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REVIEW ARTICLE

Perpendicular transport of spin-polarized electrons through magnetic nanostructures

J-Ph Ansermet

Institut de Physique Expérimentale, Ecole Polytechnique Fédérale de Lausanne, PHB-Ecublens, CH-1015 Lausanne, Switzerland

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Abstract. A quasi one-dimensional model of spin transport in heterogeneous media based on the Boltzmann equation is presented in order to define the basic properties characterizing perpendicular spin transport in nanostructures. Experimental results are reviewed, first on the giant magnetoresistance of magnetic multilayers: spin dependent scattering in bulk and at interfaces, spin-diffusion length in the ferromagnetic layers and in the non-magnetic spacers. The observations of magnetoresistance associated with spin-scattering at Bloch walls are summarized. The junction magnetoresistance of ferromagnetic–insulator–ferromagnetic structures are reviewed, including the tunnel junctions produced with materials which present colossal magnetoresistance. An outlook on possible devices and novel structures is given.

1. The emergence of solid state spin electronics

What becomes of the spin of conduction electrons as they contribute to a current flowing through a magnetic nanostructure? The question has been the focus of an intense research activity ever since the advent of 'giant magnetoresistance' (GMR). This emerging field of research is often driven by the search for some very large magnetoresistive effect because of potential applications in magnetic recording and position sensor technology. However, it all started with fundamental research. Indeed, the study of indirect exchange coupling between adjacent magnetic layers separated by non-magnetic metallic layers has led the groups of Gruenberg at Juelich and Fert at Orsay to the discovery of the so-called giant magnetoresistance of magnetic multilayers [1, 2]. Independently, Johnson and Silsbee had investigated spin injection from a ferromagnet into a non-magnetic metal. As the multilayers were produced by thin film technology, the first GMR studied used current parallel to the interfaces (current-in-plane or CIP-MR). The so-called spin-valves were developed. They were nanostructures designed to produce reliably a parallel and antiparallel configuration of the magnetization in adjacent magnetic layers. They have enabled the group of Parkin and many others to gain insight into the origin of GMR [3]. Another attempt at nanostructuring can be seen in the study of GMR in granular materials, which started in 1992 [4, 5, 6].

Early in the 1990s it was conjectured that the MR ought be larger if the current were perpendicular to the planes (CPP-MR), and the data would be amenable to a more detailed analysis [7]. For this very reason, the focus of this review is on experiments dealing with perpendicular spin transport. In 1991, the first data on CPP-MR were published [8]. Major experimental efforts followed in order to detect and study CPP-MR. They are reported in the review of Bauer and Gijs [9]. The methods involved either an extremely sensitive measurement performed on samples generated with simple lithography [10] or they

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required forming a sample with a large aspect ratio: either by lithography [11, 12] or by electrodeposition in nanoporous membranes [13, 14]. Clever alternatives which relied on multilayer deposition on grooved substrates also gave access to CPP-MR [15, 16].

It was not until this year (1997) that the first study of CPP spin-valves was reported [17, 18].

Associated with this intense search for GMR, interest again arose in the 1990s in tunnelling between two ferromagnets, now referred to as junction MR (JMR) or tunnel MR (TMR) [19, 20, 21]. We prefer the term JMR, as TMR makes a specific claim as to the transport mechanism, which not always demonstrated. Likewise, the interest in the large magnetoresistance effect sparked a renewed interest in the manganate perovskites which were known to have a metal to insulator transition simultaneous with a ferro-to-paramagnetic phase transition [22]. By comparison to GMR, these compounds exhibit a so-called colossal magnetoresistance (CMR). We will allude to tunnelling experiments with such materials and with the so-called half-metallic ferromagnets like NiMnSb.

Currently, the research on spin transport is branching out in several directions. Devices based on spin electronics are developed. New types of nanostructure are under investigation, which involve transport through the interface between ferromagnets and semiconductors or superconductors for example.

The goal of this paper is to review experimental studies of perpendicular spin transport in nanostructures containing ferromagnets. In order to appreciate fully the research activity in this field, the basic notions involved in spin transport in magnetic nansostructures must be addressed. The basic spin effects include

- spin scattering (spin dependent diffusive electron transport),
- spin dependent ballistic electron transport,
- spin precession and
- spin-dependent tunnelling.

Most of the GMR research is based on the notion of *spin-flip scattering* mechanisms: in the bulk of ferromagnets, at interfaces between ferromagnets and non-magnetic layers, by collisions with magnons or with magnetic impurities in non-magnetic hosts. The notions of spin precession and spin tunnelling refer to two opposite extremes in spin evolution. In one case, the spin precesses about the exchange field which is changing according to the local magnetic configuration at the position of the electron. In the other case, the spin is instantaneously brought into an out-of-equilibrium position with respect to the local magnetization. In the case of ballistic electrons, the spin-dependent band structure may be the determining factor for spin transport.

Associated with these spin dynamical effects, a variety of transport regimes can occur:

- *spin diffusion* for transport across a sharp interface such as between two ferromagnets separated by a thin non-magnetic metal layer;
- *spin tunnelling* and *hopping* mechanisms;
- spin transport *at point contacts*.

The text is structured as follows. First, a simple model based on Boltzmann's equation is presented in order to bring forth some of the key ingredients of diffusive spin transport. On this basis, results can be presented on magnetic multilayers. Then the MR associated with Bloch walls is addressed. Finally, tunnelling experiments are evoked, including those performed with CMR materials, inasmuch as they can be viewed as half-metallic ferromagnets. To conclude, we try to convey the flourishing of activity on spin transport with a glance at many devices (transistors, memory cells, spin-wave-emitting diodes) and several extensions to ferromagnetic–semiconductor–ferromagnetic structures, or superconductor–ferromagnetic interfaces, etc.

Further information can be found in several review articles on GMR, in particular [23–26] among the very recent ones.

2. Basics of spin transport in heterogeneous media

2.1. Semi-classical, one-dimensional model of perpendicular spin transport

We describe a one-dimensional diffusive spin transport through a single interface with a simple application of the Boltzmann equation. It is one dimensional in the sense that heterogeneity in the perpendicular direction only is taken into account. It applies to three-dimensional systems with translational symmetry parallel to the planes. Its purpose is to introduce the basic quantities which are referred to in the review of experimental work below.

We consider a region of space where the current flows along the z axis and the magnetization is either up or down along the x axis. We introduce a distribution function $f_s(\boldsymbol{p}, \boldsymbol{r})$ for each spin direction. In other words, we add to the usual phase space $(\boldsymbol{p}, \boldsymbol{r})$ a new dimension, that associated with the spin. We have two types of collision to consider: with and without spin-flips. The relaxation times are τ_+ and τ_- when there is no spin flip. In a spin-flip process, we assume that there are collisions which bring a point of the volume at $(\boldsymbol{p}, \boldsymbol{r})$ in the phase space at $s = 1/2$ to the volume at the same $(\boldsymbol{p}, \boldsymbol{r})$ but with $s = -1/2$ (figure 1). This process is characterized by a relaxation time τ_{sf}.

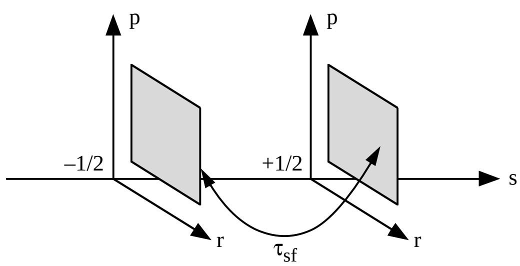

Figure 1. Schematics of configuration space $(\boldsymbol{r}, \boldsymbol{p}, s_z)$. τ_{sf} is the relaxation time for collisions with spin-flip.

