Spintronics— A retrospective and perspective

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Spintronics is a rapidly emerging field of science and technology that will most likely have a significant impact on the future of all aspects of electronics as we continue to move into the 21st century. Conventional electronics are based on the charge of the electron. Attempts to use the other fundamental property of an electron, its spin, have given rise to a new, rapidly evolving field, known as ***spintronics****, an acronym for spin transport electronics that was first introduced in 1996 to designate a program of the U.S. Defense Advanced Research Projects Agency (DARPA). Initially, the spintronics program involved overseeing the development of advanced magnetic memory and sensors based on spin transport electronics. It was then expanded to included Spins IN Semiconductors (SPINS), in the hope of developing a new paradigm in semiconductor electronics based on the spin degree of freedom of the electron. Studies of spin-polarized transport in bulk and low-dimensional semiconductor structures show promise for the creation of a hybrid device that would combine magnetic storage with gain—in effect, a spin memory transistor. This paper reviews some of the major developments in this field and provides a perspective of what we think will be the future of this exciting field. It is not meant to be a comprehensive review of the whole field but reflects a bias on the part of the authors toward areas that they believe will lead to significant future technologies.*

Introduction

Magnetic materials and magnetic devices have occupied a major place in science and technology for most of the twentieth century and played a very important role in the emergence of the digital computer by providing both ferrite core and plated wire memories. It was not until the early 1980s that thin-film magnetism was applied to higher-density nonvolatile random access memory (by Honeywell in their development of anisotropic magnetoresistive (AMR) memory [1–3]). A new path leading to the integration of magnetic devices into computer technology began to emerge with the discovery of giant magnetoresistance (GMR) in the late 1980s by Fert's group [4] and Grunberg's group [5] in MBE-grown epitaxial Fe/Co multilayers at low temperatures and high magnetic fields, as well as work by Parkin et al. [6] on sputtered polycrystalline multilayers. Although it was known for quite some time that the current from a magnetic metal is spin-polarized and that current transport through adjacent magnetic layers depends on the spin-polarization of those layers, neither the magnitude of the current nor the temperature at which it was observed were of technological significance. However, it was the discoveries by Parkin of GMR in Co/Cu multilayers at room temperature and low magnetic fields [7], oscillatory interlayer coupling through Cu and other nonmagnetic noble and transition metals [6–8], and interface engineering to create large GMR values in very small fields [9] that made spintronics a technological reality.

Discoveries in this new field were quite rapid, and the path toward a new technology started to appear quite early. The first significant GMR device was the spin valve [10], illustrated in **Figure 1**, a simple trilayer sandwich structure. A "soft" ferromagnetic layer responds to a magnetic field, while a "pinned" ferromagnetic layer does not. A thin conductor layer (normally copper) is sandwiched between the two ferromagnetic layers. When

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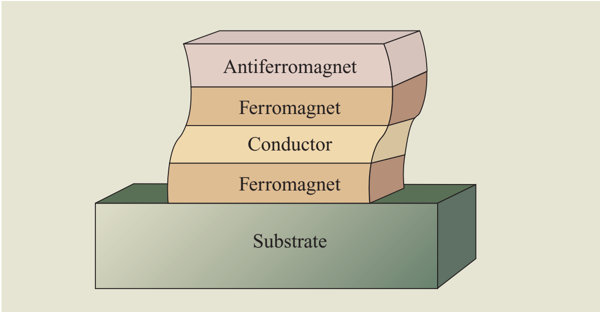

Figure 1

GMR structure. Adapted from [11], with permission; ©2003 IEEE.

