CHAPTER 4

SPIN INJECTION, SPIN TRANSPORT AND SPIN TRANSFER

Robert A. Buhrman

BACKGROUND AND OVERVIEW

Spin injection and detection

The efficient injection of charge carriers having a strong net spin polarization of controllable orientation into nonmagnetic electronic materials, particularly semiconductor device structures, along with the subsequent manipulation and detection of this injected spin polarization, is essential to the successful performance of a wide range of potential spintronics devices. The pioneering spin injection experiment of Johnson and Silsbee (1987), as well as the discovery of the giant magnetoresistance (GMR) effect (Baibich et al. 1988; Barnas et al. 1990) discussed elsewhere in this report, demonstrated over a decade ago that a strong nonequilibrium spin population can be generated in a normal metal by sending a current into it from a ferromagnetic electrode. This approach is effective because the current emanating from a ferromagnetic metal is generally substantially spin-polarized, typically >40% for the transition metal ferromagnets (Soulen et al. 1998; Upadhyay et al. 1998), since the electrical conductivity of its majority (spin up) electrons differs significantly from that of its minority spin (spin down) electrons.

Subsequent to the initial metallic spin injection work, Datta and Das (1990) proposed a current modulator device based on the electric field modification of spin precession in a narrow gap semiconductor. In this device, the spin-polarized electrons would be injected with the use of a ferromagnetic electrode that forms an ohmic contact with the semiconductor and would be detected with a second ferromagnetic electrode (spin analyzer) contact. This seminal proposal stimulated a number of efforts to realize this and related spin-based semiconductor device structures. The recent optical demonstrations of long spin coherence times and long spin diffusion lengths in compound semiconductors and successful experiments involving the optical manipulation of spins in semiconductor structures, discussed elsewhere in this report, have given renewed impetus to efforts aimed at realizing electrical spin injection into semiconductors. Yet, despite quite extensive research efforts on electrical spin injection from ferromagnetic metals, the results that have been achieved until quite recently have been limited.

In pursuing electrical spin injection into semiconductors in a manner analogous to the successful approach used for injection into normal metals, it was realized that the nature of the ohmic contact between the ferromagnetic metal and semiconductor was critical. For this reason InAs and related low band gap semiconductors have been the semiconductor material of choice since this material system, when contacted with most metals, has its Fermi level at or near the interface pinned in the conduction band. Thus the semiconductor in the vicinity of the metal acts as a semimetal, and a clean interface should provide an essentially ideal ohmic contact. While excellent materials and very careful processing and measurement techniques have been employed in such ohmic spin injection experiments, the resultant injected spin polarization in the semiconductor that has been inferred from the measurements has generally been rather small, or nil (Gardelis et al. 1999; Hu et al. 2001; Hammar et al. 1999; Monson 1999; Monson and Roukes

1999). In many cases the signals indicating a small, injected spin polarization could also be possibly attributed to a local Hall effect arising from the stray field of the ferromagnetic injector and/or spin detector electrodes (Hammar et al. 2000; Jedema, Filip, and van Wees 2001; Monson and Roukes 1999).

In these spin injection techniques, the anticipated nonequilibrium spin population is either measured potentiometrically with the use of another ferromagnetic electrode (Johnson and Silsbee 1987) or detected by the resistance presented when the current flows into a second ferromagnetic electrode, whose magnetic orientation is variable with respect to that of the injecting electrode. This latter spin valve detection scheme requires that the detector electrode be placed no farther from the ferromagnetic injector than the characteristic length for spin relaxation in the normal metal. The potentiometric detection scheme requires (1) that the spin- injected volume be sufficiently small so that a substantial increase in the spin-dependent chemical potentials can be induced and/or (2) a sensitive measurement of a small potential difference arising from the spin imbalance.

