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# MODELS IN SPINTRONICS: DRUDE, MOTT, GIANT MAGNETORESISTANCE AND VALET-FERT, SPIN TRANSFER AND TORQUE

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My tutorial will review four important phenomena of spinelectronics and some of the models which are used to describe these phenomena. The outline of the tutorial will be as follow:

## 1. Giant Magnetoresistance in metallic multilayers:

**- Introduction, spin-dependent scattering, simple picture with resistance model:**

Giant magnetoresistance (GMR) was discovered in 1988 [1]. Very quickly, it was understood that GMR originates from spin-dependent scattering due to different density of states at Fermi levels for spin up and spin down electrons. A simple resistance model based on Mott's two-current model was proposed to qualitatively explain the phenomenon

**- Modeling the in-plane transport (CIP: Current-in-plane) with Boltzmann equation, application to spin-valves**

GMR can be measured in two geometries: Current-in-plane (CIP) or current-perpendicular-to-plane (CPP) as illustrated below.

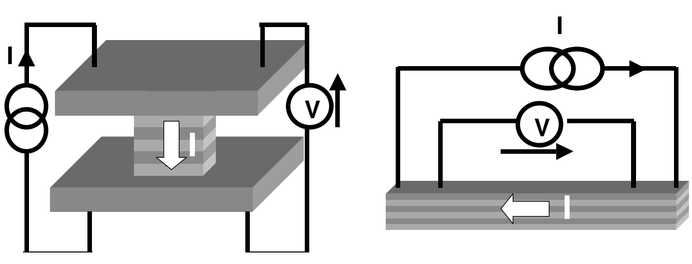


Fig.1 : Difference between Current-perpendicular-to-plane and current-in-plane geometry. Measuring the CPP transport properties requires patterning the system in a pillar with top and bottom electrodes.

Initially, the CIP GMR has been much more investigated than the CPP geometry because measuring the CIP transport properties is much more straightforward than in CPP geometry. Besides, the impedance requirement for sensor applications were much better fulfilled initially in the CIP geometry. The CIP transport properties in spin-valves and magnetic multilayers are well described in a semi-classical approach based on the Boltzmann equation taking into account bulk and interfacial spin-dependent scattering. The theory has been successfully used to interpret and optimize the properties of spin-valves for magnetoresistive heads applications [2-4]

**- Modeling the out-of-plane spin-dependent transport: Valet and Fert semi-classical theory, spin-accumulation, spin-relaxation, charge current, spin current.**

Pratt et al at Michigan State University initiated the study of GMR in CPP geometry. The measurements were performed at low T using a SQUID voltmeter with a metallic GMR pillars sandwiched between superconducting electrodes [5]. Valet and Fert developed a semi-classical theory of spin-dependent transport throughout metallic magnetic stack, introducing the concept of spin accumulation, spin-relaxation, current polarization [6]. This is illustrated in Fig.2:

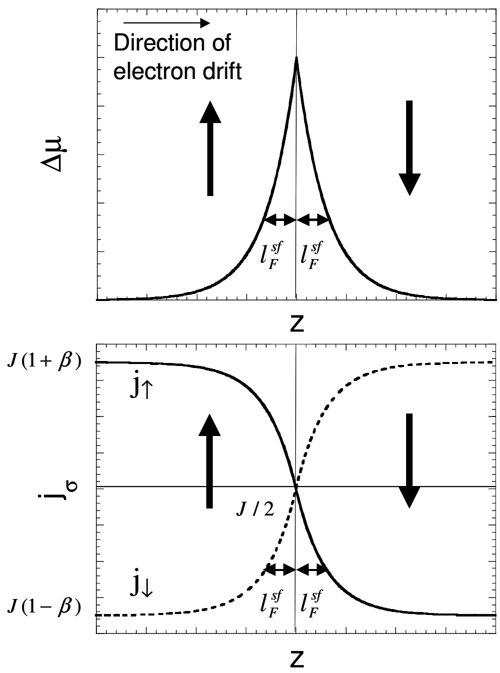



Figure 2: Illustration of the phenomenon of spin accumulation at a single interface separating two ferromagnetic layers of opposite magnetization. The electrons drift from left to right (the current flows from the right). The plot is drawn assuming that the spin ↑ (majority electrons) are less scattered than the spin ↓ electrons (β>0). The large arrows represent magnetization orientation.
(a): The spatial variation of the difference in chemical potential $\Delta\mu = \mu^{\uparrow} - \mu^{\downarrow}$ between the two species of electrons. $\Delta\mu > 0$ means an accumulation of spin ↑ electrons at the interface.
(b): The spatial variation in current density for each spin channel. The gradient of current reflects the spin relaxation which takes place within the characteristic spin-diffusion length scale $l_F^{sf}$. Adapted from (Valet-Fert, 1993) [19].