The spin flip events are described according to the principle of detailed balance with

$$\frac{\partial f_+}{\partial t} = \frac{1}{\tau_{sf}} f_- - \frac{1}{\tau_{sf}} f_+ = -\frac{f_+ - f_-}{\tau_{sf}}$$
$$\frac{\partial f_-}{\partial t} = \frac{1}{\tau_{sf}} f_+ - \frac{1}{\tau_{sf}} f_- = -\frac{f_- - f_+}{\tau_{sf}}.$$

The collision processes from spin up to spin down and conversely are assumed equally probable. This corresponds to a high temperature approximation whereby the difference in equilibrium populations is neglected [27].

We consider processes which flip spins at the same time as they redirect the momentum isotropically. We are not considering processes such as collisions with magnons, which would transfer momentum between spin channels. Such a momentum transfer from one spin channel to the other is often referred to as spin mixing. It is negligible in most cases [28, 29].

The distribution function at equilibrium is designated by f_{0s}. Since we intend to describe inhomogeneous systems, it is to be thought of as the equilibrium distribution for the *local* density $n_s(\boldsymbol{r})$:

$$f_0(n_s(\boldsymbol{r})).$$

The Boltzmann equation is then for the distribution function of each spin direction

$$\frac{\partial f_s}{\partial \boldsymbol{r}}\boldsymbol{v} + \frac{\partial f_s}{\partial \boldsymbol{p}}\boldsymbol{F} = -\frac{f_s - f_0(n_s)}{(\tau_s^{-1} + \tau_{sf}^{-1})^{-1}} - \frac{f_s - f_{-s}}{\tau_{sf}}$$

in the stationary regime and within the relaxation time approximation. The external force is given by $\boldsymbol{F} = e[\mathrm{d}V(z)/\mathrm{d}z]\hat{z}$, meaning that the electric field derives from the potential $V(z)$.

We express the distribution functions f_s as

$$f_s = f_0\left(\frac{E - \mu_s(z)}{kT}\right) = f_{1s}$$

where f_0 refers to the Fermi–Dirac distribution. This is saying that the distribution is in essence the Fermi–Dirac distribution with a chemical potential $\mu_s(z)$ dependent on spin s and the position z. We assume parabolic bands, so f_s is isotropic. The small term f_{1s} describes the departure from the Fermi–Dirac distribution due to the external force.

We introduce the difference in the chemical potentials of both spin populations:

$$\mu_+ = \mu_0 + \Delta\mu \qquad \mu_- = \mu_0 - \Delta\mu.$$

We will see that μ_0 is the chemical potential (the Fermi level) if there were no field applied, and consequently no spin accumulation. $\Delta\mu$ is presumed to be small compared to kT, and it is found that indeed it is. Consequently

$$f_{0+} - f_{0-} = f_0\left(\frac{E - \mu_0 - \Delta\mu}{kT}\right) - f_0\left(\frac{E - \mu_0 + \Delta\mu}{kT}\right) = -\frac{\partial f_0}{\partial E}2\Delta\mu.$$

The standard linearization procedure yields

$$f_{1s} = (\tau_s^{-1} + \tau_{sf}^{-1})^{-1} v_z \left(\frac{\partial\bar{\mu}_s}{\partial z}\right)\frac{\partial f_{0s}}{\partial E} + \frac{(\bar{\mu}_s - \bar{\mu}_{-s})(\partial f_{0s}/\partial E)}{\tau_{sf}(\tau_s^{-1} + \tau_{sf}^{-1})}$$

where the potential $\bar{\mu}_s = \mu_s - eV(z)$.

This is identical to the preliminary result of the Valet–Fert model [30].

The spin currents are given by the integrals

$$j_s = \frac{1}{\hbar^3}\int \mathrm{d}^3 p f_{1s}(-ev_z).$$

The second term in the expression of f_{1s} gives an integrand proportional to v_z, hence a vanishing contribution to the current. The first term in the expression of f_{1s} is analogous to the expression found for a non-spin-dependent homogeneous system, except that the electric field F is replaced by

$$\frac{1}{e}\left(\frac{\partial\bar{\mu}_s}{\partial z}\right).$$

Assuming the same Fermi velocity for both spin bands, we obtain

$$j_s = \frac{4\pi m^2 e^2}{\hbar^3}\frac{v_F^2}{3}(\tau_s^{-1} + \tau_{sf}^{-1})^{-1} v_F \frac{1}{e}\left(\frac{\partial\bar{\mu}_s}{\partial z}\right).$$

We define the *electron mean free path*

$$\lambda_s = (\tau_s^{-1} + \tau_{sf}^{-1})^{-1} v_F$$

and the conductivity

$$\sigma_s = \frac{4\pi m^2 e^2}{\hbar^3} \frac{v_F^2}{3} \lambda_s.$$

Thus we find Ohm's law for each spin channel

$$j_s = \sigma_s \frac{1}{e} \left(\frac{\partial \bar{\mu}_s}{\partial z} \right).$$

We can write a continuity equation for each electron spin current. The divergence of each spin current is equal to the source of electrons in this channel, which is equal to the rate of spin flips producing electrons coming into the channel minus the rate of electrons leaving it:

$$\mathrm{div}\,(\boldsymbol{j}_s) = \frac{\partial j_s}{\partial z} = \int \frac{1}{\hbar^3} \,\mathrm{d}^3 p \left(-\frac{f_s - f_{-s}}{\tau_{sf}} \right) (-e).$$

This yields

$$\frac{\partial j_s}{\partial z} = \frac{\sigma_s}{\frac{1}{3}(\tau_s^{-1} + \tau_{sf}^{-1})^{-1} v_F^2 e} \left(\frac{(\bar{\mu}_s - \bar{\mu}_{-s})}{\tau_{sf}} \right).$$

We recognize in this expression two characteristic lengths. First there is what it is natural to call the *spin-flip mean free path*

$$\lambda_{sf} = v_F \tau_{sf}.$$

Second, there is a coherence length of each spin band, given by

$$l_s^2 = \tfrac{1}{3} \tau_{sf} (\tau_s^{-1} + \tau_{sf}^{-1})^{-1} v_F^2.$$

Thus finally, for each spin band we have

$$\frac{e}{\sigma_s} \frac{\partial j_s}{\partial z} = \left(\frac{(\bar{\mu}_s - \bar{\mu}_{-s})}{l_s^2} \right) \qquad \text{and} \qquad j_s = \sigma_s \frac{1}{e} \left(\frac{\partial \bar{\mu}_s}{\partial z} \right).$$

The chemical potential difference

$$\Delta\mu = (\bar{\mu}_s - \bar{\mu}_{-s}) = (\mu_s - \mu_{-s})$$

$$\frac{\partial^2 \Delta\bar{\mu}}{\partial z^2} = \frac{\Delta\bar{\mu}}{l_{sf}^2}$$

with

$$\frac{1}{l_{sf}^2} = \frac{1}{l_+^2} + \frac{1}{l_-^2}.$$

If we take $\lambda_+ = \lambda_- = \lambda_e$, then $l_{sf}^2 = \frac{1}{6} \lambda_{sf} \lambda_e$. The quantity l_{sf} is known as the *spin-diffusion length*. It plays a central role in perpendicular spin transport.

The diffusion equations for the spin-dependent chemical potential which constitute the basis of the Valet–Fert model were used earlier to describe the transport through the interface between a half-metallic ferromagnet and a normal metal [31]. It was shown that the conversion of up spins to down spins and conversely gave rise to an electrochemical potential difference in analogy with the effect of charge accumulation at the interface between a normal metal and a superconductor.

Valet and Fert [30] applied the diffusion equation for the chemical potential to the case of an interface between two collinear magnetic layers. They show that a spin accumulation builds up at the interface as with the perpendicular current flows through it.