the magnetizations in the two ferromagnetic layers are parallel, conduction electrons pass between them more freely than when the magnetizations are anti-parallel, and thus the resistance is lower in the parallel magnetization case than in the anti-parallel case. Pinning is usually accomplished through coupling to an antiferromagnetic layer, as shown in the figure. This structure can be configured either as a magnetic field sensor or as a hysteretic memory device, depending on the magnetic anisotropy of the "soft" magnetic layer. In the early 1990s IBM started a project to develop such GMR devices into read-head sensors for magnetic disk drives, and in 1995 DARPA funded the GMR Consortium to explore the various potential applications that it believed would be important for both the Department of Defense (DOD) and commercial applications. The motivation of the DOD for DARPA's GMR Consortium included a strong aerospace and military need for a much better nonvolatile, radiation-based RAM—at the time, a 128-Kb portion weighed 40 lb! The funding for the consortium was provided by the Technology Reinvestment Project, or TRP, whose goal was the development of "dual-use technology," which was very much in vogue at the time. The consortium explored the potential for the use of GMR in magnetic memories as a successor to the AMR memory being developed by Honeywell. It also explored a host of novel magnetic sensors which focused on devices that were complementary to the sensors that were already being developed by IBM for read heads in their magnetic hard drives [12]. In fact, the early successes of the IBM developments gave us confidence in the future of a host of GMR applications. The GMR consortium encompassed efforts at Honeywell, the Naval Research Laboratory, HRL Laboratories, Federal Products, Inc, and Non-Volatile Electronics (NVE). As a result of the very favorable prospects that emerged from the efforts, DARPA initiated the Magnetic Materials and Devices Project, which was charted to develop magnetoresistive memory and sensors utilizing both GMR and spin-dependent tunneling (SDT) devices [13].

The largest effort in the Magnetic Materials and Devices Project focused on the development of a robust magnetic random access memory, or MRAM, which would exploit the natural radiation hardness of the magnetoresistive cell, with a secondary effort focusing on novel magnetic field sensors for DOD applications. IBM, Motorola, and Honeywell were the three major contractors that were selected to develop their own version of MRAM. Honeywell, which had a project to develop a version of MRAM based on the anisotropic magnetoresistance of single magnetic films, switched its efforts to GMR both as a consequence of its participation in the GMR consortium and as the basis for participation in the DARPA project. IBM chose to focus on a device, the magnetic tunnel junction, which was based on the spin-dependent tunneling (SDT) phenomena theoretically predicted by Slonczewski [14] of IBM and realized at room temperature independently by Moodera's group [15] and by Miyazaki and Tezuka [16]. Motorola decided to explore both GMR and SDT structures and chose the latter after the first phase of the project [17]. NVE was chosen to explore magnetic field sensors, and several smaller university-based projects were supported to explore other aspects of spin transport in magnetic heterostructures.

Since the project title "Magnetic Materials and Devices" did not reflect the efforts involved, one of us (SW) proposed that the project be renamed "Spintronics," which was an acronym for SPIN TRansport electrONICS; the name now describes this general area of research and development.

The first major product introduction involving GMR structures was the introduction by IBM of a magnetic disk drive that incorporated a GMR read head and revolutionized the magnetic disk drive industry by enabling the density of the drives to be increased at a much higher rate than was possible with previous technology. Magnetic disk drive products have had their areal density increased by a factor of 35 million since the introduction of the first disk drive, RAMAC, in 1957. Since 1991, the rate of increase has accelerated to 60% per year, and since 1997 it has accelerated further to an incredible 100% per year. The acceleration was the result of the introduction of MR read heads in 1991 and GMR read heads in 1997. Today nearly all disk drives in the industry incorporate the GMR read-head design [18].