Over the past decade and more, researchers have analyzed interfacial spin transport (van Son et al. 1987; Valet and Fert 1993; Hershfield and Zhao 1997) in electronic multilayer systems in the diffusive regime. This is the appropriate transport regime to assume when considering both normal metal and semiconductor (semimetal) spin-injection experiments that utilize ohmic contacts to a ferromagnetic injector. While the key aspects regarding interfacial spin transport have been well established, it was the recent contribution by Schmidt and colleagues (2000) that explicitly drew broad attention to a fundamental difficulty in obtaining a significant nonequilibrium spin population in a semiconductor or semiconductor via diffusive transport from a ferromagnetic electrode. Due to the large disparity between the high (spin-dependent) density of states in the ferromagnet and the low (spin- independent) density of states in the semiconductor or semimetal, a simple model calculation shows that in most experimental configurations a substantial injected spin polarization can only be achieved if the spins in the ferromagnet are nearly 100% polarized. This half-metallic condition is possibly to be found in only a limited set of comparatively challenging materials such as, e.g., the Heusler alloys and CrO_2, not the conventional and more tractable ferromagnetic metals (e.g., Co, Fe, Ni, and their alloys). The appreciation of this key point regarding electrical spin injection has shifted the focus of much current research to different transport and spin injection regimes, as discussed below, with much of the remaining effort focusing on the successful development of fully polarized half-metallic ferromagnets for ohmic contact, spin injection applications. Of course an alternative approach is to employ a ferromagnetic semiconductor, or a paramagnetic semiconductor in the presence of a strong magnetic field, like the spin source, as discussed elsewhere in this report. Assuming the density of states of the ferromagnetic semiconductor is similar to that of the nonmagnetic semiconductor, this approach avoids the fundamental difficulty with spin injection from ferromagnetic metals, but until a room temperature ferromagnetic semiconductor is developed, which may be imminent, this approach is limited to low temperature applications.

Johnson and coworkers (Hammar and Johnson 2000; Johnson 1998; Johnson 2001) have been pursuing an approach to creating a spin polarization in a semiconductor that might avoid this obstacle to ohmic spin injection by taking advantage of the splitting of the spin degeneracy of electrons confined in a semiconductor 2D quantum well structure . The splitting is due to the spin orbit effect that can arise from an asymmetry in the confining potential (Bychkov and Rashba 1984). The result can be induction of a nonequilibrium spin polarization if the 2D electron gas is carrying a current (Vorob'ev et al. 1979). In this approach the spin polarization can be detected potentiometrically with the use of a ferromagnetic contact to the current-carrying 2D semiconductor structure.

Returning to the issue of spin injection from a ferromagnetic metal, if the impedance of the interface between the ferromagnet and semiconductor is high compared to that of the semiconductor structure, then the relative conductivities of the electrodes will not play a role in defining or limiting the interfacial spin-dependent transport. This situation can be achieved by employing either a ballistic transport structure or by utilizing a potential barrier at the interface that determines the current flow. In the first case, a ferromagnetic ballistic point contact to, e.g., an InAs semimetal layer, can be expected to result straightforwardly in the injection of a current into the semiconductor whose polarization would be relatively high (~40+%) as determined by the ballistic spin-dependent interfacial transmission probabilities. These can be calculated from band structure differences in a manner similar to that employed for ferromagnetic/normal metal interfaces (Stiles 1996; Kirczenow 2001). If the objective is to both inject and detect electrically a spin-polarized current after passing through, and possibly being manipulated within, the semiconductor, then a fully ballistic device will be required. Preferably this would be a device that consists of a semiconductor layer containing only one or a few modes or electron channels that ballistically link a ferromagnetic injector, or spin polarizer, to a ferromagnetic collector, or spin analyzer. While this type of ballistic device structure has been analyzed in considerable detail (Datta and Das 1990; Tang et al. 2000), its realization poses considerable experimental challenges.