The spin-dependent chemical potential difference $\Delta\bar{\mu}$ is closely linked to the spin polarization in the system. Indeed, the magnetization at any point can be calculated as

$$\Delta M = \int \frac{1}{h^3}\,\mathrm{d}^3p \left\{\frac{1}{2}\mu_B f_+ + \left(\frac{-1}{2}\mu_B\right) f_-\right\} = \frac{\mu_B}{2h^3}\int \mathrm{d}^3p\,(f_+ - f_-) = \frac{\mu_B}{2}\Delta n.$$

The last equality is meant as the definition of Δn. We can invoke the approximation on $(f_+ - f_-)$ above and define the density of electrons of each spin direction as $n = \frac{4}{3}\pi(mv_F)^3$ to obtain the proportionality between the difference in chemical potential density of the two spin bands [28]

$$\frac{1}{3}\frac{\Delta n}{n}\mu_0 = \Delta\bar{\mu}.$$

The order of magnitude of the spin dependent potential difference $\Delta\bar{\mu}$ can be estimated in the case of an interface far away (as compared to l_{sf}) from any other interface by using

$$\Delta\bar{\mu} \approx \rho l_{sf} j$$

with j the current density. Taking for example j of 10^6 A cm^{-2}, ρ of 10^{-4} Ω cm and l_{sf} of 40 nm yields $\Delta\bar{\mu}$ of 0.4 mV.

Johnson and Silsbee first considered spin transport at the interface between a ferromagnet and a non-magnetic metal using the thermodynamics of irreversible processes [32]. Hence they showed in particular that the interface between a ferromagnet and a non-magnetic metal presents a resistance associated with spin conversions at the interface.

If the spin-dependent resistivity of the ferromagnet is given by

$$\rho_{\uparrow(\downarrow)} = \frac{1}{\sigma_{\uparrow(\downarrow)}} = 2\rho_F^*(1-(+)\beta)$$

and that of the non-magnetic metal by

$$\rho_{\uparrow(\downarrow)} = 2\rho_N^*$$

then the interface presents a resistance

$$r_{SI}^0 = 2\beta^2\frac{\rho_N^*}{\rho_N^* + \rho_F^*}l_{sf}$$

known as the *spin-coupled interface resistance*.

2.2. Angular dependence

More comprehensive models are based on the Kubo formalism. It was used to treat scattering with spin-dependent potential steps at interfaces. This formalism is particular suited to treat the case of magnetizations which are not collinear [33–35]. The reader is referred to [32] in particular for a full description of the spinodal character of internal fields and generalized currents. A generalized Boltzmann formalism has been proposed in order to treat non-collinear magnetizations also. It consists in making use of a distribution function that takes the form of a quantum mechanical density matrix [36].

Experiments to be reported below have provided data on CPP-MR as a function of the angle between adjacent magnetization. Small deviations from a simple $\cos^2(\theta)$ were interpreted within the Kubo formalism and provided evidence that interference effects with spin up and spin down electron waves contributed to the CPP-MR effect, and that mainly s-like electrons contribute to the CPP-MR [37]. Departure from the $\cos^2(\theta)$ was found also in a model where both spin-dependent scattering and spin-dependent superlattice potential were taken into account [38].

2.3. Superlattice effects and ballistic electrons

The reader is referred to [24] for theoretical models which describe superlattice effects and ballistic electrons. Giant magnetoresistance without defect scattering has been predicted [39]. The transition to Ohmic regime associated with fluctuations of the thickness of the layers has been derived [40].

Preliminary attempts at measuring ballistic transport at point contacts have been reported. They made use of the technique of a needle point-contact [41]. Much experimental work remains to be done.

3. Magnetic multilayers

3.1. The Valet–Fert model

Valet and Fert [28] used the diffusion equation for the spin-dependent chemical potential in order to derive the magnetoresistance of multilayers, for collinear configurations of the magnetization, in the absence of potential steps at the interfaces. They introduced a *spin-dependent interface resistance*

$$r_{\uparrow(\downarrow)} = 2r_b^*(1 - (+)\gamma)$$

which determined the boundary condition for the chemical potential

$$\bar{\mu}_s(0^+) - \bar{\mu}_s(0^-) = r_s J_s(0)/e$$

where $J_s(0)$ is the spin s current density at the interface, at $z = 0$.

They derived an analytical expression for the resistance per unit area and for M bilayers of an infinite multilayer. One of the great merits of this model is to settle a controversial debate as to whether the origin of GMR is in bulk or interface scattering. This model shows that in the case of current-perpendicular-to-the-plane magnetoresistance (CPP-MR) spin dependent scattering in the bulk of the layers and at the interfaces can contribute to the MR, and that the relative importance of each depends on the conformation of the multilayer. Indeed, in the limit of infinite spin-diffusion length, they found

$$\sqrt{(R^{(AP)} - R^{(P)})R^{(AP)}} = \beta \frac{t_F}{t_F + t_N} \rho_F^* L + 2\gamma r_b^* M$$

where $R^{(AP)}$ ($R^{(P)}$) is the resistance in the anti-parallel (parallel) configuration. t_F and t_N are the thicknesses of the ferromagnetic and non-magnetic layers, respectively. M stands for the number of bi-layers and $L = M(t_F + t_N)$.

Predictions of this model for a few limiting cases (figure 2) illustrate the relative importance of bulk and interface scattering relative to the layer density. Also, a spin-diffusion length which is short compared to the layer thickness is shown to reduce severely the MR effect.

Both the approach based on the Boltzmann equation and a quantum mechanical approach based on the Kubo formula show that in the limit of infinite spin-diffusion length, the CPP-MR can be described with a simple resistance model [42] but that a more careful evaluation is necessary if spin relaxation effects (finite spin-diffusion length) must be taken into consideration [43].

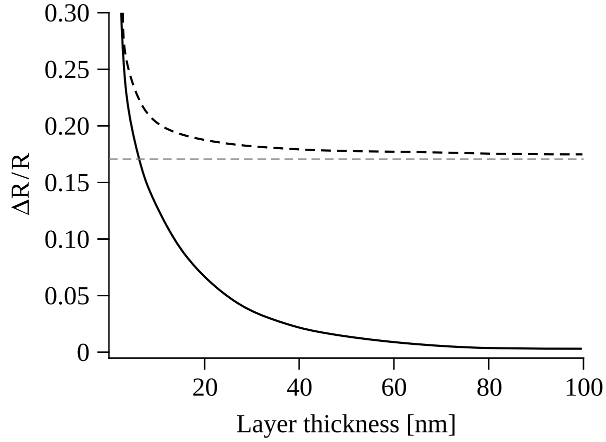

Figure 2. Magnetoresistance $\Delta R/R_{max}$ of Co/Cu multilayers of equal Co and Cu thicknesses. Predictions for (- - - -) bulk spin scattering only, $\beta = 0.4$; (— — —) the same, with interface scattering, $\gamma = 0.7$; (——) the same with spin-diffusion effects ($l_{sf} = 40$ nm).

3.2. The art of measuring CPP-MR

Most multilayers are produced by thin film technology. Consequently, the CPP-MR measurements constitute usually a technical challenge. It was not until 1991, three years after the discovery of GMR [1, 2] that the first CPP-MR data appeared [8]. In order to have a well characterized magnetic configuration, samples must have a surface area large enough so that the magnetic layers retain the properties which are well defined for large thin films. Therefore, advanced transport measurement techniques had to be developed [44, 45].

However several groups have taken the approach of producing samples with aspect ratios such as to make the transport measurement easier. Advanced lithographic techniques were developed [46, 47]. In the case where the pillars were short compared to their diameter, spatial inhomogeneity in the current density could be identified, in which case the angle of the current to the interface was ill defined [48, 49]. Several groups circumvented this problem by producing multilayered nanowires (figure 3) [50–52].