**- Generalization at 3D, new phenomena related to non-uniform currents.**

The concept of drift and diffusion currents resulting from gradient of spin accumulation was later generalized to non collinear magnetic configurations and extended at 3 dimensions. The numerical solutions of the generalized spin-diffusion equations yielded the prediction of new phenomena such as the formation of vortex of spin-currents as illustrated in Fig.3 in the case of spin transport through a magnetic nanoconstriction. The origin of such phenomenon will be discussed.

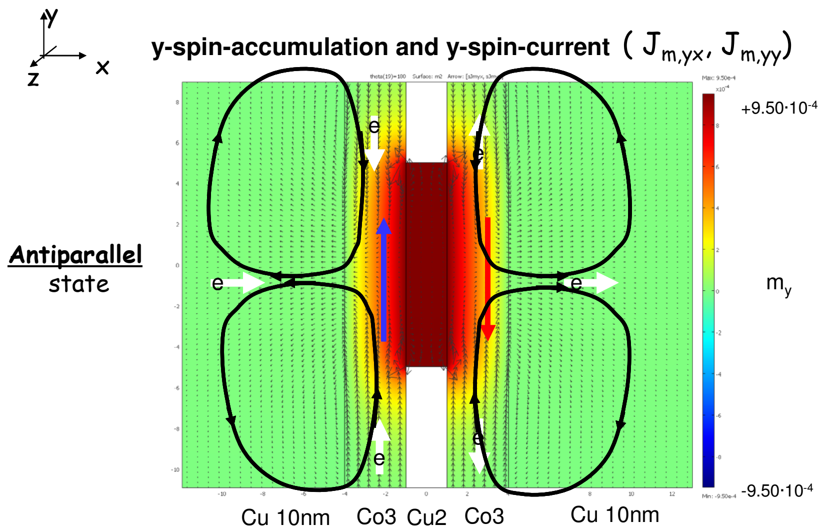


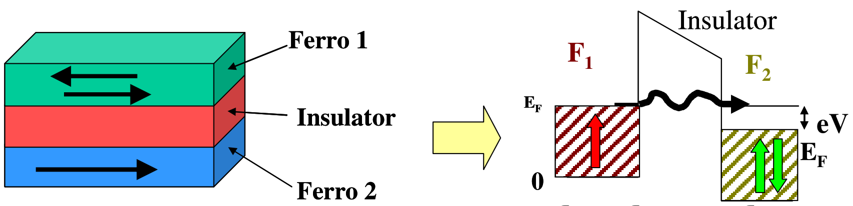

Fig.3 : Illustration of the formation of vortex of spin-current in the vicinity of a Cu nanoconstriction (2nm long, 10nm wide) separating two Co magnetic layers 3 nm thick sandwiched between Cu electrodes. [7]

**2. Tunnel magnetoresistance:**

**- magnetic tunnel junctions:**

**- Julliere's model:**

In 1975, Julliere has been first to grow magnetic tunnel junctions and observe a tunnel magnetoresistance at low temperature related to the relative orientation of the magnetization in the two magnetic electrodes adjacent to the tunnel barrier (Julliere, Physics Letters A, 1975). He proposed a simple two-current model based on the basic idea that the tunneling current for each spin direction is proportional to the product of density of states at Fermi level in the electrodes on both sides of the tunnel barrier. This model worked quite well for interpreting TMR data in amorphous MTJ where mainly s-like electrons (free like electrons) contribute to the tunneling.




$$J^{\sigma} \propto D_1^{\sigma}(E_F) \times D_2^{\sigma}(E_F)$$

Parallel state

$$J^{parallel} \propto D_1^{\uparrow} D_2^{\uparrow} + D_1^{\downarrow} D_2^{\downarrow}$$

Antiparallel state

$$J^{antiparallel} \propto D_1^{\uparrow} D_2^{\downarrow} + D_1^{\downarrow} D_2^{\uparrow}$$

$$P = \frac{D^{\uparrow}(E_F) - D^{\downarrow}(E_F)}{D^{\uparrow}(E_F) + D^{\downarrow}(E_F)}$$

$$TMR = \frac{\Delta R}{R_{AP}} = \frac{2 P_1 P_2}{1 + P_1 P_2}$$

*Jullière, Phys. Lett. A54 225 (1975)*

Fig.4 : Illustration of Julliere's model of TMR in MTJ

- **Slonczewski's model**:

Slonczewski carried out a complete calculation of the propagation of a plane wave through a Ferro/tunnel barrier/ferro sandwich. He pointed out the role played by the tunnel barrier on the polarization of the electrons and on the resulting TMR amplitude [8].