If a potential barrier such as a tunnel barrier or a Schottky barrier is present at the ferromagnet/ semiconductor interface, then the spin-dependent density of states of the ferromagnet should result in the injection of a spin-polarized current into the semiconductor when the interface is appropriately biased. Rashba (2000) has recently published a model calculation that provides a quantitative analysis of the conditions necessary for this approach to be effective when combined with a second potential barrier at the semiconductor/ferromagnetic collector interface for the purpose of spin valve detection of the spin polarization of the exiting current. For effective spin injection across a potential barrier the requirement for the barrier and the bias conditions is basically that the transport be limited by the spin-dependent transport rates across the interface and not by the spin-independent transport through the semiconductor. For a Schottky barrier device, this requires that the diode be back biased. Of course, it is also essential that there be no significant spin-flip scattering at the interface or strong spin-orbit scattering as the injected carriers pass through the depletion layer of the semiconductor.

With the use of a scanning tunneling microscope (STM) that employed a ferromagnetic tip, Alvarado and Renaud (1992) showed some time ago that a vacuum tunnel barrier could indeed be used to effectively inject spins into a semiconductor. More recently LaBella and coworkers (2001) have been using a similar STM technique to examine the spatial dependence of the effectiveness of spin injection by tunneling and to correlate the local spin injection probability with semiconductor surface structure. In these experiments the circularly polarized electroluminescence that is emitted as the injected electrons recombine is employed as the means of assessing the degree of polarization of the injected current. This optical detection of nonequilibrium spin polarization avoids the difficulty of electrical detection and is comparatively direct. However, careful experimentation and thorough analysis are still required to ensure that all alternative sources of circularly polarized optical emission have been ruled out or properly taken into account when deducing a spin polarization in this manner (Jonker et al. 2001).

The highly successful development of ferromagnet/insulator/ferromagnet tunnel junctions with high tunneling magnetoresistance has demonstrated that insulator tunnel barriers can also result in the conservation of spin during the tunneling process. Consequently a number of research groups have begun to pursue experiments focusing on spin injection via ferromagnet/insulator/semiconductor (FIS) tunnel junctions. However, while silicon dioxide can be used to form a very good and thin tunnel barrier on Si surfaces, the spin-dependent tunneling properties of such tunnel barriers have yet to be reported, and MIS diodes are quite difficult to fabricate with good electrical properties on compound semiconductor surfaces.

The alternative approach, particularly appropriate for compound semiconductors, is to form Schottky barriers with ferromagnetic electrodes, and this is currently being pursued by a number of groups investigating spin injection. The epitaxial growth of the ferromagnetic thin film on the semiconductor to form an abrupt, high-quality Schottky barrier interface is expected to be quite important, and this task is receiving careful attention (Chen et al. 2000). Here again electroluminescence is generally, if not universally, employed to establish the degree of spin polarization that is achieved in such spin injection experiments. An interesting variation on the spin-injection investigation is the “spin ejection” measurements recently reported by Crowell and coworkers (Isakovic et al. 2001). Here a careful and extensive examination has been made of the spin-dependent transport of spin-polarized carriers that are optically excited in a GaAs layer and then transit across a Schottky barrier into a Fe or FeCo electrode. Photocurrents with spin polarizations of the order of 1% have been observed to flow from the semiconductor to the ferromagnet under reverse bias. With respect to spin injection, perhaps the most striking result that has been reported to date by U.S. researchers is the work of the Hanbicki group (Hanbicki et al. 2002) where a back biased Fe/AlGaAs Schottky diode has been reported to yield a spin injection efficiency of 30%, corresponding to an injected spin polarization from the Fe electrode of approximately 13%. Here also the spin polarization is deduced from analysis of the circular polarization of the sample's electroluminescence under reverse bias.

A different spin injection technique that does not necessarily require a spin-conserving ferromagnet/semiconductor interface employs spin-polarized electrons having energies that are much greater than E_F. One such "hot electron" spin injection approach is first to tunnel-inject electrons into a ferromagnetic layer at energies $>> E_F$ (Monsma et al. 1995; Rippard and Buhrman 2000). Since the majority spin and minority spin electrons have much different inelastic mean free paths, hot electron passage through, e.g., a 3 nm Co layer, is sufficient to result in a ballistic electron current that is more than 90% polarized. This highly polarized hot electron current can then continue on, possibly through a nonmagnetic spacer layer, to an underlying metal/semiconductor interface where a portion of the polarized beam will enter the semiconductor. If there is no substantial spin-flip scattering at the interface, then the ballistic electron current entering the semiconductor will be highly polarized; and the injection energy, relative to the bottom of the semiconductor conduction band, will be tunable via the tunnel injection bias. However, the overall efficiency, as defined by the ratio of the spin-polarized current injected into the semiconductor to the current tunnel injected into the spin filter, is low due both to the attenuation of the hot electron current in the spin filtering process and to the low ballistic transmissivity of any metal/semiconductor interface.