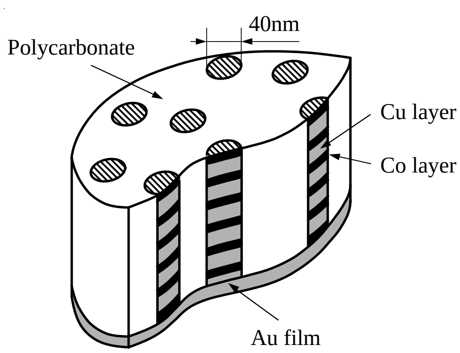

Figure 3. Schematics of the template synthesis method for the formation of multilayered nanowires. The membranes contain nanopores which are filled by electrodeposition, starting from the Au backing.

A type of stacking of small pillars permits simultaneous CIP and CPP measurements, but suffers from the problem of ill defined current direction for the CPP measurements (figure 4(a)) [53]. A well defined current density was obtained by straight deposition on a grooved substrate (figure 4(b)) [54]. Thus current-at-an-angle magnetoresistance (CAP-MR) could be conveniently measured [55].

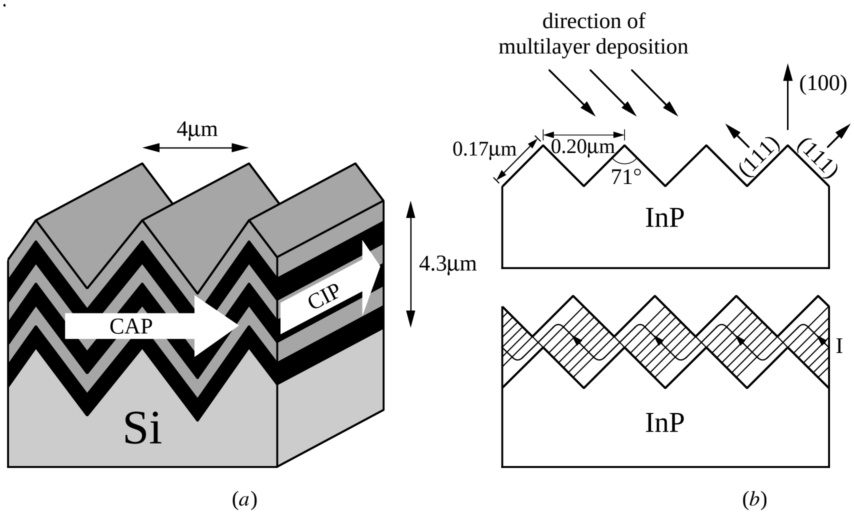

Figure 4. (a) Straight deposition of multilayers on grooved substrate for 'current-at-an-angle' and 'current-in-plane' MR (from [54]). (b) Oblique deposition on grooved substrates produces a series of multilayers in series for CPP-MR measurements (from [53]).

A lithographic process was developed [56] in order to obtain a resistance of the order of the kiloohm while maintaining pillars of fairly large cross section. Unfortunately, this compromise between cross section and overall resistance requires several vias and interconnects, the resistance of which adds in series to the MR material and reduces the relative MR effect of the overall structure.

3.3. Bulk and interface spin-dependent scattering in CPP-MR

In the Valet–Fert model, the following parameters are involved:

- the resistivity parameters r_b^*, ρ_N^*, ρ_F^*,
- the spin asymmetry parameters β, γ,
- the spin-diffusion lengths l_{sf}^N, l_{sf}^F.

The original experiments on CPP-MR aimed at determining the values of the spin-dependent parameters. There is at this point a remarkable general consensus among the groups which have been able to measure CPP-MR and have interpreted their data in terms of this model. Their results of the spin asymmetry are summarized in table 1.

The bulk asymmetry parameter β is related to the ratio α of the resistivities of up and down spins through

$$\alpha = \frac{\rho_\downarrow}{\rho_\uparrow} - \frac{1+\beta}{1-\beta}.$$

Values for α were obtained experimentally by measurements of the magnetoresistance of series of ternary alloys [63, 64] (figure 5).

Table 1. Bulk (β), interface (γ) spin asymmetry parameters and spin-diffusion lengths of Co/Cu and Co/Py multilayers.

β	γ	l_{sf}(Cu) (nm)	l_{sf}(Co) (nm)	l_{sf}(Py) (nm)	Ref.
0.45	0.7	40	>10		[57]
0.4	0.8	140	44		[58]
0.5	0.8	varies with doping			[59]
0.5	0.7				[60]
0.9	0.9	140		3	[61]
0.7	0.7	—		5.5	[62]

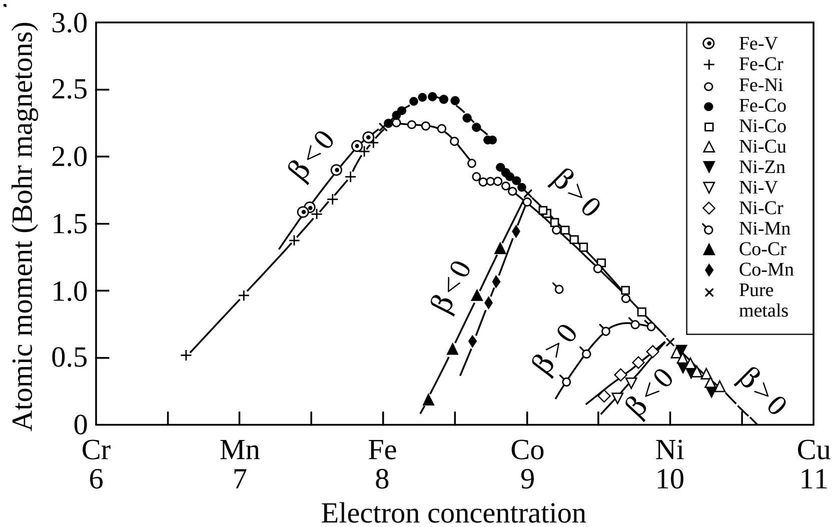

Figure 5. Stoner–Pauling plot of magnetic moment as a function of concentration (see Kittel's *Introduction to Solid State Physics*). The sign of the bulk asymmetry parameter (β) is shown.

By combining magnetic layers of positive β with layers of negative β, the model predicts an inverse CPP-MR (positive magnetoresistance). This was observed and provided further test of the validity of the model [65]. Negative β were found for example by doping iron with vanadium. This is consistent with theoretical predictions [66]. Negative β were found for NiCr, FeCr also [67, 68].

There is a fair agreement as to the value of γ among the various groups (table 1). This agreement is quite remarkable since the samples are prepared by several methods and the quality of the interfaces could be expected to vary. In fact, it was shown that the spin-dependent scattering properties of the interfaces could be modified [54] or even that the interface contribution to the MR could be destroyed completely [69] depending on the extent to which the electrodeposition conditions were modified.