The DARPA spintronics project continued until 2003, when it became clear that MRAM was a viable universal memory; see the Proceedings of the IEEE special issue on Spintronics [19]. Motorola spun off its semiconductor business into a company called Freescale, which has made

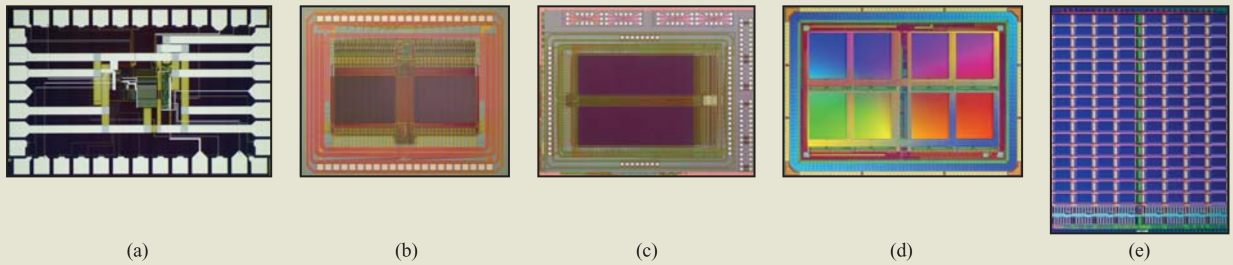

Figure 2

Photomicrographs (not to scale) showing the increasing density of prototype MRAM chips: (a) IBM 1-mm × 1.5-mm 1-Kb chip with a 5.4-μm^2 twin cell in 0.25-μm technology with approximately 3–10-ns access time. From [22], with permission; ©2000 IEEE. (b) Motorola 3.9-mm × 3.2-mm 256-Kb chip with 7.1-μm^2 cell in 0.6-μm technology with 35-ns access time. From [23], with permission; ©2001 IEEE. (c) Motorola 4.25-mm × 5.89-mm 1-Mb chip with 7.1-μm^2 cell in 0.6-μm technology with 50-ns access time. From [24], with permission; ©2002 IEEE. (d) Motorola 4.5-mm × 6.3-mm 4-Mb chip with 1.55-μm^2 cell in 180-nm technology with 25-ns access time. From [17], with permission; ©2003 IEEE. (e) IBM 7.9-mm × 10-mm 16-Mb chip with 1.42-μm^2 cell in 180-nm technology with 30-ns access time. Adapted from [21], with permission; ©2004 IEEE.

available to its preferred customers samples of a 4-Mb MRAM memory chip based on SDT devices and a very novel switching scheme (toggle switching [20]). IBM is developing a 16-Mb product "demonstrator" [21], although no plans have been announced for its commercialization. In addition, Freescale and Honeywell are developing a radiation-hard 1-Mb MRAM memory that is earmarked for several DOD applications. See **Figure 2** for photomicrographs, details, and references for several prototype MRAM chips fabricated roughly during the time frame of the DARPA program or shortly thereafter. Also, during the course of the Spintronics project, NVE developed several unique sensors, including an isolator for computer applications that outperforms in both performance and cost the optoelectronic isolators that it replaces [11].

As the spintronics project progressed, it became clear that there was significant interest in more general research into spin transport devices and possible technologies that might emerge. Several key discoveries were reported in the late 1990s. One of them was the discovery of ferromagnetism at a relatively high temperature (110 K) in GaMnAs containing only 5% of Mn [25]. Another was the discovery of a very long-lived magnetic spin state in photoexcited GaAs in which the spins behave coherently [26], and a third was the discovery of spin-momentum transfer in nanoscale GMR-type heterostructures [27]. It was clear that efforts should be made to explore these newly discovered materials to determine their potential as the basis for a new technology. Accordingly, DARPA initiated the SPins IN Semiconductors project (SPINS), which was focused on exploring the role of spin, spin transport, spin coherence, and spin dynamics in various materials, primarily but not exclusively in semiconductors. The project was initiated late in 1999 and extended through the end of 2004. There were three main thrusts in the project. The first was designated *spin quantum devices*; its purpose was to explore the benefits of adding the spin degree of freedom to mainstream semiconductor devices such as light-emitting diodes, transistors, and resonant tunneling diodes. The second thrust focused on optoelectronic devices based on the long-lived spin coherence observed in the work of Kikkawa and Awschalom [26]. The purpose of the last thrust, designated *quantum spin effects*, was to explore the possibility of using the spin degree of freedom as a quantum bit for quantum information processing. The latter was incorporated into a new DARPA project called *quantum information science and technology*, or QuIST, which is not described in this paper.[1] Underlying all of these thrusts was and still is the development and understanding of the behavior of the spin degree of freedom in various semiconductors, both ferromagnetic and non-ferromagnetic, and the vigorous pursuit of new ferromagnetic compounds that have Curie temperatures well above room temperature.

