NANO FOCUS

The 2007 Nobel Prize in Physics: Magnetism and Transport at the Nanoscale

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ABSTRACT The 2007 Nobel Prize in Physics was awarded to Peter Grünberg and Albert Fert for the discovery of giant magnetoresistance (GMR). GMR is a phenomenon that is intimately linked to the nanostructuring of magnetic materials and has had broad scientific and economic impact. Here, we summarize the early scientific studies of magnetic thin films and superlattices that enabled the discovery of GMR, and we describe the evolution of spin-electronics (spintronics) that has emerged since its discovery.

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New materials in unusual configurations are the main drivers in many studies in condensed matter physics and are the basis for a large number of novel technologies. Recent materials research has focused on artificially structured materials, driven by the convergence of improvements in deposition technologies, lithography processes, characterization techniques, theoretical understanding of nanoscale systems, and the need for miniaturization in all areas of high technology. The unique physical properties produced in these types of systems cannot simply be extrapolated from the bulk properties of the constituents. These "emergent phenomena" include confinement and proximity effects. Confinement refers to (mainly) quantum mechanical phenomena which are induced by the physical confinement at the nanoscale. Proximity effects, of many sorts, occur principally because these types of nanostructured materials are invariably in contact with other dissimilar materials (*e.g.*, superconductors with ferromagnets, ferromagnets with antiferromagnets, or ferroelectrics with ferromagnets), generally denoted as "hybrids". Many new hybrid geometries with one or more length scales of the order of 1–100 nm have been envisioned and/or observed to exhibit interesting properties. These include horizontal and vertical superlattices, quantum dots in a variety of configurations, nanocrystals, quantum lines grown at step edges, arrays of magnetic dots, interacting superconducting and magnetic nanostructures, *etc.* Such structures are particularly susceptible to external driving forces, such as time-varying electric and magnetic fields, electromagnetic waves, pressure, sound, *etc*. This in turn produces a variety of new functionalities as summarized schematically in Figure 1.

MAGNETIC NANOSTRUCTURES

One of the more dramatic examples of the opportunities in this field is illustrated by the award of the 2007 Nobel Prize in Physics[1] to Peter Grünberg and Albert Fert for the discovery of giant magnetoresistance (GMR).[2–4] GMR arises from combining magnetic and non-magnetic materials at the nanoscale, resulting in "giant" changes in the electrical resistance to an external magnetic field. This initially basic research has led to the development of novel materials and devices that have had a revolutionary effect on magnetic storage, sensors, and electronic applications.

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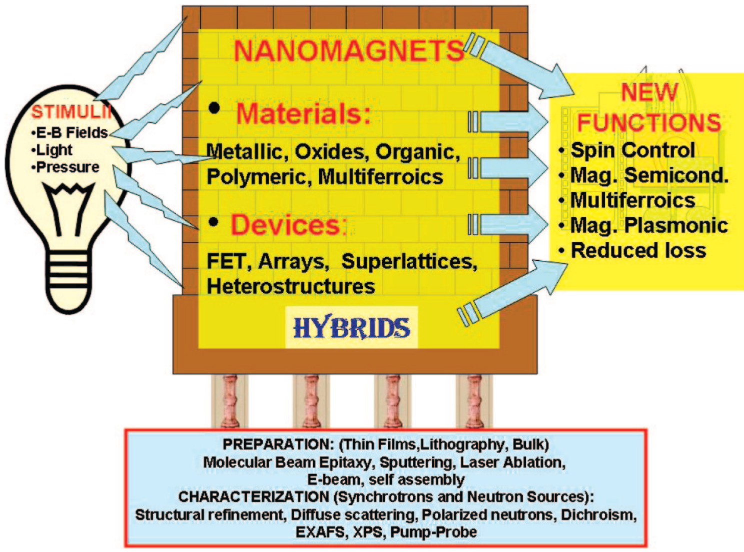

Figure 1. Schematic diagram showing the field of nanomagnetism, in which hybrid materials are driven by external stimuli to produce new functionalities.

