Thin Solid Films 517 (2008) 2–5

Contents lists available at ScienceDirect

Thin Solid Films

journal homepage: www.elsevier.com/locate/tsf

The present and the future of spintronics

Albert Fert

Unité Mixte de Physique CNRS/Thales, 91767, Palaiseau, and Université Paris-Sud, 91405, Orsay, France

ARTICLE INFO

Available online 31 August 2008

Keywords:
Spintronics
Giant magnetoresistance
Spin transport
Nanomagnetism

ABSTRACT

The article describes the development of spintronics from the first studies of spin dependent transport in ferromagnetic materials to the discovery of the giant magnetoresistance and to the most recent advances.
© 2008 Elsevier B.V. All rights reserved.

1. 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.

2. 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” and “minority spin” directions (spin up and spin down in the usual notation) 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. 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], which led to the so-called “two current model” for the conduction in ferromagnets [4,5] (Fig. 1).

Some experiments [4,5] with metals doped with two types of impurities 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. 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. Similar results were obtained practically at the same time by Peter Günberg at Jülich [2]. Rapidly, these results attracted attention for their fundamental interest as well as for the many possibilities of application. The first applications, magnetic sensors for the automotive industry, appeared in 1993. The application to the read heads of hard discs appeared in 1997 and led rapidly to a considerable increase of the density of information stored in discs (from 1Gbit/in^2 to 600Gbit/in^2 today) (Fig. 2).

3. 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

E-mail address: albert.fert@thalesgroup.com.

0040-6090/$ – see front matter © 2008 Elsevier B.V. All rights reserved.
doi:10.1016/j.tsf.2008.08.172

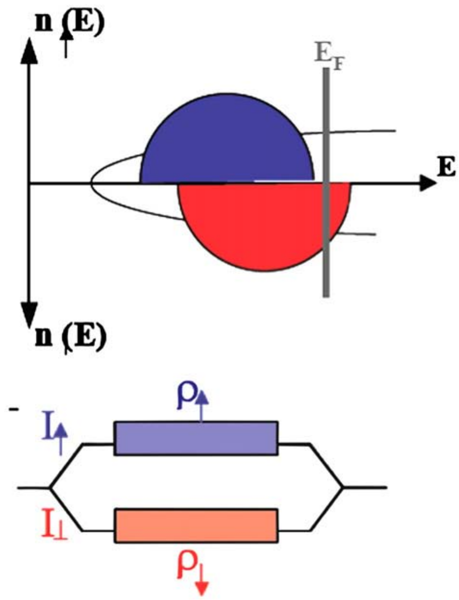

Fig. 1. Top: typical band structure of a ferromagnetic metal. Bottom: Schematic of the two-current conduction in a ferromagnetic material.

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 [7] in 1975, but they were not easily reproducible and actually could not be really reproduced during 20years. 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 [8] (Fig. 3).

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

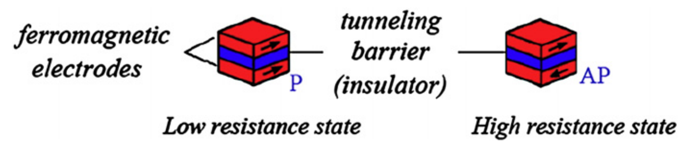

Fig. 3. Magnetic tunnel junction composed of two ferromagnetic layers separated by an insulating layer. The resistance of the junction is different for the parallel (P) and antiparallel (AP) magnetic configurations.

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. The next generation of MRAM, based on MgO tunnel junctions [9] and a switching process by spin transfer, is expected to have a much stronger impact on the technology of computers (Fig. 4).

4. Magnetic switching and microwave generation by spin transfer

The study of the spin transfer phenomena is one of the most promising new fields of research 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 has been introduced by John Slonczewski [10] and appears also in papers of Berger [11]. The transfer of a transverse spin current to the "free" magnetic layer can be described by a torque acting on its magnetic moment. This torque can induce an irreversible switching of this magnetic moment [12,13] or, in a second regime, generally in the presence of an applied field, it generates precessions of the moment in the microwave frequency range [14]. Switching by spin transfer will be applied to the writing process of the next generation of MRAM, while