To add the spin degree of freedom to a device from which information is to be extracted, one must create a spin population, transport it across the device, and manipulate and detect it. Semiconductor or metal–semiconductor heterostructures have shown the promise of adding a spin degree of freedom to conventional electronics. In a spin light-emitting diode (spin-LED), the recombination of spin-polarized carriers results in

[1] To learn more about the DARPA QuIST program, see *http://www.darpa.mil/dso/thrust/math/quist.htm*.

Table 1 Curie temperatures for several new ferromagnetic semiconductor systems. All compounds except for $MnGeP_2$ are doped, carrier-mediated ferromagnets.

Material	*Curie temp.*	*Year*	*Ref.*
$GaMn_{0.05}As$	110 K	(1998)	[39]
	250 K	(2004)	[40]
$GaMn_{0.05}Sb$	25 K	(1999)	[41]
	80 K	(2003)	[42]
Mn_xGe	25–116 K	(2002)	[43]
Co_xTiO_2	600 K	(2001)	[44]
$GaMn_xN$	400 K	(2001)	[45]
$MnGeP_2$	340 K	(2001)	[46]
$Co_xSnO_{2-\delta}$	600 K	(2003)	[47]
$La_{0.5}Sr_{0.5}Ti_{0.985}Co_{0.015}O_3$	450 K	(2003)	[48]
Cr_xZnTe	>300 K	(2003)	[49]
$Zn_{0.978}Mn_{0.022}O$	~300 K	(2003)	[50]
$In_{1.7}Sn_{0.2}Mn_{0.1}O_{3-\delta}$	~300 K	(2004)	[51]
$Al_xGa_{1-x}Cr_yN$	800–900 K	(2002–2004)	[52, 53]

the emission of right (σ^-) or left (σ^+) circularly polarized light in the direction normal to the surface according to selection rules [28]. Polarization analysis of the resulting electroluminescence provides quantitative measurement of the spin injection efficiency. Two groups [29, 30], using a spin-LED to measure the electrical spin injection of electrons into a GaAs quantum well at low temperatures and with an external magnetic field, have respectively achieved a 90% and a 50% injection efficiency. Another group has electrically injected holes [31] into III–V heterostructures based on GaAs at $T < 52$ K. Injection into a nonmagnetic semiconductor was achieved at zero field using a p-type ferromagnetic semiconductor (Ga, Mn)As as the spin polarizer. It was measured that hole spins could be injected and transported across the interfaces for a distance of more than 200 nm, which confirmed that spin-polarized transport could survive the length of the semiconductor. Although there are no plans at this time to mass-produce spin-LEDs, they are very useful in the measurement of spin injection despite their low-temperature and high-magnetic-field requirements. If progress in new materials development brings to fruition an n-doped high-Curie-temperature ferromagnetic semiconductor, the possibility of a mass-produced spin-LED can be reconsidered.

The magnetic tunnel transistor (MTT) is a three-terminal metal–semiconductor hybrid device in which hot electrons are injected into a semiconductor. The electrons have enough energy to overcome the Schottky barrier at the metal–semiconductor interface provided there are available states in the semiconductor. The magnetic tunnel junction (MTJ) forms the emitter and base of a metal base transistor and Si or GaAs serves as a collector. Associated efforts at IBM using MTJs and MTTs for MRAM [12], led by Parkin, demonstrated a 3,500% change in MTT collector current [32, 33] and almost 100% spin polarization at room temperature. Recently an MTT was used as a source of hot-electron spin injection into a semiconductor and an LED was used for optical detection [34].

