ORIGIN, DEVELOPMENT AND FUTURE OF SPINTRONICS

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Introduction

Spintronics, at the interface between magnetism and electronics, is a new field of research in considerable expansion. The basic concept of spintronics is the manipulation of spin currents, in contrast to mainstream electronics in which the spin of the electron is ignored. Adding the spin degree of freedom provides new effects, new capabilities and new functionalities. Everybody has already a spintronic device on their desktop, since the read heads of the hard disc drives of today use the giant magnetoresistance (GMR) phenomenon to read the magnetic information on the disc. The GMR, discovered at Orsay[1] and Jülich[2] in 1988, exploits the influence of the spin of the electrons on the electrical conduction in a magnetic multilayer composed of alternate ferromagnetic and nonmagnetic layers, Fe and Cr for example. The influence of the spin on the mobility of the electrons in ferromagnetic metals, first suggested by Mott[3], had been experimentally demonstrated and theoretically described in early works[4-5] more than ten years before the discovery of 1988. The GMR was the first step on the road of the utilization of the spin degree of freedom in magnetic nanostructures and triggered the development of an active field of research which has been called spintronics. Today this field is extending considerably, with very promising new axes like the phenomena of spin transfer, spintronics with semiconductors, molecular spintronics or single-electron spintronics.

From spin dependent conduction in ferromagnets to giant magnetoresistance

The roots of spintronics are in preceding researches on the influence of the spin on the electrical conduction in ferromagnetic metals[3-5]. The splitting between the energy band of the “majority spin” (spin up in the usual notation) and “minority spin” (spin down) directions, as shown in Fig. 1a, makes that the electrons at the Fermi level, which carry the electrical current, are in different states for opposite spin directions and exhibit different conduction properties. In first approximation, the conduction is by two channels in parallel (Fig. 1b). This spin dependent conduction, proposed by Mott[3] in 1936 to explain some features of the resistivity of ferromagnetic metals at the Curie temperature, was experimentally demonstrated in the sixties[4-5]. In Fig. 1c I show an example of experimental results[4] for Ni doped with different types of impurity. This led to the so-called “two current model” for