Initially, most of the research on magnetic nanostructures was dedicated to studies in which only one dimension of the material was reduced to the nanoscale *via* thin-film deposition. This gave rise to extensive research in the field of metallic superlattices and heterostructures in which different elements or compounds are layered at the nanoscale to produce new and sometimes unexpected properties. A particularly fruitful area of research was magnetic/non-magnetic/magnetic trilayers and magnetic/non-magnetic superlattices and heterostructures that were used to probe finite size effects, coupling, and transport properties. Although much of the original work was studied in multilayers and superlattices, it was established that these studies could be accomplished in a simple four-layer hybrid heterostructure known as a "spin valve", as illustrated by Figure 2D.[5] This consists of a trilayer ferromagnet/spacer (metal or insulator)/ferromagnet in which one of the ferromagnetic layers is pinned by an antiferromagnet, exploiting the exchange bias interactions.[6] Many of the interesting properties and the functionality are obtained by rotation of the unpinned ("free") ferromagnetic layer with respect to the pinned ferromagnetic layer. This general structure is ubiquitous to most applications of GMR, as outlined below.

A fascinating outcome of this research was the observation of interlayer coupling between ferromagnetic layers separated by a non-magnetic metallic spacer (shown schematically in Figure 2A). This coupling oscillates from positive (ferromagnetic) to negative (antiferromagnetic) with increasing spacer layer thickness. The coupling is related to the Ruderman−Kittel−Kasuya−Yosida (RKKY) interaction that describes indirect spin coupling through the conduction electrons in metals. The ferromagnetic layers, viewed as macrospins, couple *via* the non-magnetic metallic spacer, as was anticipated in the 1960s.[7] Improvements in thin-film growth techniques led to the observation of coupling effects in rare earth[8,9] and transition metal superlattices[10−14] in the 1980s. Commensurate with the coupling is the formation of the spin-polarized quantum well states within the non-magnetic metallic spacer.[15] The ability to modulate the coupling of ferromagnetic layers is an example of quantum engineering of magnetic metals that emerged from these studies and is now a standard component of commercially available magnetic devices.[16]

GIANT MAGNETORESISTANCE

The study of the magneto-transport in metallic superlattices[17] had suggested anomalous properties in these structures, and the groundbreaking work of Johnson and Silsbee had shown that is was possible to inject and detect spins in a non-magnetic material using ferromagnetic leads.[18] However, studies combining magneto-transport and interlayer coupling in metallic heterostructures led to the discovery of GMR in Fe/Cr/Fe trilayers[2] and Fe/Cr superlattices.[4] GMR was observed when the Fe layers were antiferromagnetically coupled *via* the Cr interlayer. GMR is a dramatic decrease in the resistance in an applied magnetic field as the antiferromagnetically coupled Fe layers (in zero field) align ferromagnetically at high magnetic fields (Figure 2B). For Fe/Cr superlattices, the size of the effect was more than an order of magnitude greater than that observed for single Fe films, resulting in the "giant" aspect of GMR. This remarkable dependence of resistance produced by local magnetic configurations in nanostructures has sparked research into transport in magnetic nanostructures and the emergence of the field of magnetoelectronics or spintronics.[19]

The origins of GMR can be traced to the general interaction between currents and magnetism. It has been known since the 1800s that the resistance of ferromagnetic materials depends on the current flow direction, parallel or perpendicular to the magnetization direction. This resistance difference, known as anisotropic magnetoresistance (AMR), is a bulk property. The modern understanding of AMR and GMR is based on a two-current model proposed by Mott.[20] In this model, the current is carried in separate spin-up and spin-down channels. Non-magnetic materials carry the current equally in the spin-up and -down channels. In ferromagnetic materials, the exchange interactions shift the spin-up and -down bands, producing a difference in spin density which gives rise to the ferromagnetic moment. The spin density imbalance also results in a conductance difference in the spin-up and -down channels. Thus, for ferromagnetic materials, the current flow is unbalanced between the two spin channels and the current becomes spin-polarized.