Another novel device concept for a memory cell and a readout head for magnetically stored information is a spintronic transistor based on the spin relaxation properties in a two-dimensional electron gas (2DEG) [35]. The device design would be very similar to that of the Datta and Das spin transistor [36], but it would function in the diffusive regime rather than in the ballistic regime. The switching action would be achieved through the biasing of a gate contact, which would control the lifetime of spins injected into the 2DEG from a ferromagnetic emitter, thus allowing the traveling spins to be either aligned with a ferromagnetic collector or randomized before collection.

An optically addressed coherent polarization switch, designated as a Stark spin switch, is based on the near-resonant excitation of a spin-polarized population of "virtual excitons" in unstrained multiple quantum wells, with a switching time of less than 2 ps. Such a switch has been demonstrated [37], found to exhibit a pulse-width-limited response, and found to be capable of producing relatively large contrast ratios in thin samples. The switching mechanisms were experimentally analyzed by systematically performing spectrally and temporally resolved differential transmission measurements and by fully determining the polarization state of the transmitted signal as a function of time delay; they were theoretically analyzed using a microscopic theory that included many-body effects [38].

Since the discovery in 1998 of the ferromagnetic semiconductor GaMnAs, considerable associated materials work has been conducted. For example, the Curie temperature of GaMnAs has been increased from 110 K to at least 173 K [39], and that of Mn delta-doped GaAs to about 250 K [40]. In addition, several new materials systems have been evaluated, with the Curie temperature of some reaching and exceeding room temperature, as indicated in **Table 1**. One of the key features of these materials is that most exhibit carrier-mediated ferromagnetism. The significance of this type of ferromagnetism is that it can be controlled by changing the carrier concentration by gating, whether optically or in other unusual ways. For example, researchers at the

Table 2 Projected performance of MRAM and SMT-MRAM, including the performance of conventional semiconductor memories; listings in color are technological shortcomings for the indicated type of memory device.

	Standard MRAM (90 nm)*	*DRAM* (90 nm)†	*SRAM* (90 nm)†	*SMT-MRAM* (90 nm)*	*FLASH* (90 nm)†	*FLASH* (32 nm)†	*SMT-MRAM* (32 nm)*
Cell size (μm^2)	0.25 256 Mb/cm	0.25 256 Mb/cm	**1–1.3** **64 Mb/cm**	0.12 512 Mb/cm	0.1 512 Mb/cm	0.02 2.5 Gb/cm	0.01 5 Gb/cm
Read time	10 ns	10 ns	1.1 ns	10 ns	10–50 ns	10–50 ns	1 ns
Program time	5–20 ns	10 ns	1.1 ns	10 ns	**0.1–100 ms**	**0.1–100 ms**	1 ns
Program energy per bit	120 pJ	**5 pJ** **Needs refresh**	5 pJ	0.4 pJ	**30–120 nJ**	**10 nJ**	0.02 pJ
Endurance	$>10^{15}$	$>10^{15}$	$>10^{15}$	$>10^{15}$	$>10^{15}$ read, **$>10^{6}$ write**	$>10^{15}$ read, **$>10^{6}$ write**	$>10^{15}$
Nonvolatility	yes	**no**	**no**	yes	yes	yes	yes

*MRAM performance values projected by the authors.
†Values from the International Technology Roadmap for Semiconductors (ITRS).

University of California at Santa Barbara (UCSB) have found that the magnetism of a digitally doped GaMnAs heterostructure can be dramatically affected by placing on the surface an organic monolayer which, in its ordered state, provides electrons that compensate for the hole-carriers, completely suppressing the ferromagnetism [54]. This ability to gate the magnetism by controlling carrier concentration presents a new paradigm for novel devices in which there can be concurrent control of carrier concentration and spin polarization. This may provide a pathway to novel spin-FETs.