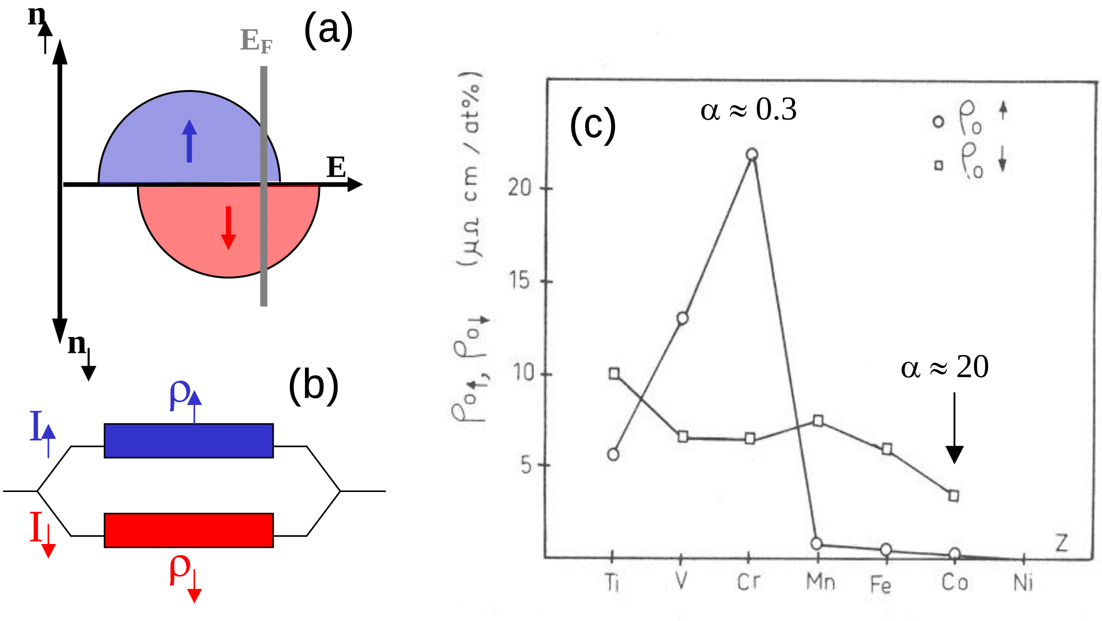

Figure 1. Basics of spintronics. (a) Schematic band structure of a ferromagnetic metal showing the energy band spin-splitting . (b) Schematic for spin dependent conduction through independent spin ↓ and spin↑ channels in the limit of negligible spin mixing ($\rho_{\uparrow\downarrow} = 0$ in the formalism of Ref.[4]). (c) Resistivities of the spin up and spin down conduction channels for nickel doped with 1% of several types of impurity (measurements at 4.2 K)[4]. The ratio α between the resistivities $\rho_{0\downarrow}$ and $\rho_{0\uparrow}$ of the spin ↓ and spin↑ channels can be as large as 20 (Co impurities) or, as well, smaller than one (Cr or V impurities).

the conduction in ferromagnets[4-5]. Some experiments[4] with metals doped with two types of impurities (ternary alloys) were already anticipating the GMR concept but proceeding to the GMR of multilayers was requiring layer thicknesses in the nm range and was not possible at this time But the concept In the mid-eighties, with the development of techniques like the Molecular Beam Epitaxy (MBE), it became possible to fabricate multilayers composed of very thin individuals layers and I could consider trying to extend my experiments on ternary alloys to multilayers. In addition, in 1986 Brillouin scattering experiments of Peter Grünberg and coworkers[6] revealed the existence of antiferromagnetic interlayer exchange couplings in Fe/Cr multilayers. Fe/Cr appeared as a magnetic multilayered system in which it was possible to switch the relative orientation of the magnetization in adjacent magnetic layers from antiparallel to parallel by applying a magnetic field. We fabricated Fe/Cr multilayers and this led to our first observation[1] of GMR in 1988 (Fig.2a). Similar results were obtained practically at the same time by Peter Günberg at Jülich[2] (Fig. 2b). The interpretation is illustrated in Fig. 2c. Rapidly, these results attracted attention for their fundamental interest as well as for the many possibilities of application to the detection of small magnetic fields. The first