There is extensive debate as to the origin of the spin-dependent interface resistance [70]. Experiments carried out by the group of Chaussy appear to bring insight to this issue. The CPP-MR was measured as a function of the angle between adjacent layers. The relative orientation of adjacent layers was obtained in two ways. One way was to take advantage of the difference in coercivity of Co and permalloy in large ($Ni_{80}Fe_{20}$/Ag/Co/Ag) multilayers [71]. The other was to pull the magnetizations of layers which were ferromagnetically exchange coupled away from one another by applying a magnetic field in the plane of the layers [72]. CIP-MR measured on the same samples was used to estimate the angle, making use of the fact that in CIP, the MR was found to depend linearly on the cosine of the angle between the orientations of adjacent magnetizations. The current-perpendicular-to-the-plane magnetoresistance of the multilayers was found to vary as

$$1 - A\cos^2\left(\frac{\theta}{2}\right) + B\cos^4\left(\frac{\theta}{2}\right)$$

where θ is the angle is the angle between the magnetizations of adjacent magnetic layers. The ratio B/A was found to be in the range of 0.1 to 0.3. This result was interpreted in terms of reflections of the electronic wave function at step voltages at the interfaces. It was concluded that electronic conduction arises mainly from s-state electrons, as very little spin splitting was deduced from the measurement. The physical origin of the s-like nature of the charge carriers has been argued to arise because d-like electrons experience a much larger resistance at interfaces which is proportional to the square of the potential step [73]. This is to be contrasted with CIP measurements. In CIP, s-like electrons dominate the magnetoresistive effect, as demonstrated by the linear $\cos(\theta)$ dependence, because d-like electrons are channelled in the layers and, consequently, they contribute little to the MR effect, although they contribute to the current.

3.4. Spin-diffusion length in the non-magnetic metal

The spin-diffusion length is closely related to to the spin-flip mean free path

$$\lambda_{sf} = v_F \tau_{sf}.$$

The importance of spin-flip scattering at magnetic sites in dilute alloys, such as at Mn impurities in Cu, was recognized long ago. Their magnetoresistance which is proportional to the square of the magnetization ($\Delta\rho/\rho \propto M^2$), was accounted for by the spin-flip scattering at the magnetic sites [74]. The theory of electron spin relaxation was reviewed by Barnes [75].

If there is a low density N of scattering centres of scattering cross section σ_{sf}, then the spin-flip mean free path is given by

$$\lambda_{sf} = \frac{1}{N\sigma_{sf}}.$$

After the seminal work of Slichter *et al* which showed how electron spin resonance (ESR) can provide a direct measure of σ_{sf} [76], the technique of transmission conduction electron resonance (TESR) was developed and applied to the study of a wide variety of dilute magnetic systems, reviewed by Monod and Schultz [77].

TESR can be thought of as a contactless spin transport experiment. Its principle of operation is as follows. Consider the sample to be a thin infinite sheet of a metal with the rf magnetic field incident on one side (transmit) and a sensitive detector on the other (receive) side. The transmitted field is strongly attenuate via the shielding effects of the conduction electrons. In practice the sample is a sufficient number of skin depths thick that this transmitted source of power is negligible. The TESR technique makes use of the fact that when one is near the resonance frequency, electrons with a skin depth of the transmit surface respond to the excitation field and develop a net transverse magnetization. Then, via a diffusion process they carry this information (i.e., a nonequilibrium magnetization) deep into the metal and over to the far side. At the far side, one simply has a precessing transverse magnetization which radiates power. Thus, if, as usual (in a resonance experiment), one sweeps the dc magnetic field while applying a fixed frequency rf field, one expects zero transmitted power except in the vicinity of the resonant field. In addition to the usual requirement that the relaxation time of the transverse magnetization (T_2) not be too short (so that the resonance line is observable), one has the additional physical requirement that the *characteristic diffusion length* δ_s of the electronic magnetization during the time T_2 be equal to or greater than the thickness of the sample! For a simple three-dimensional random walk, $\delta_s^2 = \frac{2}{3} v_F^2 \tau T_2$, where $v_F \tau$ is the electron mean free path [78].

Multilayers produced by sputtering could be doped in the non-magnetic layers with centres of spin–orbit or exchange scattering. The spin-diffusion length was deduced from data on series of samples of variable thicknesses. The deduced scattering cross section was consistent with TESR data when available [79, 80].

Multilayers of Co and Cu grown by electrodeposition suffer from a spurious Co deposition in the Cu layers. Because the Cu electrodeposition potential is much less than that of Co, this should not occur, but it does. Under typical deposition conditions, about 0.5% Co in Cu was found [81]. It was shown that it was possible to deliberately increase the Co concentration by depositing Cu at an inordinately high deposition potential. The analysis of the CPP-MR data performed on series of multilayered nanowires revealed a spin-diffusion length consistent with scattering at the Co impurities found in the Cu layers.

It has been observed in granular materials also that a short spin-diffusion length reduces the MR. The material processing can indeed generate ferromagnetic impurities in the non-magnetic metal [82].

3.5. Spin-diffusion length in the ferromagnet

In Co/Cu multilayers of equal thicknesses, the spin-diffusion length of the Co can be taken as infinity if its actual value is larger than about 10 nm. In order to obtain a good measure of its value, multilayers with thin Cu layers and Co layers of variable thicknesses can be studied. Recent results have been obtained by the group of Piraux. The anti-alignment of the magnetizations of adjacent layers when the multilayer structure is actually a chain of magnetic rods close to one another may seem surprising. They explain the fact that they obtain a fair amount of anti-alignment by invoking that their growth condition produces hcp Co with the easy axis normal to the wire. Their analysis of the MR data yields a spin-diffusion length of 44 nm at low temperature [83]. The anti-alignment was not obtained in the case of Py/Cu multilayers. The same group produced a series of pairs of Co layers, 7 to 30 nm in thickness, separated by 10 nm of Cu. The pairs favoured anti-alignment of the layers, as they were separated from one another by 100 nm of Cu. This group found a spin-diffusion length of 6 nm for permalloy [84].

The group at Michigan State University has produced the first CPP exchange-biased spin-valves in order to lift any ambiguity concerning the magnetic configuration of the multilayers [85, 86]. The analysis of their data, based on the Valet–Fert model, yields a spin-diffusion length of permalloy of 5.5 ± 1 nm at low temperature.

A short spin-diffusion length in the ferromagnet is to be expected in view of the scattering cross section for spin-flip scattering of conduction electrons at Fe impurities in Cu. Since the spin–orbit scattering is an event that occurs at the core of the atom [73], we can take the value of scattering cross section of spin-flip scattering of Fe in Cu (1.8×10^{-17} cm^2) [74] to estimate the spin-flip mean free path in Fe. It would be about 2 nm. It is of about the correct order of magnitude for a spin-diffusion length of 5 nm given that the ferromagnets have fairly short mean free paths.

The knowledge of spin-diffusion lengths, both in the ferromagnets and in the non-magnetic metal, is of practical relevance for all kinds of device based on spin transport. We saw above its importance in magnetic multilayers. Fert *et al* also considered its relevance in the operation of the bipolar spin switch [87]. The current data on spin switches appear to contradict the findings of short spin-diffusion length in the ferromagnets. Hence further work will be needed to clarify this controversy.

4. Bloch-wall scattering and MR

Spin transport through Bloch walls is of current interest for several reasons. Firstly, all MR phenomena have gained renewed interest because of the appeal of GMR. Secondly, magnetic nanostructures, which are studied so intensively, can lead to the well defined magnetic configurations which are necessary to distinguish Bloch-wall scattering from anisotropic magnetoresistance (AMR). Finally, scattering by Bloch walls has been considered as a mechanism responsible for the colossal magnetoresistance of manganate perovskites [88, 89].

When domain walls are involved, several mechanisms can give rise to a magnetoresistance. They were reviewed early on by Berger [90], including the spin tracking the exchange field, as discussed below.

4.1. Anisotropic magnetoresistance

AMR refers to the dependence of the resistance on the angle between the magnetization and the current. This effect is due to the anisotropy of the spin–orbit scattering [91]. A systematic study of AMR in submicron wires of NiFe alloys was recently reported [92].

4.2. Modelling spin transport through Bloch walls

The issue of spin scattering at Bloch walls was first addressed by Cabrera and Falicov in the limit of long electronic mean free path compared to the wall thickness [93]. A substantial contribution of Bloch walls to the resistivity was predicted in the case of very different density of states of the majority and minority spins at the Fermi level.