Spintronics—A perspective

Looking forward to the future of spintronics is difficult because technology often moves in unforeseen directions. The research on semiconductor spintronics, which was a significant part of the DARPA-funded SPINS project, revealed a host of new phenomena that in many instances were novel and unexpected. For example, ferromagnetic imprinting and coherent spin transfer through molecular bridges at ambient temperature [55] may become significant, but the path is not at all clear.

However, with regard to the future of MRAM, there have been some significant developments which ensure that MRAM can be scaled to 60 nanometers and below. The most notable of these was the discovery of the spin-momentum-transfer effect (SMT), which was theoretically predicted in 1996 [56, 57] and was experimentally observed in 2000 [27].

Conventional MRAM utilizes current-generated magnetic fields to rotate the magnetization in the free layer. Although there have been advances in the switching methodology to make the switching robust to disturbances [17, 58] and the lower current required for rotation by magnetic cladding of the word lines and bit lines [59], SMT offers the potential of orders of magnitude lower switching currents and concomitantly much lower energy per bit write. SMT works because of the net angular momentum that is carried by a spin-polarized current and the transfer of this momentum to the magnetization of the free layer. This effect becomes important when the minimum dimension of the memory cell is less than 100 nanometers and becomes more efficient as the cell size is reduced. This is the opposite of what occurs with the use of conventional magnetic field switching, for which the fields necessary to switch a nanoscale cell become larger as the size of the cell shrinks.

One of the surprises that arose from the spintronics efforts was that the free layer could be rotated in both directions by reversing the direction of the current [27]. This bidirectionality is enhanced when the easy axes of the two magnetic layers have a small misalignment so that the moments of the two magnetic layers (hard and soft) are not collinear.

It appears that SMT switching can significantly improve the performance of MRAM and make it the truly universal memory that was envisioned when the spintronics efforts were initiated. The cell may become more complicated, since the switching and magnetoresistive elements may have to be separated using a structure with additional layers. However, the memory cells are already complex, and the additional layers should be easy to add. A summary of the projected performance of MRAM and SMT-MRAM is shown in **Table 2**, which also includes entries pertaining to the performance of conventional semiconductor memories. Note that SMT-MRAM has the potential to dominate this aspect of the memory market, particularly because of its nonvolatility and very low power! Although