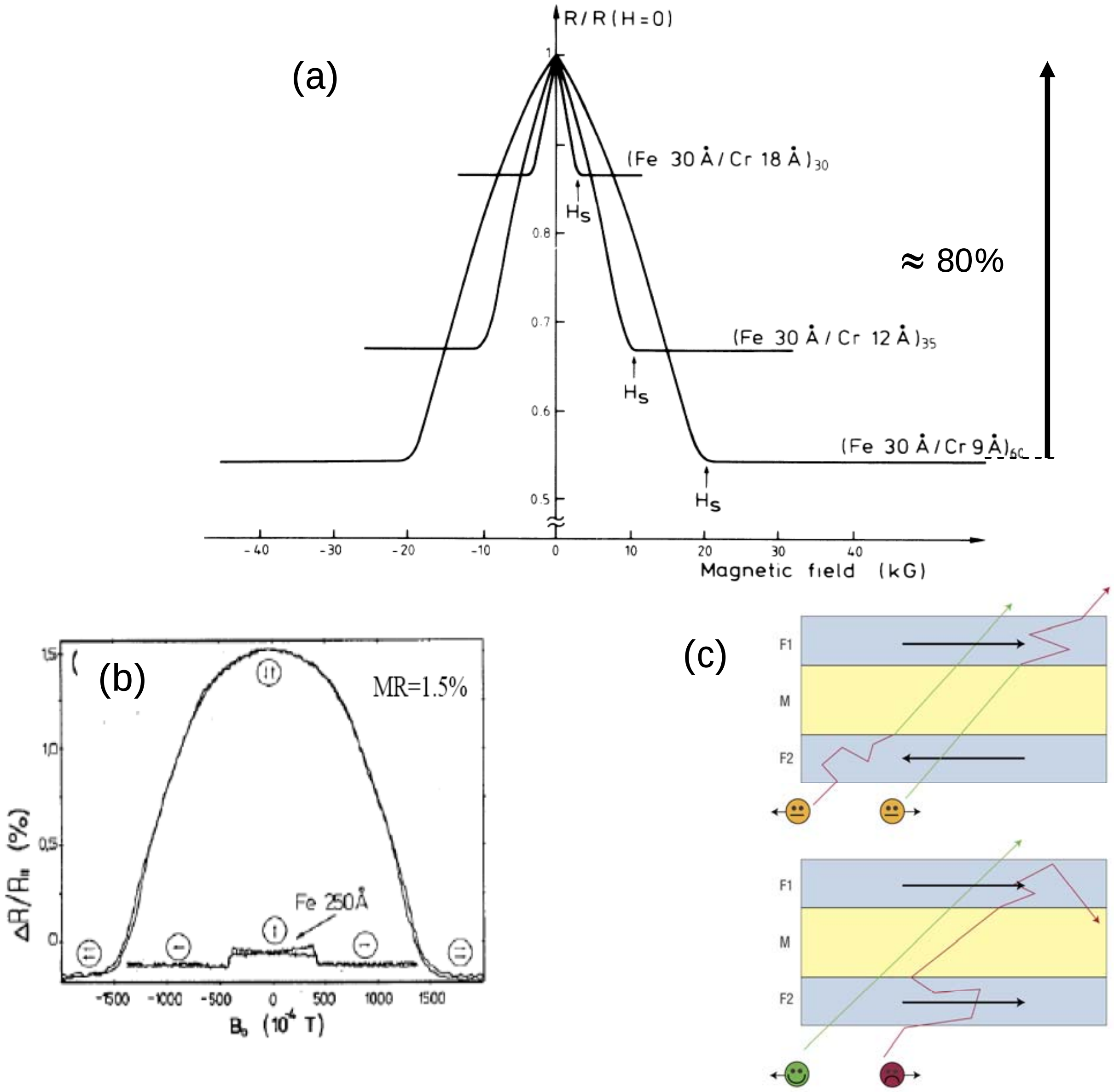

Figure 2: First observations of giant magnetoresistance. (a) Fe/Cr(001) multilayers[1] (with the current definition of the magnetoresistance ratio, MR= $100(R_{AP}-R_P)/R_p$, MR = 85% for the (Fe 3nm/Cr 0.9nm) multilayer). (b) Fe/Cr/Fe trilayers[2]. (c) Schematic of the mechanism of the GMR. In the parallel magnetic configuration (bottom), the electrons of one of the spin directions can go easily through all the magnetic layers and the short-circuit through this channel lead to a small resistance. In the antiparallel configuration (top), the electrons of each channel are slowed down every second magnetic layer and the resistance is high.

applications, magnetic sensors for the automotive industry, appeared in 1993. The application to the read haeds of hard discs appeared in 1997 and led rapidly to a considerable increase of the the density of information stored in discs (from 1 Gbit/in^2 to 200 Gbit/in^2 today).