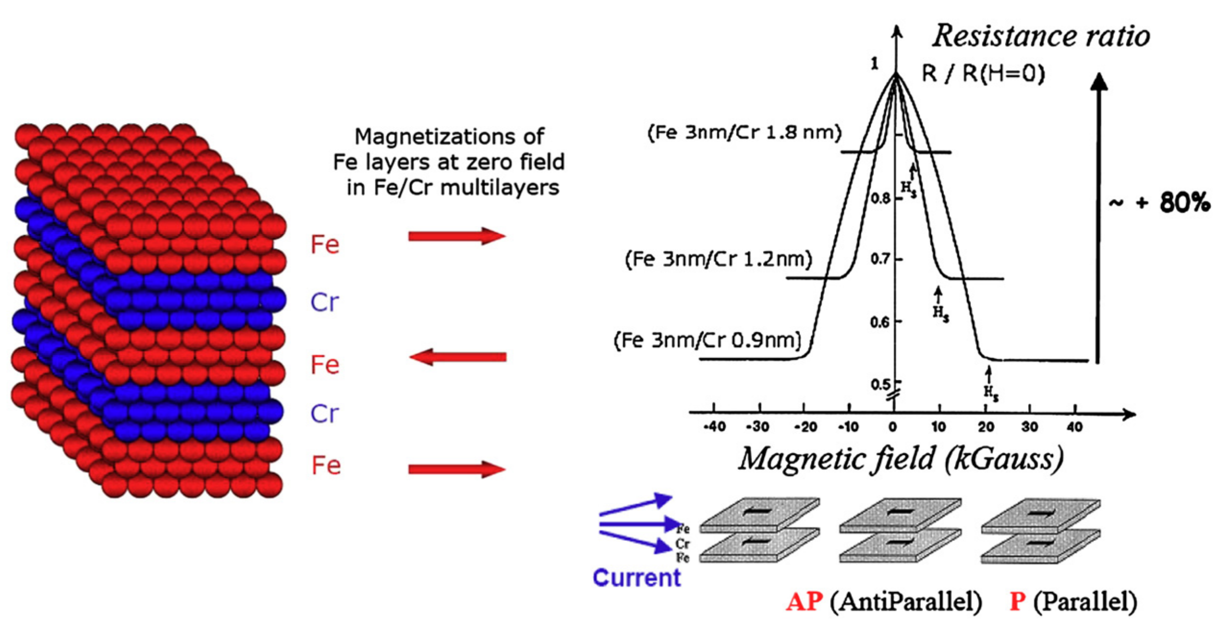

Fig. 2. Left: Structure of a Fe/Cr multiplayer. The arrow indicate the relative orientations of the magnetization in successive Fe layers at zero field when the interlayer coupling is antiferromagnetic. Right: Magnetoresistance measurements (4.2 K) for $(Fe/Cr)_n$ multilayers. To the far right ($>H_S$, where H_S is the saturation field) as well as to the far left ($<-H_S$) the magnetizations of all iron layers are aligned by the external magnetic field and the resistivity is low. At zero field the magnetizations of adjacent Fe layers are in opposite directions (as in the left figure) and the resistivity is large. From Baibich et al [1].

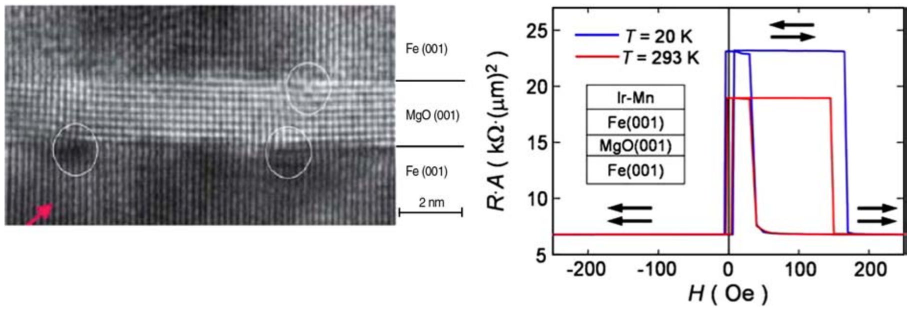

Fig. 4. Magnetic Tunnel Junction with epitaxial MgO tunnel barrier. Left: TEM image. Right: TMR curves. The TMR ratio can be as high as 250%. From Yuasa et al. [9].

the generation of microwave will have multiple applications in telecommunications (Fig. 5).

5. Spintronics with semiconductors and molecular spintronics

Spintronics with semiconductors [15,16] 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. However, the long standing problem of the Spin FET it still far from being solved.