The resistivity of Bloch walls in the mesoscopic regime was analysed in the framework of linear response theory [94]. Bloch walls are shown to produce a decoherence of the electrons so that the nucleation of a wall actually decreases the resistivity in the weak localization limit. The model describes also the conductance fluctuations associated with domain-wall motion. These considerations shed new light on resistivity studies of nanowires [95, 96].

An important aspect of spin scattering in ferromagnets has been raised by the group which has succeeded in obtaining clean measurements of domain-wall scattering [97]. As an electron traverses a domain wall, its spin experiences an exchange field which changes orientation as the electron advances through the wall. This situation is well known in magnetic resonance spectroscopy. If the spin precession about the applied field is fast compared to the angular velocity of the rotation of the magnetic field, then the spin precession follows the magnetic field in its rotation. This situation is known as a 'fast adiabatic passage' (figure 6).

The other extreme situation would be the 'sudden' passage, in which the spin is suddenly (compared to its Larmor period) subjected to another field. This would be the case of electrons traversing a magnetic multilayer, a tunnel barrier or a granular material [98, 99]. According to the model which is outlined below, the resistance of a domain wall arises

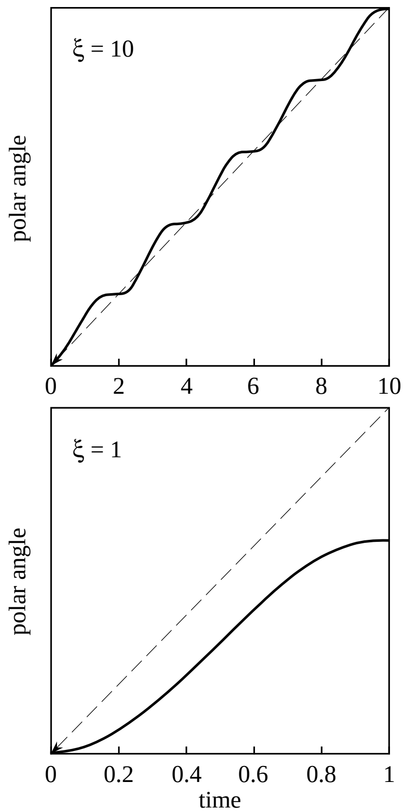

Figure 6. Polar angle of magnetic field and of a spin precessing about it, as the field is rotated at constant angular velocity about the x axis. ξ defined as ratio of precession frequency to angular velocity.

because the spin precession does not quite follow the exchange field as the electron traverses the wall.

The angular velocity of rotation of the exchange field H_{ex} can be approximated as v_F/d where v_F is the Fermi energy and d the wall thickness. The spin precession frequency is $g\mu_B H_{ex}/h$. Defining the exchange energy as $E_x = \frac{1}{2}h\mu_B H_{ex}$, the precession frequency becomes $2E_x/h$. The ratio of the precession frequency to angular velocity of rotation of the exchange field is

$$\xi = \frac{2E_x d}{hv_F}.$$

Higher ξ values correspond to spins better tracking the exchange field, and, consequently, less resistance. The angle of departure of the spin from the exchange field can be approximated as the angle of rotation of the field in one Larmor period of the spins

$$\theta_0 = \left(\frac{v_F}{d}\right)\left(\frac{2E_x}{h}\right)^{-1} = \frac{1}{\xi}.$$

The deviation of the spins from the exchange field has two consequences as far as transport is concerned. One is that the spins experience a potential barrier, the magnitude of which is of the order of

$$\tfrac{1}{2} g\mu_B H_{ex} - \tfrac{1}{2}\cos(\theta_0) g\mu_B H_{ex} = \sin^2(\theta_0) g\mu_B H_{ex}$$

therefore varies like $(1/\xi)^2$. The second contribution to transport is the spin-flip scattering induced in the process by which the spin sets into precession about the exchange field. The scattering probability varies too as $(1/\xi)^2$.

The validity of the model is not limited to electron mean free paths that are long compared to the domain-wall width. This model, being based on the precessional behaviour of the spin, requires instead that the spins precess (on average) at least once about the exchange field before a scattering event occurs. Another model was developed by Levy and Zhang [100]. It is based on the Boltzmann equation. The electron eigenstates in the wall are spin mixed. As a consequence, the effect of the wall is to remove the 'short circuit' (that is the low resistivity spin channel also invoked in GMR) that would be present in the absence of a wall. That is, the wall increases the resistance.

4.3. Experimental measurements of Bloch wall scattering

These concepts have been successfully tested in a couple of studies of the MR associated purely with domain walls in homogeneous films. In the first study [93] the longitudinal and the transverse magnetoresistance were measured on a square sample. Hence the contributions from domain walls could be distinguished from the AMR. Films of Co and Ni were studied. The resistance values were found to scale with $(1/\xi)^2$, as predicted by the model above. A new type of transport measurement was also proposed by the same group in order to detect exclusively the effect of domains [101, 102]. A striped pattern of domain walls was obtained by demagnetizing thin Co films with field cycling in the plane of the film (figure 7(a)). Then the resistance of the film was measured with a field applied normal to it (figure 7(b)).

The magnetoresistance observed in these samples corresponds to a wall resistance per unit area of 7.8×10^{-17} Ohm m^2 (figure 7(c)), which is similar to the value found for the interface resistance in multilayers.

As a final remark, we note the work of Hong and Giordano who, instead of studying transport through domain walls, use transport measurements in order to study domain-wall motion [103, 104]. The question of the effect of a current on a domain wall was addressed by Berger and Hung [105]. We report also below on the prediction of current-driven spin oscillations at Bloch walls.

5. Tunnelling junction MR (JMR) and spin blockade

5.1. Basics

Spin-polarized electron tunnelling has been reviewed by Meservey and Tedrow [106]. Tunnelling between ferromagnet films was first addressed by Julliere [107]. He expressed the change in tunnel conductance when the magnetizations of both films change from a parallel to an anti-parallel configuration in terms of the spin polarizations of the conduction electrons P and P' of the layers:

$$\frac{\Delta G}{G} = \frac{2PP'}{(1 + PP')}.$$

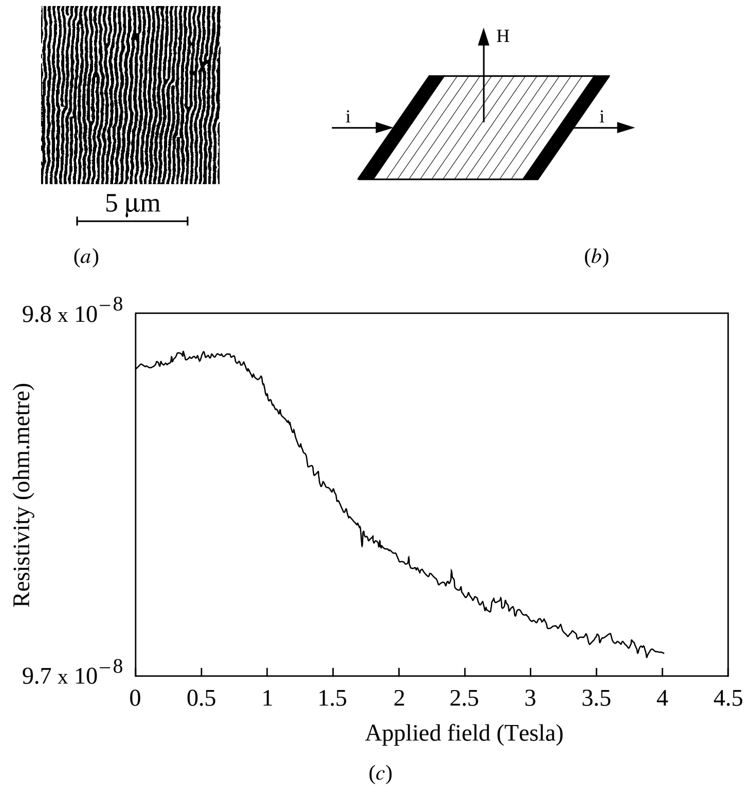

Figure 7. (a) Striped domain pattern of a thin Co film. (b) Geometry of the measurement. (c) Magnetoresistance. (From [96].)