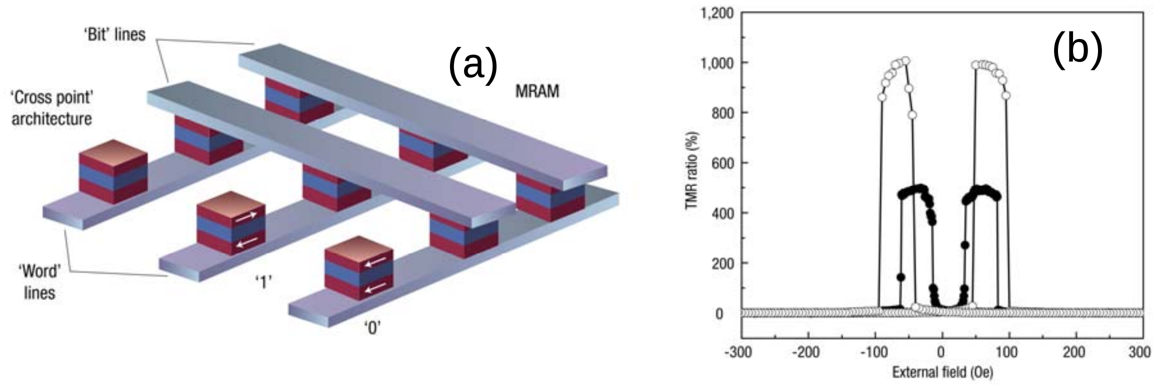

Figure 3. : (a) Principle of the magnetic random access memory MRAM in the basic "cross point" architecture. The binary information "0" and "1" is recorded on the two opposite orientations of the magnetization of the free layer of magnetic tunnel junctions (MTJ), which are connected to the crossing points of two perpendicular arrays of parallel conducting lines. For writing, current pulses are sent through one line of each array, and only at the crossing point of these lines the resulting magnetic field is high enough to orient the magnetization of the free layer. For reading, one measures the resistance between the two lines connecting the addressed cell.. (b) High magnetoresistance, $TMR=(R_{max}-R_{min})/R_{min}$, measured by Lee et al[12] for the magnetic stack: $(Co_{25}Fe_{75})_{80}B_{20}$(4nm)/MgO(2.1nm)/$(Co_{25}Fe_{75})_{80}B_{20}$(4.3nm) annealed at 475°C after growth, measured at room temperature (black circles) and low temperature (open circles).

During the first years of the research on GMR, the experiments were performed only with the current flowing along the layer planes, in the geometry we call now CIP (Current In Plane). It is only in 1993 that experiments of CPP-GMR begun to be performed, that is experiments of GMR with the Current Perpendicular to the layer Planes. This was done[7] either by sandwiching a magnetic multilayer between superconducting electrodes, and by electrodepositing the multilayer into the pores of a polycarbonate membrane. In the CPP-geometry, the GMR is not only definitely higher than in CIP, but also subsists in multilayers with relatively thick layers, up to the micron range[7]. In a theoretical paper with Valet[8], I showed that, due to spin accumulation effects occurring in the CPP-geometry, the length scale of the spin transport becomes the long spin diffusion length in place of the mean free path for the CIP-geometry. Actually, the CPP-GMR has revealed the spin accumulation effects which govern the propagation of a spin-polarized current through a succession of magnetic and nonmagnetic materials and play an important role in all the present developments of spintronics.

Magnetic tunnel junctions and tunnelling magnetoresistance (TMR)

Another important phenomenon in spintronics is the Tunnelling Magnetoresistance (TMR) of the Magnetic Tunnel Junctions(MTJ) which are tunnel junctions with ferromagnetic electrodes. The resistance of MTJ is different for the parallel and antiparallel magnetic configurations of their electrodes. Some early observations of TMR effects, small and at low temperature, had been already reported by Jullière[9] in 1975, but they were not easily reproducible and actually could not be really reproduced during 20 years. It is only in 1975 that large (≈ 20%) and reproducible effects were obtained by Moodera's and Miyasaki's groups on MTJ with a tunnel barrier of amorphous alumina[10]. From a technological point of view, the interest of the MTJ with respect to the metallic spin valves comes from the vertical direction of the current and from the resulting possibility of a reduction of the lateral size to a submicronic scale by lithographic techniques. The MTJ are at the basis of a new concept of magnetic memory called MRAM (Magnetic Random Access Memory) combining the short access time of the semiconductor-based RAM and the non-volatile character of the magnetic memories. In the first MRAM, put on the market in 2006, the memory cells are MTJ with an alumina barrier. The magnetic fields generated by "word" and "bit" lines are used to switch their magnetic configuration, see Fig.3a. The next generation of MRAM, based on MgO tunnel junctions and a switching process by spin transfer, is expected to have a much stronger impact on the technology of computers.