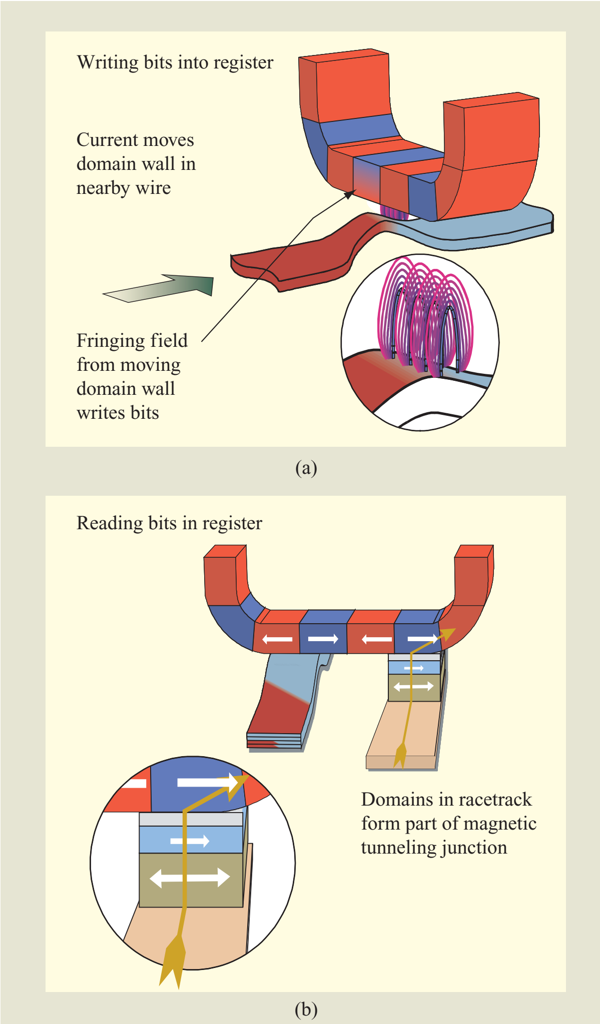

Figure 3

Domain wall "Racetrack" memory proposed by Parkin [63].

SMT should contribute significantly to the write speed of MRAM, extremely large magnetoresistive ratios approaching 300% using MgO tunnel barriers [60, 61] should significantly improve the read speed. The overall expected improvement is by a factor of 2 or 3 [62]. Additionally, for performance-optimized MRAM, the overall performance could be improved by a factor of 5 to 6, that is, to 4 to 5 ns compared to 25 to 30 ns in the first MRAMs.

Spin momentum transfer should also provide a pathway to another type of memory that may eventually be a solid-state replacement for the magnetic hard drive—e.g., storing information through the presence or absence of a domain wall in a linear array of domain walls in a magnetic thin-film loop confined to a channel in a silicon chip. The domain wall would be moved back and forth using spin momentum transfer. The writing of bits would be accomplished by using the very large fields from a domain wall that would be shuttled close to the memory strip, and reading would be accomplished by using a nanoscale GMR or SDT sensor just as in a conventional hard drive. This approach has been proposed by Parkin [63]; it is depicted in **Figure 3**.

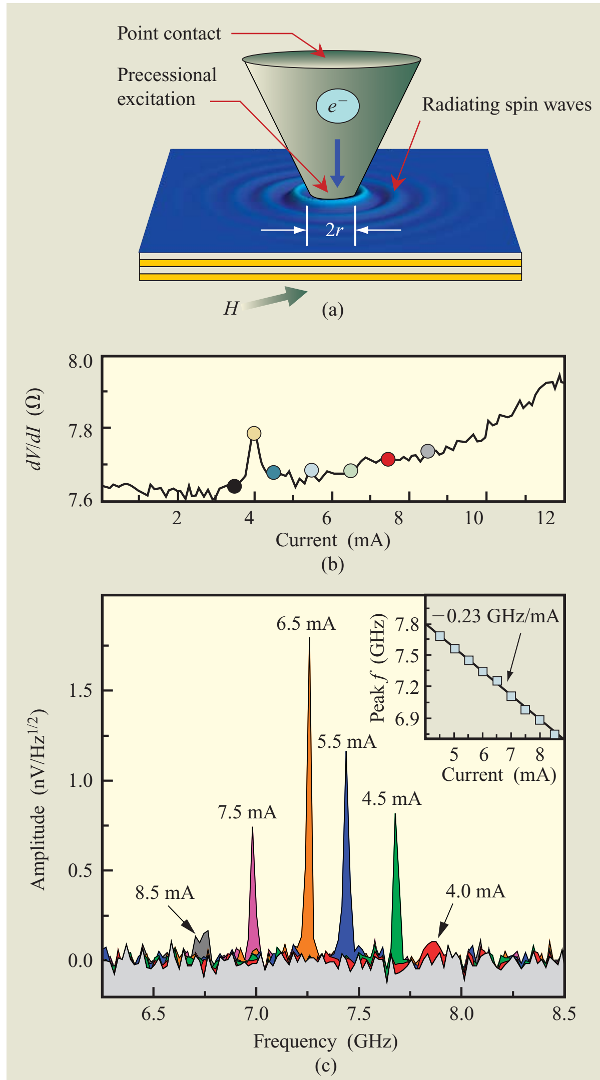

Figure 4

Conversion of the momentum of spin-polarized current into coherent spin waves. (a) Experimental configuration; (b) differential resistance dV/dI, measured using an in-plane field of 0.1 T; (c) amplitude of rf signals arising because of the presence of the spin waves. The differently colored circles in (b) correspond to associated peaks in (c). Adapted from [64], with permission; ©2004 American Physical Society.