Experimental values for spin polarization had been obtained by Tedrow and Meservey by analysing data on tunnelling from a ferromagnet to a superconductor [108]. Updated results have been reviewed [101].

Slonczewski carried much further the analysis of tunnel barriers between two ferromagnets [109]. He used a free-electron model for the conduction electrons, a rectangular barrier potential and an internal exchange energy in the magnetic layers of the form

$$-\boldsymbol{h} \cdot \boldsymbol{\sigma}.$$

The directions of the molecular fields in the layers differ by an angle θ and their magnitudes are the same. The junction conductance is found to vanish when the magnetizations of the layers are anti-parallel if only one spin band is present at the Fermi level. This is the case of the so-called half-metallic ferromagnets to be discussed below. In the imperfect case where both spin bands cross the Fermi level, the junction conductance has the form

$$G = G_{fbf}(1 + P_{fb}^2 \cos\theta)$$

with

$$P_{fb} = \frac{(k_\uparrow - k_\downarrow)}{(k_\uparrow + k_\downarrow)} \frac{(\kappa^2 - k_\uparrow k_\downarrow)}{(\kappa^2 + k_\uparrow k_\downarrow)}$$

where $k_\uparrow$ and $k_\downarrow$ are the spin up and spin down momentum values in the metals, and iκ is the imaginary momentum in the barrier. G_{fbf} is proportional to $\mathrm{e}^{-2\kappa d}$ where d is the barrier thickness. The first factor of P_{fb} is a fractional spin polarization. The second one is conceptually novel relative to Julliere's model. It expresses a dependence of the effective relative polarization on the height of the barrier. It can vanish and even change sign!

This simple model provides a basis for deriving two other effects. First, an effective junction exchange coupling is found, of the form

$$E(\text{coupling}) = -J \cos\theta$$

where the coupling constant varies in sign and magnitude with the barrier height. Second, a dynamical term is derived which represents damping for one sign of the applied voltage, and excitation of oscillation of the magnetization for the other sign of the applied voltage.

Chui considered the difference in spin up and spin down chemical potentials, $\Delta\mu$, at the ferromagnet/insulator interface. It depends on whether the magnetization vectors of the adjacent layers are parallel or antiparallel. He points out that these chemical potential differences result in a large bias dependence of the magnetoresistance [110].

Veyayev *et al* have indicated the possibility of strongly enhanced tunnelling magnetoresistance obtained by adding to the tunnel structure a thin paramagnetic layer. Selective multiple reflections of either spin up or spin down electrons in this layer result in very large MR effects at specific values of the thickness of the paramagnetic layer, in a similar fashion to what happens in optical filters [111].

Butler *et al* cautioned against using the simple potential barrier models as discussed above. A calculation of the electronic structure of spin-dependent structures such as Fe/Ge/Fe or Fe/GaAs/Fe indicate that the local density of states at the Fermi level at the interfacial metal layer differs significantly from its value in the bulk of the metal. Furthermore the band structures of the majority and minority spins in the semiconductor barrier are quite different, although the barrier remains non-magnetic [112].

Magnetic effects in the hopping of charge carriers among ferromagnetic ultrafine grains embedded in an insulating matrix were considered back in the 1970s by Helman and Abeles [113]. A magnetic exchange energy was introduced in the energy barrier of the tunnelling probability. The several magnetic configurations possible for the magnetization orientation of adjacent grains give rise to three possible barrier heights (figure 8).

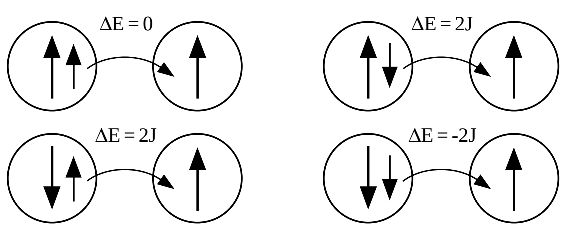

Figure 8. Change in energy of a spin (small arrow) as it jumps from one magnetic grain to the next with various relative orientation of the magnetization (big arrow).

The generalization to non-collinear magnetization can be summarized with an exchange energy term of the form

$$E_m = \frac{1}{2} J \left(1 - \frac{\langle \boldsymbol{S} \cdot \boldsymbol{S}' \rangle}{\boldsymbol{S}^2}\right)$$

thereby introducing a correlation function for the magnetization of adjacent grains which is reminiscent of the correlation function used by de Gennes and Friedel to account for the temperature dependence of the conductivity when conduction electrons undergo collision via exchange coupling to metal ions of rare earths or of alloys such as AuMn or Au_3Mn [114]. There, the atomic spins are aligned at low temperature, thus producing little scattering. At high temperatures, the atomic spins are random and shorten the mean free path.

The same notion of correlation functions of localized moments is invoked also by Zhang and Levy who derive constructive interference between spin-dependent scattering amplitudes from the ordering of impurities which arise from interdiffusion between the metals at the interface of magnetic multilayers [115].

5.2. Experiments with ferro/insulator/ferro junctions

Long after the initial experimental work of Julliere, the magnetoresistance of tunnel junctions where both electrodes are ferromagnets is becoming the subject of intense research activity. Potential uses in reading heads and magnetic random access memories have been invoked. However, while the interest of such tunnel junctions for challenging our understanding of solid state spin electronics is evident, their application in electronic devices is not obvious. The possible advantage of a very large MR effect is offset by the technical concern over the inherent noise that comes with the high effective resistance typical of tunnel junctions of sizes relevant to integrated technology [116].

Relative magnetoresistance values in the range of 25 to 30% have been observed in structures of surface area of about 10^{-3} cm^2, using CoFe for one electrode, Al_2O_3 for the insulating barrier and Co or $Ni_{0.8}Fe_{0.2}$ for the other electrode [117]. Such values are in agreement with the Julliere model and the spin polarization measured by tunnelling to a superconductor [101]. Moodera *et al* warned against measurements of junctions where the lead resistance is not much smaller than the junction resistance [118]. Unless the lead resistance is completely negligible, the relative magnetoresistance can appear very large, or even negative because the current in the leads may not be uniform, so that a four-point technique (figure 9) can result in misleading measurements [119]. Hence the need to work with small junctions [120, 121] and to perform lithography in such a way as to obtain low lead resistance [122].

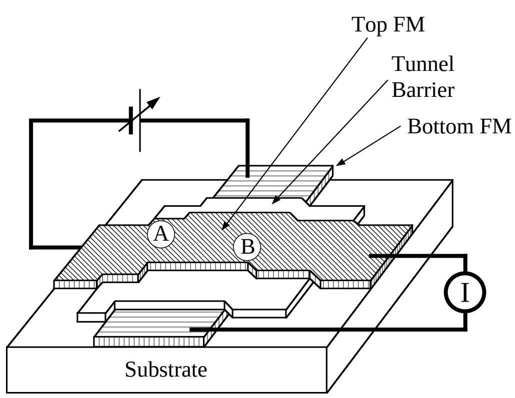

Figure 9. Junction magnetoresistance: typical configuration (from [118]).

Most work has relied on Al_2O_3 junctions [123]. Other oxide barriers have been tested [124]. Using HfO_2 barriers, MR of 31% was obtained [125]. If JMR is to be used in devices, the tunnel junction resistance must be brought down to the kiloohm range. Consequently, much effort is put into developing structures with ever thinner oxide barriers, thereby reaching much lower resistances (figure 10) [126].