The research on the TMR is currently very active and an important recent step was the transition from MTJ with amorphous tunnel barrier (alumina) to single crystal MTJ and especially MTJ with MgO barrier, see Fig. 3b. The first results on MTJ with epitaxial MgO barriers we obtained in 2001 in a collaboration with a Spanish group[11] were rapidly and greatly improved by two laboratories in 2004[12].A single crystal barrier filters the symmetry of the wave functions of the tunnelling electrons, so that the TMR depends on the spin polarization of the electrodes for the selected symmetry and can be very high. Today the research on TMR is still very active and tunneling through ferromagnetic, ferroelectric or multiferroic barriers is a promising direction of research[13].

Magnetic switching and microwave generation by spin transfer.

The study of the spin transfer phenomena is one of the most promising new directions in spintronics today. In spin transfer experiments, one manipulates the magnetic moment of a ferromagnetic body without applying any magnetic field but only by transfer of spin angular momentum from a spin-polarized current. The concept, which has been introduced by John Slonczewski[14] and appears also in papers of Berger[15], is illustrated in Fig.4. As described in the caption of the figure, the transfer of a transverse spin current to the "free" magnetic layer F_2 can be described by a torque acting on its magnetic moment. This torque can induce an irreversible switching of this magnetic moment or, in a second regime, generally in

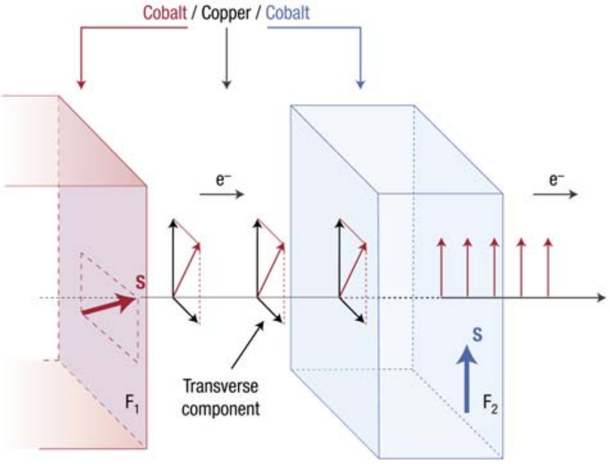

Figure 4: Illustration of the spin transfer concept introduced by John Slonczewski in 1996. A spin-polarized current is prepared by a first magnetic layer F with an obliquely oriented spin-polarization with respect to the magnetization axis of a second layer F_2. When this current goes through F_2, the exchange interaction aligns its spin-polarization along the magnetization axis. As the exchange interaction is spin conserving, the transverse spin-polarization lost by the current has been transferred to the total spin of F_2, which can also be described by a spin-transfer torque acting on F_2.This can lead to a magnetic switching of the F_2 layer or, depending on the experimental conditions, to magnetic oscillations in the microwave frequency range.

the presence of an applied field, it generates precessions of the moment in the microwave frequency range.

Most experiments are performed on pillar-shaped metallic trilayers (Fig.5a). In Fig.5b, I present examples of our experimental results in the low field regime of irreversible switching, for a metallic pillar and for a tunnel junctions with electrodes of the ferromagnetic semiconductor $Ga_{1-x}Mn_xAs$. For metallic pillars or tunnel junctions with electrodes made of a dilute ferromagnetic transition metal like Co or Fe, the current density needed for switching is around 10^6-10^7 Amp/cm^2, which is still slightly too high for applications, and an important challenge is the reduction of this current density. The switching time has been measured in other groups and can be as short as 100 ps, which is very attractive for the switching of MRAM. For the tunnel junction of Fig.5c, the switching current is only about 10^5 Amp./cm^2 and smaller than that of the metallic pillar by two orders of magnitude. This is because a smaller number of individual spins is required to switch the smaller total spin momentum of a dilute magnetic material.