This model was used by Fert and Campbell[21,22] to explain magneto-transport in ferromagnetic metals and

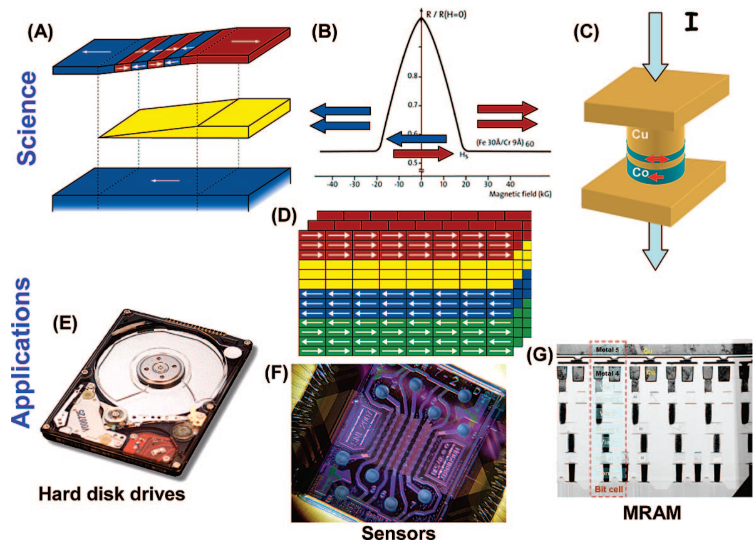

Figure 2. Examples of the exciting science and technological advance in magnetic nanoscience. (A) Schematic representation of interlayer coupling between two ferromagnetic layers across a non-magnetic (yellow) spacer layer. As the spacer layer thickness changes, the coupling oscillates between ferromagnetic and antiferromagnetic coupling, resulting in parallel and antiparallel alignment of the magnetization. Adapted with permission from ref 10. (B) GMR response from an Fe/Cr superlattice. In zero magnetic field the layers are antiparallel (as indicated by the arrows). Applying a large magnetic field saturates the Fe layers and causes a "giant" decrease in the resistance. Reprinted figure with permission from ref 4. Copyright 1988 American Physical Society. (C) Schematic of a spin-transfer device where current can switch the direction of the magnetization of a layer. (D) Schematics of a spin-valve GMR sensor where the reference (blue) magnetic layer is pinned by an antiferromagnetic layer (green) and the free magnetic (red) is separated from the reference layer by a thin conducting spacer (yellow). (E) A hard disk drive which uses a GMR sensor to read the data stored on the disk. (F) Top view of a micro-fluidic magneto-nanochip with an 8 × 8 GMR sensor array and eight microfluidic channels [Courtesy of Sebastian J. Osterfeld and Shan X. Wang, Stanford University.] (G) Cross-sectional transmission electron microscope image of a 4-megabit toggle MRAM showing backend integration of magnetic tunnel junctions and Cu write lines. [Courtesy Freescale Semiconductor, Inc.]

provides the basis for understanding GMR. For current flowing through two magnetic layers separated by a thin non-magnetic spacer, the current becomes spin-polarized by transmission through the first magnetic layer. If the spacer layer is thin enough, the current maintains its polarization as it passes through the non-magnetic spacer and interacts with the second ferromagnetic layer. This interaction leads to a change of resistance depending on the relative orientation of the magnetic layers. If the layers are parallel, the spin-polarized current flows more easily into the second ferromagnetic layer. As the angle between the ferromagnetic layer increases, there is increasing resistance resulting from spin-dependent scatterings (Figure 2B). While this grossly oversimplifies the detailed processes of GMR, it highlights the basic principle that is used in most spin-based devices: manipulation of the spin rather than the charge of the electron *via* spin injection from one ferromagnetic material, manipulation within a non-magnetic layer, and then detection by a second ferromagnetic material.

The GMR effect was discovered for two ferromagnetic layers separated by a metal, and the conduction in the spacer layer is either diffusive or ballistic. If, however, the ferromagnetic layers are separated by a thin insulator (generally an oxide) and the conduction is through quantum mechanical tunneling, the effect is known as tunnelling magnetoresistance (TMR).[23] Analogous to GMR, the tunneling can be treated as the independent tunneling of spin-up and spin-down electrons, where the tunneling current depends on the densities of states of the two electrodes and the matrix elements coupling them. The tunnel current is high when the ferromagnetic leads are parallel (low resistance) and low when they are antiparallel (high resistance). The TMR effect depends on the spin polarization of the ferromagnetic material,[24] which for typical transition metals leads to a 50–70% effect. However, as was predicted and later observed experimentally, further spin filtering of tunneling electrons by particular oxide barriers leads to TMR as high as 500%.[25–27]