Spin Transport

Spin lifetimes and coherent spin transport in semiconductor systems and thin film heterostructures are of primary concern to the spintronics field. While optical methods are quite effective in examining spin transport and coherence times in "bulk" semiconductors and quantum well structures, optical measurements can only indirectly infer the spin transmission efficiency for spin injection across interfaces. With regard to electrical spin injection and electrical spin detection, the issues of spin-dependent transport and spin-flip scattering during transit of Schottky barrier interfaces are of particular concern. Equally important is the related issue of spin relaxation and spin-orbit scattering of hot electrons while passing through the depletion region of a semiconductor layer. Thus an electrical means of directly examining spin-dependent transport across Schottky barrier interfaces, perhaps with a scanned probe instrument or a nanofabricated device approach, would be particularly valuable.

On the theoretical side, an extensive examination of the coherence of mobile spins in semiconductor systems has recently been completed by Flatté and colleagues (Flatté and Byers 2000). Related to this work is the interesting question of whether the quasi-independent electron model can adequately account for experimental results or whether many body or correlated electron processes are important in various aspects of spin transport. Flatté and others have examined this issue in the diffusive transport regime and have concluded that an independent electron approach is quite capable of quantitatively explaining the results of optical measurements of spin lifetimes, particularly the room temperature measurements. Sham and colleagues (Sham 1999; Sham and Ostreich 2000) have considered the low temperature regime where collective electron processes may well be important in determining the spin relaxation rates and spin lifetimes, although experimental results in this regime are quite limited.

On the device front, Flatté and Vignale (2001) have considered the possibility of constructing unipolar electronic devices by utilizing ferromagnetic semiconductor materials with variable magnetization directions. They have shown that such devices should behave very similarly to p-n diodes and bipolar transistors and suggest that these could be applicable for magnetic sensing, memory, and logic. Another interesting device is the spin-polarized solar battery that has recently been proposed and analyzed by Zutic and colleagues (Zutic, Fabian, Das Sarma 2001; 2001b).

Spin Transfer

Some time ago, Berger showed that the spin-polarized current in a ferromagnet could exert a nonequilibrium exchange force on a domain wall, causing the domain wall to be dragged along in the direction of the spin current. More recently Slonczewski (1996; 1999) and Berger (1996) predicted that a spin-polarized current that is caused to flow between one relatively thick, and hence fixed, ferromagnetic layer through a nonmagnetic layer to another thin-film “free” nanomagnet in an FNF current perpendicular to the plane (CPP) device configuration could, by spin-dependent scattering of the polarized current, transfer spin momentum from the current to the free layer. Depending on the direction of the spin current flow, this “spin transfer” effect can either force the free layer into parallel or antiparallel alignment with the fixed layer once the spin transfer force is strong enough to overcome the coercive field of the free nanomagnet. Since this spin transfer effect depends on the local spin current density, it dominates any effect of the Oersted self field generated by the current once the sample diameter is small enough (≤ 200 nm) for a Co nanomagnet (Myers et al. 1999; Katine et al. 2000). Alternatively, if a strong external pinning field is applied to such a nanoscale CPP structure, the effect of spin transfer can be the excitation of strong, uniform spin wave precessional modes in the nanomagnet (Tsoi et al. 1998a; Tsoi et al. 1998b; Rezende et al. 2000). This nanomagnet precession could be a source of microwave radiation and possibly a source of a precessing spin current. Recent work has definitively demonstrated these spin transfer switching and spin wave excitation effects. These spin transfer phenomena open up the possibility of new types of nanoscale magnetic devices for memory and other spin electronics applications. Efforts to understand, enhance and utilize spin transfer phenomena are now being pursued at a number of research labs.