In the presence of a large enough magnetic field, the regime of irreversible switching of the magnetization of the “free” magnetic layer in a trilayer is replaced by a regime of steady precessions of this free layer magnetization sustained by the spin transfer torque. As the angle between the magnetizations of the two magnetic

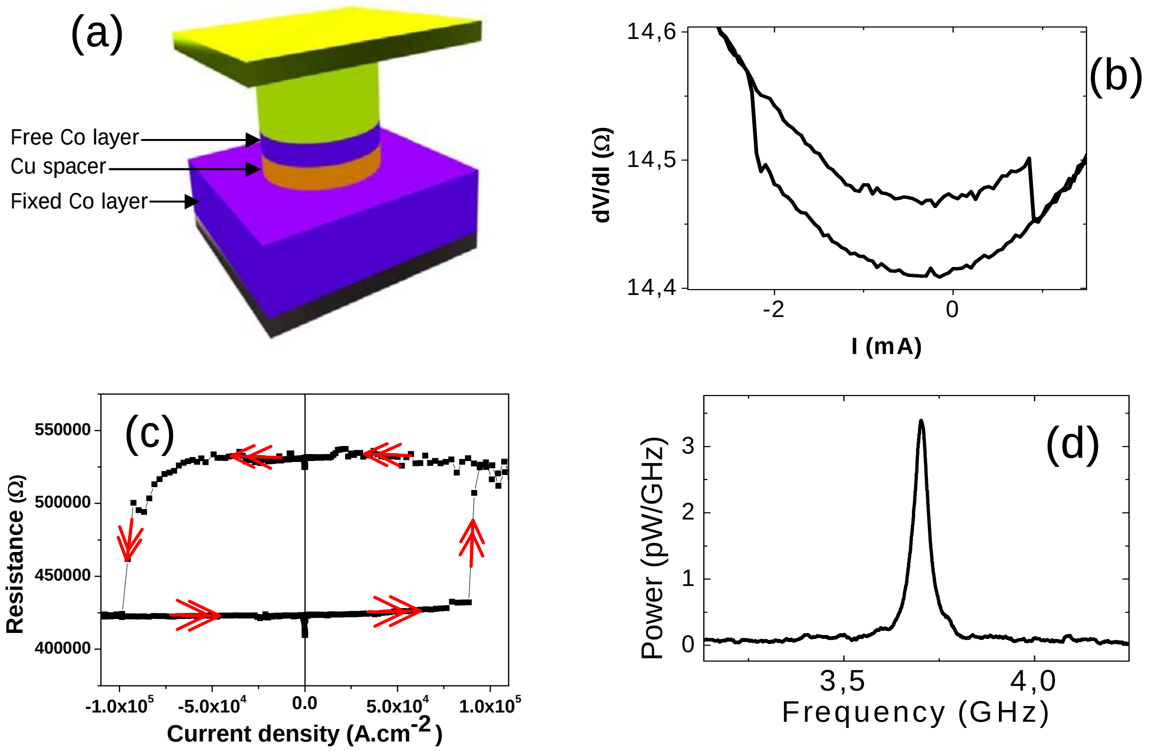

Figure 5: Experiments of magnetic switching and microwave generation induced by spin transfer from an electrical DC current in trilayered magnetic pillars. (a) Shematic of a trilayered magnetic pillar. (b) Switching by spin transfer between the parallel and antiparallel magnetic configurations of a Co/Cu/Co metallic pillar. The switching between parallel and antiparallel orientations of the magnetizations of the two magnetic layers of the trilayer is detected by irreversible jumps of the resistance at a critical value of the current. The critical current density is of the order of 10^7 A/cm^2. (c) Switching by spin transfer of a pillar-shaped tunnel junction composed of electrodes of the dilute ferromagnetic semiconductor GaMnAs separated by a tunnel barrier of InGaAs. The critical current is about hundred times smaller than in the Py/Cu/Py pillar. (d) Typical microwave power spectrum of a Co/Cu/Py pillar (Py =permalloy).

layers varies periodically during the precession, the resistance of the trilayer oscillates as a function of time, which generates voltage oscillations in the microwave frequency range, see the record of the microwave power versus frequency in Fig.5d. In other conditions, the spin transfer torque can also be used to generate an oscillatory motion of a magnetic vortex.

