oscillations in exchange coupling and magnetoresistance in metallic superlattice structures: Co/Ru, Co/Cr, and Fe/Cr," *Phys. Rev. Lett.*, vol. 64, pp. 2304–2307, 1990.
[14] J. Daughton, J. Brown, E. Chen, R. Beech, A. Pohm, and W. Kude, "Magnetic field sensors using GMR multiplayer," *IEEE Trans. Magn.*, vol. 30, pp. 4608–4610, Nov. 1994.
[15] J. Vijayan. The next step in RAM tech. *Computerworld* [Online] Available: http://apps.computerworld.com/industrytopics/manufacturing/story/0,10801,55915,00.html
[16] H. Ohno, "Making nonmagnetic semiconductor ferromagnetic," *Science*, vol. 281, pp. 951–956, 1998.
[17] Y. Matsumoto *et al.*, "Room-temperature ferromagnetism in transparent transition metal-doped titanium dioxide," *Science*, vol. 291, pp. 854–856, 2001.
[18] E. A. de Andrada e Silva and G. C. La Rocca, "Electron spin polarization by resonant tunneling," *Phys. Rev. B*, vol. 59, pp. R15583–R15585, 1999.
[19] E. I. Rashba, "Theory of electrical spin injection: tunnel contacts as a solution of the conductivity mismatch problem," *Phys. Rev. B*, vol. 62, pp. R16267–R16270, 2000.
[20] O. Voskoboinikov, C. P. Lee, S. S. Lin, and O. Tretyak, "Spin-polarized electronic current in resonant tunneling heterostructures," *J. Appl. Phys.*, vol. 87, pp. 387–391, 2000.
[21] L. Hoddeson and V. Daitch, *True Genius: The Life and Science of John Bardeen*. Washington, DC: Joseph Henry Press, 2002, p. 245.

Stuart A. Wolf received the A.B. degree from Columbia College, New York, in 1964, and the M.S. and Ph.D. degrees from Rutgers University, New Brunswick, NJ, in 1966 and 1969, respectively.

He is currently a Research Professor at the University of Virginia, Arlington, and a consultant in the Defense Sciences Office at the Defense Advanced Research Projects Agency (DARPA), Arlington, VA. He is a former Program Manager at DARPA, and a former Senior Scientist at the Naval Research Laboratory (NRL). 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 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) Quantum Information Science and Technology (QuIST), which aims to develop communication and computing systems and architectures based on the principles of quantum coherence and entanglement; and 3) Molecular Observation, Spectroscopy And Imaging using Cantilevers (MOSAIC), which has the goal of 3-D imaging of molecules and nanostructures with atomic scale resolution. Dr. Wolf coined the term Spintronics in 1996. He was a Research Associate at Case Western Reserve University (1970–1973) and a Visiting Scholar at the University of California at Los Angeles (1981–1982). He has authored or coauthored two books, over 300 articles, and has edited numerous conference proceedings. He was a Divisional Councilor for the Condensed Matter Division (1990–1991) and is currently the Divisional Councilor for the Forum on Industrial and Applied Physics.

Dr. Wolf is a Fellow of the APS

Daryl M. Treger received the B.S. degree in chemical engineering from the University of Buffalo, Buffalo, NY, in 1979.

He is currently a Program Manager at Strategic Analysis, Inc., Farmington Hills, MI. He provides technical and administrative assistance to the Defense Advanced Research Projects Agency (DARPA) through Scientific, Engineering and Technical Assistance (SETA) Support. He has worked extensively on the DARPA Spintronics, Spins IN Semiconductors (SPINS), Quantum Information Science and Technology (QuIST), and Molecular Observation, Spectroscopy And Imaging using Cantilevers (MOSAIC) programs.