RESEARCH ACTIVITIES IN JAPAN

The emergence and rapid growth of the field of spintronics is being driven by important contributions from scientists in all the major industrial nations that strongly support broad based research and development efforts and which have a strong research infrastructure.

In Japan, as discussed elsewhere in this report, a very extensive spintronics materials R&D effort is leading the field to a great degree, both experimentally and theoretically. Japanese researchers and their external collaborators are making very effective use of these new and improved materials systems for spin transport and spin injection research. A recent notable achievement in spin injection, published simultaneously with a report of a fairly similar low temperature spin injection experiment in Europe, has been the use of the ferromagnetic semiconductor $Ga_{1-x}Mn_xAs$ as a low temperature source for electrical spin injection into a GaAs layer across a p-n diode interface (Ohno et al. 1999). In this work, which was carried out through a collaboration between researchers at Tohoku University and the University of California, Santa Barbara, spin injection was convincingly detected through measurement of the circular polarization of the light emitted when the spin-polarized injected holes and unpolarized injected electrons recombined in an underlying InGaAs quantum well layer. The development of other ferromagnetic semiconductors with higher Curie temperatures for such spin injection applications is now a major focus of a number of Japanese research groups. The development of fully spin-polarized, half-metallic ferromagnets for spin injection and magnetic tunnel junction applications is also receiving rather widespread attention.

Extensive expertise and capabilities have been developed at a number of Japanese research laboratories in the area of transport studies of mesoscopic semiconductor systems, and several have been or now are beginning to apply these capabilities to the study of spin transport, spin manipulation, and spin injection. Almost certainly the most extensively equipped research laboratory in the area of mesoscopic and semiconductor device physics is at the NTT Basic Research Laboratories. A few years ago, Nitta and co-workers (1997) reported some seminal work demonstrating that the spin orbit interaction in a quantum well structure can be varied with the application of an electric field, applied through a gate voltage bias. This and related work were important steps towards the realization of the control of the precession of the polarization of an injected spin current as proposed by Datta and Das (1990). Yamada’s group at the Japan Advanced Institute of Science and Technology (JAIST) also has established an extensive mesoscopic materials science and nanofabrication laboratory and has recently reported a careful measurement and study of the gate controlled spin splitting of the 2D electron gas in InGaAs/InAlAs heterojunction structures (Sato et al. 2001). A particularly large spin orbit coupling constant was obtained in this system, which could be important for the spin FET applications.

The NTT group, in collaboration with two European research teams, has also been pursuing spin injection research. A recent experiment made use of an interdigitated permalloy structure to make ohmic contacts to an InAs channel (Hu et al. 2001). By switching the magnetic orientation of alternating permalloy electrodes the spin polarization of the injected current could be assessed from measurement of the changes in the resistance of the channel. The estimated spin polarization of the current through the ferromagnetic-2D electron gas interface was 4.5% in the experiment. While alternative explanations of the data based on local Hall effects and anisotropic magnetoresistance have to be considered when examining this type of spin injection data, the careful study of the temperature dependence of the effect gives good support to the spin injection interpretation. As is happening elsewhere in spin injection research, the NTT group has recently been examining the issue as to whether the presence of potential barriers at the ferromagnetic/ semiconductor interface will enhance the spin injection efficiency.

Spin-dependent tunneling between gated quantum dots is the basis of a recent proposal for a quantum bit that is receiving attention worldwide, both theoretically and experimentally. Professor Tarucha's group at the University of Tokyo (Sasaki et al. 2000), in collaboration with NTT researchers and with members of the mesoscopic electronics group at Delft, has been fabricating this type of spin device structure and is currently pursuing measurements to establish the longitudinal spin lifetime in the quantum dot. Theoretical work on the orbital and spin levels in such quantum dots is underway at NEC Fundamental Research Laboratories, where they are beginning to pursue spin-dependent transport in various nanoscale systems, including magnetically doped carbon nanotubes.