The spin transfer phenomena will have certainly important applications. Switching by spin transfer will be used in the next generation of MRAM and will bring great advantages in terms of precise addressing and low energy consumption. The generation of oscillations in he microwave frequency range will lead to the design of Spin Transfer Oscillators (STOs). One of the main interests of the STOs is their agility, that is the possibility of changing rapidly their frequency by tuning a DC current. Their disadvantage is the very small microwave power of an individual STO, metallic pillar or tunnel junction. The solution is certainly the synchronization of a large number of STOs.

Spintronics with semiconductors.

Spintronics with semiconductors is very attractive as it can combine the potential of semiconductors (control of current by gate, coupling with optics, etc) with the potential of the magnetic materials (control of current by spin manipulation, non-volatility, etc). It should be possible, for example, to gather storage, detection, logic and communication capabilities on a single chip that could replace several components. New concepts of components have also been proposed, for example the concept of Spin Field Effect Transistors (Spin FETs) based on spin transport in semiconductor lateral channels between spin-polarized source and drain with control of the spin transmission by a field effect gate[17]. Some nonmagnetic semiconductors have a definite advantage on metal in terms of spin-coherence time and propagation of spin polarization on long distances. Spintronics with semiconductors is currently developed along several roads.

i) The first road is by working on hybrid structures associating ferromagnetic metals with nonmagnetic semiconductors. Schmidt et al[18] have raised the problem of "conductivity mismatch" to inject a spin-polarized current from a magnetic metal into a semiconductor. Solutions have been proposed by the theory[19-20] and one knows today that the injection/extraction of a spin-polarized current into/from a semiconductor can be achieved with a spin-dependent interface resistance, typically a tunnel junction. Spin injection/extraction through a tunnel contact has been now demonstrated. in spin LEDs and magneto-optical experiments. However, in structures for lateral spin transport between spin-polarized sources and drains (typical structures for logic gate or transistor applications), only very modest results have been obtained up to now, the contrast between parallel and antiparallel magnetic configurations of the source and the drain never exceeding a few %.

a. Another road for spintronics with semiconductors is based on the fabrication of ferromagnetic semiconductors. The ferromagnetic semiconductor $Ga_{1-x}Mn_xAs$ ($x \approx$ a few %) has been discovered[21] by the group of Ohno in Sendai in 1996, and, since this time, has revealed very interesting properties, namely the possibility of controlling the ferromagnetic properties with a gate voltage, and also large TMR and TAMR (Tunnelling Anisotropic Magnetoresistance) effects. However its Curie temperature has reached only 170 K, well below room