Another important aspect of spin momentum transfer is the generation of rf and microwave signals by the conversion of the momentum of the spin-polarized current into coherent spin waves in the magnetic host in the presence of a magnetic field [64], as shown in **Figure 4**. The spin waves have been shown to radiate significant power in the frequency range from a few to tens of GHz, and theoretical prediction indicates a much larger bandwidth than has been experimentally observed to date. Figure 4(a) shows how current is injected through a point contact with radius *r* into a ferromagnetic metal–normal metal–ferromagnetic metal trilayer sandwich. The current is spin-polarized in the first ferromagnetic layer; in transferring spin momentum as it is scattered from the second ferromagnetic layer in the presence of a magnetic field *H*, it produces monochromatic rf radiation through the generation of spin waves. The frequency of these spin waves is dependent on the magnitude of the injected current, as shown in Figures 4(b) and 4(c). A frequency-agile nanoscale source of electromagnetic radiation over a frequency range of tens to potentially hundreds of GHz would be attractive for a host of applications. For example, such an oscillator might provide tunable sources for phased array transceivers, sources for chip-to-chip and on-chip clocks, and local oscillators for a handheld wideband radio (see **Figure 5**).

Looking further into the future, an ultimate goal for spintronics is an extremely low-power replacement for the CMOS transistor. The end of the scaling predicted by Moore's law is expected to occur sometime during the first quarter of this century. The end is predicted because charge motion is inherently dissipative, and it is the heat generated in the ever-smaller, ever-faster CMOS transistors that will limit the scaling. Coherent spin rotation is not dissipative; it is by itself a thermodynamically reversible process. Of course, there will always be dissipation in the circuit that is used to perform the spin operations, but that may be remote from the spin itself and may allow for scaling beyond Moore's law. The spin replacement for the CMOS transistor has not yet been devised, but it could appear when we least expect it. We are confident that there will still be many new discoveries and new applications for spintronics in the next decade and beyond.

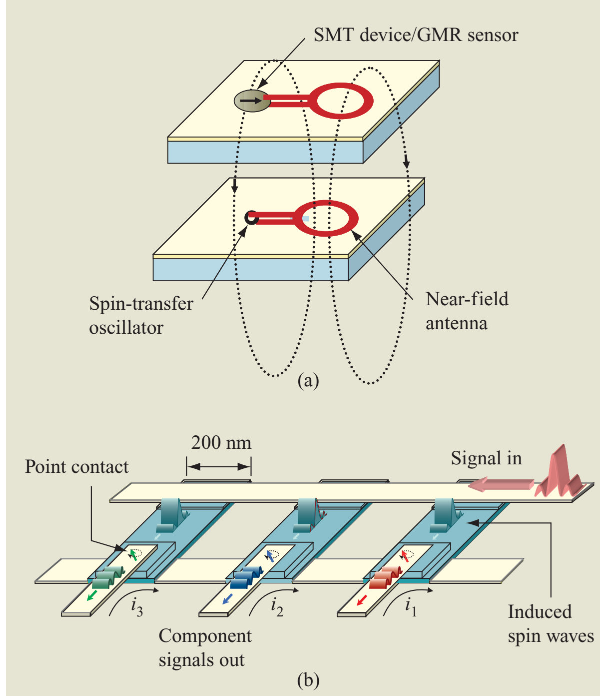

Figure 5

Potential use of spin-based, frequency-agile, nanoscale source of rf radiation for (a) high-speed, chip-to-chip communication; (b) local oscillator for a handheld wideband radio.

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