Investigation of the converse effect—the effect of the current on the magnetization—gives rise to the so-called "spin torque" effect, illustrated in Figure 2C. In this case, a transport current can flip one of the magnetic layers in a trilayer structure. Spin torque is caused by the transfer of angular momentum from the polarized current to the free layer magnetization. This spin torque can oppose the intrinsic damping of the magnetic layer, exciting spin waves and, for sufficiently large currents, reversing the direction of the magnetization. These effects were predicted in 1996[28,29] and were observed experimentally starting in 1998.[30,31] Thus, spin transport not only probes the local magnetic configurations of nanosystems but also provides a way to manipulate the magnetization. Spin torque links the physical phenomena of magnetic excitations, damping, reversal, and micromagnetic configurations with spin transport. This gives rise to a variety of interesting basic research questions related to the mechanism of the effect, the behavior of spin waves, the generation of microwaves, the possibility of coherent radiation and coupling between different devices, *etc.*

One of the first and most important applications of GMR was as a read sensor for reading data in hard disk drives (Figure 2E). In its simplest form, the GMR sensor is a spin valve with free and fixed layers (Figure 2D).[5] As the free layer rotates in the presence of a magnetic field, the resistance of the device changes due to the GMR (or TMR). This simple design provides an effective field sensor and has been the basis for read heads for the past 10 years.[16] The GMR read head was introduced by IBM in 1997, and replaced the AMR read head that had been introduced in 1991. While both the AMR and GMR heads sense magnetic field by changes in resistance, GMR heads have a distinct advantage, particularly for small devices. AMR is based on bulk scattering. So, the thinner the magnetic sense layer is made, the more surface scattering plays a role in transport and can overwhelm the magnetic scattering. On the other hand, GMR is dominated by interfacial scattering at the magnetic−non-magnetic interface. GMR sensors work only when the layers are on the nanoscale, and the GMR signal generally increases with decreasing layer thickness. This high field sensitivity and improved performance at smaller scales was one of the main drivers for the dramatic growth in hard disk drive storage densities that began in 1997. Recently, the hard disk drive industry began introducing TMR heads to use the enhanced amplitude possible from the tunneling process.

Although they were first implemented in hard disk drives, GMR sensors have become ubiquitous as field sensors in a broad range of applications. GMR sensors have found many applications, such as linear and rotational position sensors, current and current limit detectors, and vehicle sensors, where they work by detecting small changes in the magnetic field.[32] As an example of a promising application in biomagnetism, magnetic nanoparticles can be attached to interesting biological molecules ("tagged"). Sensitive GMR or TMR sensors can then be used in microfluidic devices to detect the magnetic particles and provide a quantitative assay of the tagged molecule. An example device is shown in Figure 2F that consists of an 8 × 8 GMR sensor array with eight microfluidic channels.

While magnetic materials have dominated information storage *via* the hard disk drive for the past 50 years, magnetic random access memory (MRAM) technologies are only recently emerging.[33] MRAM technology combines a spintronic device with standard silicon-based microelectronics (Figure 2G). The memory cell is typically a TMR junction that is designed to have two stable magnetic configurations. The bit state is programmed to a "1" or "0" by aligning the magnetization of the free layer either antiparallel or parallel to the magnetic reference layer, and the cell retains this state without any applied power (*i.e.*, it is non-volatile). The cells are read by sensing the resistance and analyzing it to determine if the resistance state is a high (antiparallel) or low (parallel) magnetic configuration. MRAM provides non-volatility, infinite endurance, and fast memory with a broad range of applications.

BEYOND GMR

Beyond GMR, there is a range of exciting developments that exploit spin-polarized transport. While we cannot give an exhaustive list, it is worth pointing out some of the more fascinating and active areas: spin transport across interfaces; spin injection and diffusion into semiconductors; magnetic semiconductors; spin effects in organics; spin drag; spin transistors; magnetic proximity effects; magnetic ratchets; hybrid magnetic materials in general, including multiferroics; and development and study of novel inhomogeneous magnetic materials, such as complex oxides or fluorides. For all these studies, the role of interfacial structure and modification of the physical and magnetic structure at interfaces highlights the importance of structural and magnetic measurements at the atomic scale. This is receiving attention with the usage of laboratory techniques such as scanning probe microscopes, optical,[34] electron and/or He scattering/imaging techniques, which provide useful surface information. These, when combined with studies using synchrotron and neutron sources,[35,36] may provide a complete structural and magnetic description of nanoscale magnetic systems and are crucial ingredients in the understanding of the physical properties.