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 the "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 now been demonstrated in spin LEDs and magneto-optical experiments.

ii) 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 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.

iii) 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 [22], 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.

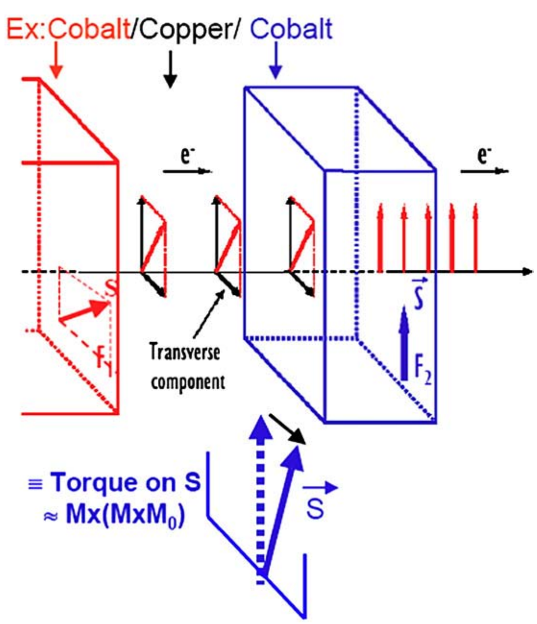

Fig. 5. Schematic illustrating the transfer of the transverse component of the spin current to the total spin of the layer on the right.

6. 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.

References

[1] M.N. Baibich, J.M. Broto, A. Fert, F. Nguyen Van Dau, F. Petroff, P. Etienne, G. Creuzet, A. Friederich, J. Chazelas, Phys. Rev. Lett. 61 (1988) 2472.
[2] G. Binash, P. Grünberg, F. Saurenbach, W. Zinn, Phys. Rev., B 39 (1989) 4828.
[3] F. Mott, Proc. Roy. Soc. A 153 (1936) 699.
[4] A. Fert, I.A. Campbell, Phys. Rev. Lett. 21 (1968) 1190;
B. Loegel, F. Gautier, J. Phys. Chem. Sol. 32 (1971) 2723.
[5] A. Fert, I.A. Campbell, J. Physique 32 (1971) C1;
A. Fert, I.A. Campbell, J. Phys. F 6 (1976) 849.
[6] P. Grünberg, R. Schreiber, Y. Young, M.B. Brodsky, H. Sowers, Phys. Rev. Lett. 57 (1986) 2442.
[7] Jullière, Phys. Lett. 54A (1975) 225.

[8] J.S. Moodera, L.R. Kinder, T.M. Wong, R. Meservey, Phys. Rev. Lett. 74 (1995) 3273; T. Miyazaki, N. Tezuka, J. Magn. Magn. Mater. 139 (1995) 231.
[9] S.S.P. Parkin, et al., Nature Mater. 3 (2004) 862; Yuasa, et al., Nature Mater 3 (2004) 868.
[10] J.C. Slonczewski, J. Magn. Mat. 159 (1996) L1.
[11] L. Berger, Phys. Rev., B 54 (1996) 9353.
[12] Katine, et al., Phys. Rev. Lett. 84 (2000) 3149.
[13] J. Grollier, V. Cros, A. Hanzic, J.M. George, H. Jaffres, A. Fert, G. Faini, J. Ben Youssef, H. Le Gall, Appl. Phys. Lett. 78 (2001) 3663.
[14] W.H. Rippart, et al., Phys. Rev. Lett. 92 (2004) 027201.
[15] B.T. Jonker, M.E. Flatté, in: D.L. Mills, J.A.C. Bland (Eds.), Nanomagnetism, Elsevier, 2006, p. 227.
[16] D.D. Awschalom, M.E. Flatté, Nat. Phys. 3 (2007) 153.
[17] S. Datta, B. Das, Appl. Phys. Lett. 56 (1990) 665.
[18] G. Schmidt, et al., Phys. Rev., B 62 (2000) 4790.
[19] E. Rashba, Phys. Rev., B 62 (2000) R46267.
[20] A. Fert, H. Jaffrès, Phys. Rev., B 64 (2001) 184420. A. Fert, J-M. George, H. Jaffrès, R. Mattana, preprint at http://arxiv.org/abs/cond-mat/0612495.
[21] H. Ohno, et al., Appl. Phys. Lett. 69 (1996) 363.
[22] Y. Kato, R.C. Myers, A.C. Gossard, D.D. Awschalom, Science 306 (2004) 1910.