While spin-dependent transport in semiconductor systems is the focus of the majority of the spin electronics research activities in Japan, apart from extensive research and development efforts on magnetic tunnel junctions, there are also some notable activities in the area of spin injection and spin transport in metallic systems. For example, Prof. Otani at Tohoku University has been pursuing an innovative program in nanoscale magnetic phenomena in metallic systems, including studies of electrical spin injection and magnetic reversal in devices and measurements of spin transport lengths and spin injection efficiencies. Prof. Otani is moving to the Institute for Physical and Chemical Research (RIKEN), where he will be organizing and leading a new nanomagnetics research project.

RESEARCH ACTIVITIES IN EUROPE

There is a very strong history of top rank research activities throughout Europe in the areas of magnetism and magnetic materials, semiconductor materials, and device physics research, particularly notable work in transport studies in the mesoscopic and nanoscale regimes. A number of research groups are now taking advantage of this expertise and of their world-class research capabilities to pursue a broad range of important spin injection and spin transport studies.

The investigation of spin-dependent interfacial transport in ferromagnetic nonmagnetic normal metal (FN) thin film multilayer systems some time ago led to the discovery and development of the giant magnetoresistance (GMR) effect. The understanding and theoretical models that were established in GMR research provided many of the foundation and the experimental approaches for the first generation of spin injection experiments, both into metals and into semiconductors. As noted above, these initial studies focused on diffusive spin transport across ohmic interfaces, with one major approach being the potentiometric detection of the nonequilibrium spin-dependent chemical potential that should develop near a FN interface due to the spin-polarized current flowing to or from the ferromagnet. Recently, Prof. van Wees's group at Groningen (Jedema, Filip and van Wees 2001) has reported the successful room temperature electrical detection with nanoscale potentiometric probes of a spin polarization injected into a Cu nanostructure by a current flowing from a nearby permalloy electrode. However, extensive efforts to detect a nonequilibrium spin population in a semiconductor when injected with a current flowing from a ferromagnetic electrode through an ohmic contact were not successful (Filip et al 2001). These results, together with the rather small spin polarizations deduced from other experiments on ohmic electrical spin injection into semiconductors, led Prof. Mollenkamp's group at Wurzburg (Schmidt et al. 2000), in collaboration with the Groningen team, to reexamine the spin injection issue. This important contribution, which was based on the understanding gained from the prior GMR related analyses, has had a major impact in evolving the current direction of much spin injection research worldwide.

The Wurzburg group has recently applied its extensive semiconductor materials capabilities to the successful demonstration of the low temperature electrical spin injection of polarized carriers, from a strongly paramagnetic semiconductor ($Be_yMn_xZn_{1-x-y}Se$) in a high magnetic field, across a p-n diode interface into a nonmagnetic semiconductor layer (Fiederling et al. 1999). The circular polarization of the light emitted by the injected carriers as they recombined indicated that an injected spin polarization of approximately 90% was achieved in this important demonstration of effective spin injection.

In Europe, as elsewhere, a number of research groups are now pursuing experiments concerned with fabricating and employing high quality ferromagnetic metal/semiconductor Schottky barrier interfaces for room temperature spin injection applications. Prof. Ploog's group at Berlin has recently reported quite promising results from electrical injection across a back biased Fe-GaAs Schottky diode, with the spin injection efficiency again being determined from the optical emission of the recombining carriers (Zhu et al. 2001).

Other leading research teams in Europe engaged in semiconductor spin injection studies include the Heitmann group at Hamburg and the Bland group at Cambridge. Part of these spin injection efforts is also focused on developing half-metallic or nearly half-metallic materials, such as CrO_2 and the Heusler alloys, as sources of fully polarized or nearly fully polarized spin sources for ohmic injection into the low bandgap semiconductors, InAs and (In,Ga)As. This is also a focus of Prof. Guenterodt's program at Aachen, Dr. Cohen's at Imperial College, and Prof. Coey's at Trinity College. At Trinity, there is a fairly unique focus on point contact spin injection.