As the study of spin transport continues to evolve, several general themes emerge. One is to exploit spin injection from ferromagnetic leads into non-magnetic materials. The long spin diffusion lengths found in metallic systems opened up the possibility for studies of non-local spin diffusion, in which the spin and electrical degree of freedom are decoupled. Spin injection and detection in lateral geometries were first reported by Johnson and Silsbee.[18] In non-local devices, spin-polarized currents were injected from one ferromagnetic electrode into a non-magnetic material.[37] The resulting spin accumulation diffuses away from the injection point and can be detected as a voltage change at a second ferromagnetic electrode. This signal results from a pure spin current that can be separate from the charge current. While initially studied in metals, this approach can be extended to semiconductors and superconductors, leading to novel phenomena such as non-local Andreev reflection and spin Hall effect. Issues related to spin reflection at metal−semiconductor interfaces are motivating many attempts to develop doped magnetic semiconductors which may serve as spin injectors. An important aspect of this field will be revolutionized by recent advances in time-dependent measurements of spin diffusion.[38] This allows real-time measurements of spin production and spin diffusion almost at the atomic scale. In this fashion, it is possible to study spin dynamics. Spin drag has been predicted in trilayer ferromagnetic/antiferromagnetic/ferromagnetic structures, in which spin-polarized currents in one of the fer-

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romagnetic electrodes produces a drag of spins in the second electrode. This is similar in spirit to earlier observations of phonon drag in semiconductor trilayers and vortex drag in superconducting trilayers. Several proposals have been advanced using multilayered structures for the design of magnetic qubits (quantum bits) and their communications by using spin-polarized currents.

Several ideas have been advanced for the development of novel spin-based devices exploiting spin currents. This includes an electrically controlled spin transistor, a three-terminal device in which the GMR effect between two electrodes is controlled by an electric field.[39] A more complicated five-terminal device relies on the use of magnetic electrodes and proximity effects for the polarization and propagation of electrons in non-magnetic layers[40] and other unipolar[41] and dipolar[42] magnetic transistors. All these open up the possibility for using the spin degree of freedom in devices, with the consequent possibility of controlling the functionality of devices using combined electric and magnetic fields.

As with non-local spin devices, the observation of spin-transfer torque has led to tremendous excitement about its potential for device applications. Spin-transfer effects provide a local means of manipulating magnetization rather than relying on long-range effects mediated by an externally generated magnetic field. High-density MRAM and current-tunable high-frequency oscillators are applications for which the spin-transfer effect could find commercial viability. In spin-transfer MRAM, current is injected directly into the tunnel junction, where the spin-transfer effect is used to write the bits, instead of using an external write line. In spin-transfer-driven switching, it is the current density, not the current, that determines the threshold for writing, and therefore a spin-transfer-based structure may scale better to higher densities. In addition to switching the magnetization, spin torque effects can produce voltage-controlled high-frequency radiation through the emission of microwaves from coupled spin wave modes. Moreover, closely spaced lithographically defined spin torque devices may couple together to radiate coherently, thus providing the means for producing a highly coherent beam of radiation which can be controlled by a voltage. This is quite similar in spirit to the radiation obtained from closely spaced Josephson junctions which radiate coherently.

CONCLUSIONS

The progress in magnetic nanoscience has been dramatic in the past 30 years, with GMR being one of the most exciting findings, spurring the field of spintronics. While much of the physical phenomena can be understood by quantum descriptions of magnetism developed in the 1950s, it was only the ability to grow, control, and characterize materials at the nanoscale that allowed these phenomena to emerge. With continued developments of new materials and device architectures, better control of magnetism at the nanoscale, and improved understanding of spin transport, new phenomena will be discovered and new technologies will emerge. While it is difficult to predict, magnetic nanostructures will certainly play a major role in data storage, memory, and sensors applications. Whether spin currents can replace charge currents in processors remains to be seen. However, it is clear that there are many exciting scientific questions still to be answered when one combines magnetism and transport at the nanoscale.

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