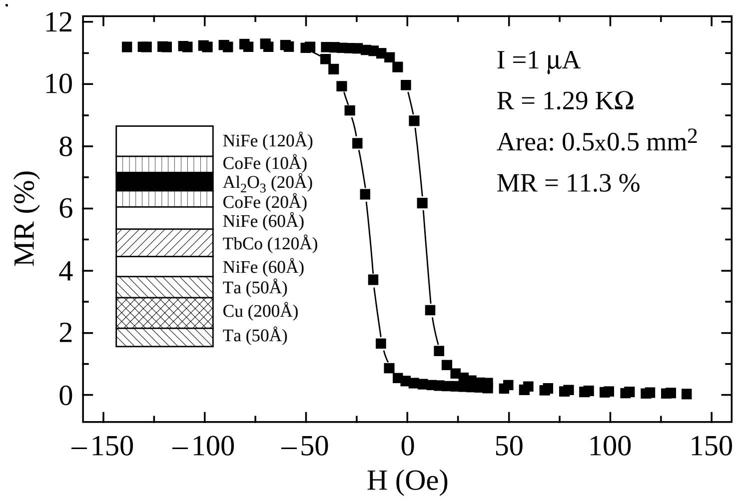

Figure 10. Tunnel magnetoresistance of the junction shown in the inset [126].

5.3. Experiments with ferromagnetic grains in an insulating matrix

In the early 1970s, a negative magnetoresistance was observed with composite materials made of nanoscale Ni grains (about 5 nm in diameter) embedded in a silica matrix [127]. The data were interpreted with the model of variable range hopping with spin-dependent tunnelling [128].

MR effects as large as 8% at room temperature and 17% at 4.2 K have been obtained with similar systems by Fujimori *et al* [129]. The maximum MR appeared near the percolation threshold. The field dependence reflected the superparamagnetic behaviour of the particles [130, 131].

New configurations of magnetic elements alternating with an insulating barrier have been devised. For example, a multilayer structure in which discontinuous layers of CoFe alternate with HfO_2 was shown to have high field sensitivity, and present a high reliability with regard to electrical breakdown [132]. With Co in Al_2O_3, Schelp *et al* obtained 21% at room temperature [133].

The production of junction areas less than 0.01 μm^2 by electrodeposition in nanoporous membranes revealed a large magnetoresistance and a hierarchy of two-level fluctuations. The largest fluctuations could be as large as 50%. The authors suggested that the MR they observe arises from the trapping of a charge at impurities in the barrier with a probability distribution of the residence times which depends on the local magnetic configuration [134].

5.4. Half-metallic ferromagnets

Half-metallic ferromagnets have one spin band only across the Fermi surface. They appear conceptually as ideal candidates in the search for large MR effects based on perpendicular transport [30]. NiMnSb is known as such a half-metallic ferromagnet. At this point, practical difficulties in maintaining the stoichiometry at the interface prevent the observation of very large MR effects [135]. Progress in thin film deposition is under way [136]. Attempts at forming multilayers where such Heusler metals alternate with Cu have been reported [137].

The manganite perovskites such as $La_xSr_{1-x}MnO_3$, which exhibit the so-called colossal magnetoresistance, deserve a review article of their own. Here, results are reported which can be well understood with the notion that manganites are half-metallic ferromagnets [138].

Astounding junction MR effects were produced with structures consisting of an $SrTiO_3$ barrier sandwiched between two layers of $La_{0.7}Sr_{0.3}MnO_3$. Resistance changes of a factor of 2 to 5 in a field change of about 50 Oe have been reported [139, 140]. Maintaining the stoichiometry at the interface is, here too, a critical issue. Theoretically, the effect could be infinite. It may not be because of the presence of defects in the barrier. Also, it can be expected that the manganites are not perfect half-metallic ferromagnets in the sense that there is some overlap of both spin bands at the Fermi level. Estimates indicate that the on-site spin repulsion may be not much more than the band breadth [141]. Indeed, recent results an exchange splitting of 2.7 eV and a band 3 to 4 eV wide [142]. Granular-type tunnel magnetoresistance has also been evidenced in polycrystalline manganates [143].

6. Devices and novel structures

The field of giant magnetoresistance is driven by the prospect of applications in reading head technology and as position sensors. This is a rapidly expanding field which would deserve a review of its own. Here, we mention novel devices based on spin transport and recent studies of spin transport through a great variety of interfaces.

Johnson proposed a *bipolar spin-switch*, based on the concept of spin injection from a ferromagnet to a non-magnetic metal [144]. Lodder *et al* demonstrated that a *metal-gate transistor* in which the gate consists of a magnetic multilayer constitutes field sensor of great sensitivity [145]. The device is of interest for fundamental studies, as it yields a measure of the GMR of the hot electrons which pass over the Schottky barrier at the interface between the multilayer and the semiconductor. *Memory cells* based on magnetoresistance are under development [146].

Berger predicts the possibility of *stimulated emission of spin waves* associated with a sufficiently strong current (approximately 10^7 A cm^{-2}) driven through the interface between a ferromagnet and a normal metal. Hence, he suggests a magnetic analogue to an injection laser: the SWASER (spin wave amplification by stimulated emission of radiation) [147, 148]. The same author points out that one can expect that a current driven through a Bloch wall can induce an oscillation of the wall [149]. In the case of thin film, a resonance frequency in the range of 10 to 100 MHz is predicted. This oscillation of the wall is expected to reduce the coercive field.

A *micro-magnetometer* based on GMR has been demonstrated [150]. Using electron lithography, it is possible to pattern a magnetic trilayer as a microsensor of the magnetization reversal occurring in a magnetic nanoparticle on top of the sensor. Indeed the magnetic particle and the layers underneath constitute a spin valve structure, because the bulk layer and the nanoparticles have different coercivities. There are of course other alternatives for accessing magnetization reversal of a single nanoparticles. MicroSQUIDs have been developed to this effect [151]. Magnetic force microscopy also provides information on switching fields [152]. A far less conventional approach consists of using the magnetotransport properties of a two-dimensional electron gas with nanomagnets on top of it [153].

Spin injection through a variety of interfaces are now considered. For example, the *spin-polarized transport in silicon* is currently under study [154]. Spin injection into superconductors is known to cause a so-called *Andreev reflexion* process. Anomalies are expected when the metal is a ferromagnet, owing to the non-conservation of spin in the process [155]. The *separation of spin and charge* in a superconductor is predicted to occur in adequate geometries of spin injection [156]. Transport through ferromagnetic nanostructures sandwiched between superconductors is also investigated [157].

Finally, we recall that spin-dependent transport has also been considered for near-probe imaging [158, 159].

7. Conclusion

One of the open questions in the area of giant magnetoresistance of magnetic multilayers [160] is the relative importance of spin-dependent scattering potentials and of spin-dependent density of states. Much theoretical work is addressing this issue [161].

In view of the models involving current-induced spin precession, spin wave generation and spin accumulation at interfaces, experiments which could probe such phenomena in a direct way (neutron scattering, x-ray magnetic dichroism, nuclear magnetic resonance) are much needed.

The lack of knowledge of the magnetic configuration appears particularly detrimental to some studies, such as in the determination of spin-diffusion length in magnetic multilayers or in experiments based on AMR in nanostructures. Therefore, further significant advances may come from studies of magnetic nanostructures in which the magnetic configurations are well controlled. The CPP-spin valve is a welcome development in this regard. Likewise, studying point contacts may help bring out a much clearer picture of the fundamental mechanisms as the ballistic regime could be reached and the magnetic configuration could be locally well defined [162].

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