MAGNETORESISTANCE PHENOMENA IN MAGNETIC MATERIALS AND DEVICES

J. M. De Teresa

Instituto de Ciencia de Materiales de Aragón, Universidad de Zaragoza-CSIC, Facultad de Ciencias, 50009 Zaragoza, Spain.

E-mail: deteresa@unizar.es

The study of electrical transport in magnetic materials has a long history. However, since the discovery in 1988 of the so-called giant magnetoresistance (GMR) in metallic multilayers [1], the subject has generated a great deal of interest. This was important not only from the basic research point of view but also from the applied research point of view. In 1997 IBM introduced in the hard-disk technology magnetoresistive read heads based on the GMR effect, which has allowed the increase in the density of the stored information in hard disks at a rate much beyond previous technologies [2]. GMR can be considered to be the first paradigm of the so-called ***Spin Electronics***, where, in sharp contrast with semiconductor technology, the spin as well as the charge transport is taken into account. This field could be developed thanks to the fine nanometric control of thin films in the growth direction .

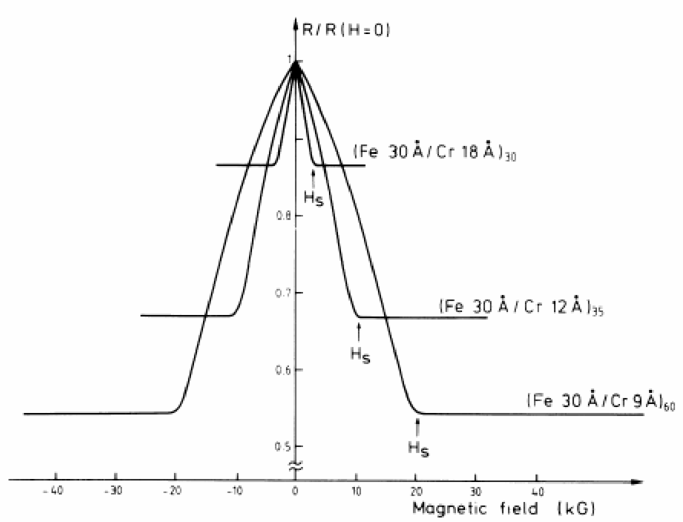

FIG. 3 Magnetoresistance of three Fe/Cr superlattices at 4.2 K. The current and the applied field are along the same [110] axis in the plane of the layers.

Figure 1. *Original figure included in reference [1], where the GMR effect was first reported*

In my talk I will start by introducing the basic concepts to understand the transport properties in magnetic solids. From the form of the resistivity tensor that relates the electric field and the current in a solid [3], I will introduce the concepts of anisotropic magnetoresistance, the ordinary and extraordinary Hall effect and the planar Hall effect. I will show some experimental examples of these phenomena and discuss the microscopic origin where basic ingredients are the Lorentz force acting upon the carriers and the spin-orbit interaction.

Afterwards, I will introduce other intrinsic magnetoresistance phenomena such us the spin-disorder magnetoresistance and the colossal magnetoresistance effect. An additional contribution to the resistance from spin disorder comes from the exchange interaction between the conduction electrons and the local magnetic moments and at low temperatures from the magnon-electron scattering [3]. By applying a magnetic field the local magnetic moments will tend to align and the spin-disorder resistance will change giving rise to the spin-disorder magnetoresistance. A very large magnetoresistance effect was discovered in the early nineties in manganese oxides which was coined "colossal magnetoresistance" (CMR) [4, 5]. In these materials the electrical resistance can be changed several orders of magnitude by application of a large magnetic field. This is a serious drawback for applications, which normally use small magnetic fields. I will discuss some examples of CMR compounds and the origin of the CMR effect, which is due to the release of the trapped carriers (at zero field) by the presence of a large magnetic field [6].

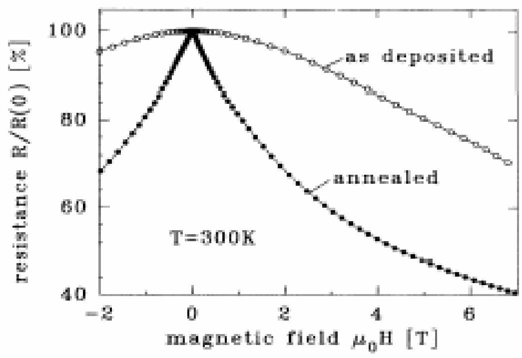

FIG. 3. Resistivity versus field curves for the as-deposited sample (T_S =600 °C) and after annealing at T_A =900 °C for 12 h, measured at T =300 K.