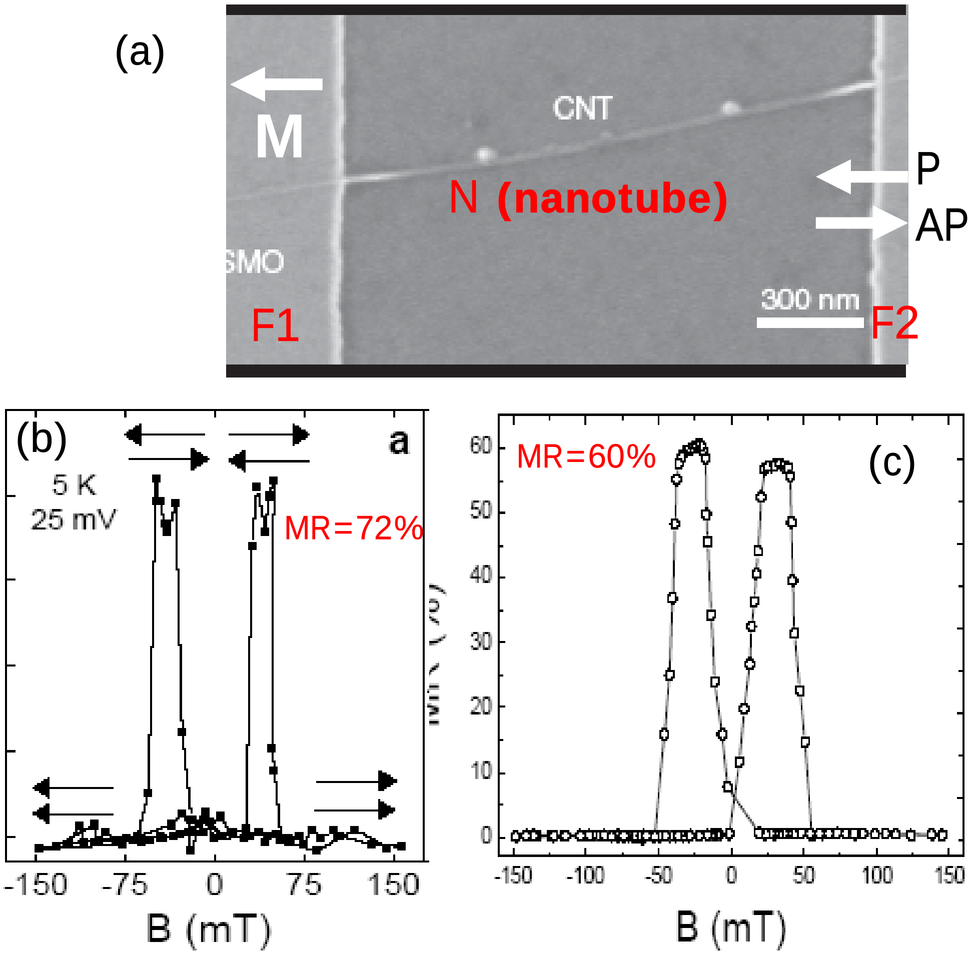

Figure 6. Spintronics with molecules illustrated by, (a): Electron microscopy image of a carbon nanotube between LSMO electrodes (LSMO = $La_{2/3}Sr_{1/3}MnO_3$). (b-c): Magnetoresistance experimental results[22] at 4.2 K on carbon nanotubes between electrodes made of LSMO. A contrast of 72% and 60 % is obtained between the resistances for the parallel (high field) and antiparallel (peaks) magnetic configurations of the source and drain.

temperature, which rules out most practical applications. Several room temperature ferromagnetic semiconductors have been announced but the situation is not clear on this front yet.

ii) The research is now very active on a third road exploiting spin-polarized currents induced by spin-orbit effects, namely the Spin Hall, Rashba or Dresselhaus effects. In the Spin Hall Effect[21], for example, spin-orbit interactions deflect the currents of the spin up and spin down channels in opposite transverse directions, thus inducing a transverse spin current, even in a nonmagnetic conductor. This could be used to create spin currents in structures composed of only nonmagnetic conductors.

Spintronics in carbon-based materials

Spintronics with carbon nanotubes, graphene or organic molecules is a very promising road. The advantage is the long spin lifetime due to the sall spin-orbit coupling of carbon and also, for nanotubes ot graphene, and also the very high electron velocity in natubes and graphene which makes that, for exemple, their dwell time in a long lateral channel can be shorter then the spin lifetime. In contrast with what is found for transport in devices based on semiconductors, experiments on carbon nanotubes have shown that the spin information can be transported to long distances and transformed in large electrical output signals. In Fig.6 we present an example of experimental result with a nanotube between LSMO electrodes[22]. This show the potential of carbon-based electronics.

Conclusion

In less than twenty years, we have seen spintronics increasing considerably the capacity of our hard discs and getting ready to enter the RAM of our computers or the microwave emitters of our cell phones. Spintronics with semiconductors or molecules is very promising too. It can also be mentioned that another perspective, out of the scope of this lecture, might be the exploitation of the truly quantum mechanical nature of spin and the long spin coherence time in confined geometry for quantum computing in an even more revolutionary application. Spintronics should take an important place in the technology of our century.

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