Considerable attention is also being paid in Europe to the question of interfacial spin transport in the ballistic regime. To date, published reports in this area have been primarily theoretical, with recent contributions from Grundler at Hamburg (Grundler 2001), C.M. Hu and T. Matsuyama at Hamburg (Hu and Matsuyama. 2001), from Halle (Bruno and Pareek 2001), from a Wurzburg and Delft collaboration (Molenkamp, Schmidt, and Bauer 2001), and from Orsay (Fert and Jaffres 2001), but experimental work in the ballistic regime is said to be underway at several laboratories.

Ballistic and quasiballistic spin transport in the high energy, hot electron regime has been a major focus of Prof. Lodder's group at Twente. There work continues on the study and development of the spin valve transistor, which utilizes for its functionality the spin-dependent inelastic scattering length of injected hot-carriers as they pass through a ferromagnetic multilayer base to a semiconductor collector. The knowledge regarding the spin-dependent scattering of hot electrons that this program is developing could also be quite useful for future hot electron spin injection experiments (Monsma et al. 1995; Jansen et al. 2001b).

The control of the spin orientation of carriers in a 2D electron structure by application of a gate electrode bias has been the subject of considerable research interest in Europe for some time. Researchers at Hamburg are particularly active in this area and have had significant collaborations with the NTT spin electronics group on this topic recently (Hu et al. 2001).

The proposal of Loss (Basel) and collaborators of a qubit based on gated spin-dependent tunneling between quantum dots is stimulating experimental programs to attempt to realize this new type of quantum computation device. An example of a recent quantum dot study relevant to this area is the study by Kouwenhoven and coworkers at Delft, in collaboration with NTT researchers, of the Kondo effect in an integer spin quantum dot (Sasaki et al. 2000).

Given the very strong research base and expertise in Europe in the area of GMR and magnetic tunnel junction research, it is not surprising that there is strong interest in the application of the spin-dependent scattering of polarized currents to manipulate the magnetic orientation of thin film nanomagnets. An important early demonstration of spin transfer phenomena was the point contact spin injection experiments of Tsoi and coworkers at Grenoble (Tsoi et al. 1998a; 1998b), which demonstrated that strong spin-polarized currents could excite uniform spin wave modes in thin film magnetic multilayers. At Lausanne, Wegrowe and coworkers have been actively pursuing the study of current-induced magnetization reversal in magnetic nanowires for the past few years (Wegrowe et al. 1999). Recently the magnetics group at Orsay has also begun research into the spin transfer effect, demonstrating the reversible, hysteretic switching of a free Co nanomagnet with a spin-polarized current (Grollier 2001). A number of other research groups are also indicating interest in this new area of spin-based research.

CONCLUDING COMMENTS

Spin injection, spin transport, and spin transfer research is being actively pursued in a number of top rank laboratories in Japan and in Europe. After a period of time in which experimental progress in the area of spin injection was slow, there now is a rapidly developing understanding of the advantages and challenges of various alternative approaches for spin injection, and the past year has seen rapid progress. Materials quality and materials control are clearly key issues in spin injection and spin transport research, particularly the challenge of forming nearly ideal ferromagnet/semiconductor interfaces for high efficiency spin injection. For progress to continue it will perhaps be necessary to substantially advance understanding and control of spin lifetimes at and near metal/semiconductor interfaces; new approaches for the study of spin-dependent transport at such interfaces would be highly desirable. The broad and impressive strengths in Japan in the area of new materials discovery and development can be expected to result in a number of additional leading contributions to the emerging spin electronics field. Similarly, the very well equipped thin film growth and nanofabrication laboratories that participate in spin electronics research in Japan can be expected to make major contributions in the years ahead. In Europe, broad theoretical and experimental capabilities are being brought to bear on the fundamental questions of spin transport in heterogeneous systems. The extensive expertise in the areas of magnetism, electronic and magnetic materials, and mesoscopic physics that is very well established in Europe also indicates that the upcoming decade will be a very productive and competitive time for spin-based electronics research efforts worldwide.

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