Figure 2. *Original figure included in reference [4], where the CMR effect was first reported on $La_{2/3}Ba_{1/3}MnO_3$ thin films.*

A new perspective for new magnetoresistive phenomena in magnetic heterostructures was open after the discovery of GMR in the late eighties [1] as explained before. GMR was observed in multilayers composed of alternating magnetic and non-magnetic layers. Basic ingredients to understand this effect are the different bulk and interface scattering probability of spin-up and spin-down conduction electrons, the spin-diffusion length compared to the layers thickness, the magnetic exchange coupling between the magnetic layers, the spin-accumulation effects, etc [2, 7]. In my talk I will first discuss the basic experiments that allow the understanding of this effect such as the magnetoresistance as a function of the non-magnetic and magnetic layers thickness, the influence of interface doping, etc. I will also discuss the difference between the current-in-plane (CIP) and current-perpendicular-to-plane (CPP) GMR geometries. The GMR effect can be also observed in granular materials containing magnetic and non-magnetic materials [8] and I will also show some example in this kind of system.

In order for the GMR to be of practical use, some technological improvements have been required. In that sense, I will discuss the spin-valve concept, which was developed in the early nineties at IBM [9] and allows one to obtain the full GMR effect at low magnetic field. This technology requires only two ferromagnetic layers separated by one non-magnetic layer and the exchange-biasing of one of the ferromagnetic layers with an antiferromagnetic layer. As the spin-dependent process only takes place along a few layers in the spin-valve device, the magnetoresistance ratio at room temperature is typically below 20%. In some applications a linear response of the GMR effect as a function of the magnetic field is desired. Some strategies have been envisaged to obtain such a response but one of the most used technologies is the crossed geometry of the easy axes of the ferromagnetic layers in a spin-valve configuration [10].

Another important phenomenon leading to very large magnetoresistance ratios has attracted much interest in recent years: the tunnel magnetoresistance effect (TMR). The TMR effect was proposed by Jullière in 1975 [11] but it was not actually developed until the late nineties [12]. Basically it consists of two ferromagnetic layers (electrodes) separated by a thin nanometric insulating layer (barrier). The conduction proceeds via electron tunnelling and the electrical resistance of such a device is different if the ferromagnetic layers have parallel or antiparallel magnetizations. The origin of this effect lies at the different tunnelling probability of spin-up and spin-down electrons.

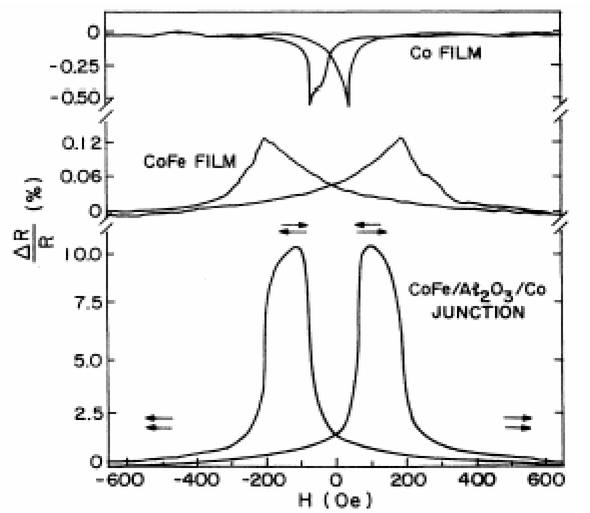

FIG. 2. Resistance of $CoFe/Al_2O_3/Co$ junction plotted as a function of H in the film plane, at 295 K. Also shown is the variation in the CoFe and Co film resistance. The arrows indicate the direction of M in the two films (see text).

Figure 3. *Original figure included in reference [12], where reproducible and large TMR values were first reported.*

Jullière proposed that the TMR ratio only depends on the spin polarization at the Fermi level of the ferromagnetic materials (P_1, P_2): TMR=100x(R_{AP}-R_P)/R_P=100xP_1P_2/(1-P_1P_2). The spin polarization at the Fermi level can be measured for example with the technique developed by Tedrow and Meservey [13]. By using CoFe ferromagnetic materials and Al_2O_3 barriers, high TMR ratios at room temperature (50%) have been achieved [14]. Motorola already announced in 2003 a 4-Mbit magnetic random access memory (MRAM) based on this kind of tunnel junctions implemented on the 180 nm CMOS technology and several companies are striving to place MRAM on the market [15]. The use of half-metallic ferromagnetic electrodes (P=±1) is very promising for getting the maximum TMR response. In fact, TMR ratios greater than 1000% were demonstrated at low temperature by using manganite electrodes but in these manganite-based junctions the response vanishes at room temperature [16]. An important step towards the understanding of the TMR came from experiments in junctions with one half-metal electrode ($La_{0.7}Sr_{0.3}MnO_3$), different barriers (Al_2O_3, $SrTiO_3$, Ce_xO_y) and interfaces, and a Co counter-electrode which showed that the TMR depends on bonding effects at the interface and can even give rise to inverse TMR (lower resistance in the antiparallel magnetic configuration of the electrodes) [17]. Definitely, this discovery fostered the use of new barriers and epitaxial junctions, where the response can be enhanced with respect to traditional Al_2O_3–based junctions. One of the most promising systems is Fe/MgO/Fe, where very large TMR ratios have been found at room temperature [18].

Finally, if time allows for it, I will discuss magnetoresistive effects which can be achieved in other systems such as spin-filtering devices, nanocontact-based devices, intergrain magnetoresistance, domain-wall magnetoresistance, etc.

References:

[1] M. Baibich et al., Phys. Rev. Lett. 61, 2472 (1988)

[2] "Spin dependent transport in magnetic nanostructures", edited by S. Maekawa and T. Shinjo. Advances in condensed matter science, volume 3, Taylor and Francis 2002.

[3] I.A. Campbell and A. Fert, "Transport properties of ferromagnets", Magnetic Materials, Vol. 3, Holland Publishing Company, 1982.

[4] R. Von Helmolt et al., Phys. Rev. Lett. 71, 2331 (1993)

[5] S. Jin et al., Science 264, 413 (1994)

[6] J.M. De Teresa et al., Nature (London) 386 (1997) 256

[7] A. Barthélémy et al., "Giant magnetoresistance in magnetic multilayers", Handbook of magnetic materials, vol. 12, edited by K.H.J. Buschow, Elsevier Science 1999.

[8] A.E. Berkowitz et al., Phys. Rev. Lett. 68, 3745 (1992); J.Q. Xiao et al., Phys. Rev. Lett. 68, 3749 (1992); X. Batlle and A. Labarta, J.Phys. D: Appl. Phys. 35, R15 (2002)

[9] B. Dieny et al., Phys. Rev. B 43, 1297 (1991)

[10] T. Rijks et al., Appl. Phys. Lett. 65, 916 (1994)

[11] M. Jullière, Phys. Lett. A 54, 225 (1975)

[12] J. Moodera et al., Phys. Rev. Lett. 74, 3273 (1995)

[13] R. Meservey and P.M. Tedrow, Phys. Rep. 238, 173 (1994)

[14] M. Tsunoda et al., Appl. Phys. Lett. 80, 3135 (2002); S. Colis et al., Appl. Phys. Lett. 83, 948 (2003)

[15] http://www.mram-info.com/

[16] M. Bowen et al., Appl. Phys. Lett. 82, 233 (2003)

[17] J. M. De Teresa et al., Phys. Rev. Lett. 82 (1999) 4288 and J. M. De Teresa et al., Science 286 (1999) 509

[18] M. Bowen et al., Appl. Phys. Lett. 79, 1655 (2001); J. Faure-Vincent et al., Appl. Phys. Lett. 82, 4207 (2002); S.S.P. Parkin, Nature Materials 3, 862 (2004); S. Yuasa et al., Nature Materials 3, 868 (2004); D.D. Djayaprawira et al., Appl. Phys. Lett. 86, 092502 (2005)