- **Spin filtering according to symmetry of Bloch waves in crystalline tunnel junctions**.

The first investigated MTJ were based on amorphous alumina barriers. In 2001, Butler and Mathon predicted that much larger TMR amplitude could be observed in crystalline MTJ due to a new spin filtering mechanism [9, 10]. The general idea is that when electrons tunnel through a crystalline barrier, the tunneling electrons propagate in evanescent waves which have the same symmetry as the Bloch states in the ferromagnetic electrodes. For MgO (001), mainly electrons with $\Delta_1$ symmetry can tunnel through the barrier. The electrons with $\Delta_5$ symmetry have much faster decay rate in the barrier and an even faster decay rate for those of symmetry $\Delta_{2'}$. Now, in the ferromagnetic electrodes (assumed to be bcc Fe), only majority electrons have the $\Delta_1$ symmetry. The minority sub-band of $\Delta_1$ symmetry is entirely below the Fermi level. As a result, the effective polarization of the electrons tunneling through the MgO is much enhanced due to this spin-filtering mechanism based on symmetry of wave function. Consequently, the TMR of these junctions can be much larger than in amorphous barriers.

The experimental observations of Yuasa and Parkin [11, 12] confirmed these very large TMR in crystalline barriers although the TMR amplitude never reached the extremely large values predicted theoretically.

### 3. Spin-transfer in non-collinear magnetic configuration

- **spin-transfer phenomenon:**

The spin transfer phenomenon was predicted by Slonczewski and Berger in 1996 [13, 14]. It appears when a current flows perpendicular-to-plane in magnetic multilayers (metallic stacks or magnetic tunnel junctions) in non-colinear magnetic configuration. The spin transfer torque is the torque that the spin of the conduction electrons exert on the local magnetization due to their exchange interaction with the electrons responsible of the local magnetization.

In diffusion limit, the basic equations describing the charge and spin currents are given by [15, 18]:

Charge current (1x3 vector): $$\mathbf{J_e} = 2\sigma\nabla\varphi - \frac{2\beta\sigma}{\nu}(\mathbf{M}, \nabla\mathbf{m}) \qquad (1)$$

Spin current (3x3 tensor): $$\mathbf{J}_m = 2\sigma\beta(\mathbf{M}\nabla\varphi) - \frac{2\sigma}{\nu}\nabla\mathbf{m} \quad (2)$$

Conservation of charge: $$div\mathbf{J_e} = 0 \quad (3)$$

Spatial evolution of spin: $$div\mathbf{J_m} + \frac{2\sigma}{\nu l_J^2}\left(1-\beta^2\right)(\mathbf{M}\times\mathbf{m}) + \frac{2\sigma}{\nu l_{sf}^2}\left(1-\beta^2\right)\mathbf{m} = 0 \quad (4)$$

The charge current is mainly driven by the gradient of electrical potential φ whereas the spin current is mainly driven by the gradient of spin accumulation **m**.

σ is the local conductivity, β is the scattering asymmetry [19], ν is a parameter related to the local density of states, $l_{SF}$ is the spin-diffusion length [19], $l_J$ is the spin-reorientation length.

(3) and (4) represent 4 equations with 4 unknowns: the electrical potential and the 3 components of spin accumulation. The local electrical potential, spin accumulation and all charge and spin-currents can be calculated from the above formula with appropriate boundary conditions.

The spin-torque is then expressed as $\mathbf{T} = \frac{2\sigma}{\nu l_J^2}\left(1-\beta^2\right)(\mathbf{M}\times\mathbf{m})$. Note the similarity between this expression and the precessional term in Landau Lifshitz Gilbert equation: $\frac{d\vec{M}}{dt} = -\gamma\,\vec{M}\times\vec{H}$. This means that due to exchange interactions, the spin accumulation **m** plays the role of an effective field acting on the local magnetization.

**- Slonczewski's term in metallic magnetic pillars:**

In a multilayer geometry, the spin transfer torque can be expressed by two terms: Slonczewski's term [13] and effective field term. In metallic pillar, the effective field term is usually negligible being of the order of 1% of the Slonczewski's term.

$$\Gamma_{spin-torque} = \underbrace{a_J.M\times\left(M\times M_p\right)}_{\text{Slonczewski's term or in-plane torque}} + \underbrace{b_J M\times M_p}_{\text{Effective field term or perpendicular torque}}$$

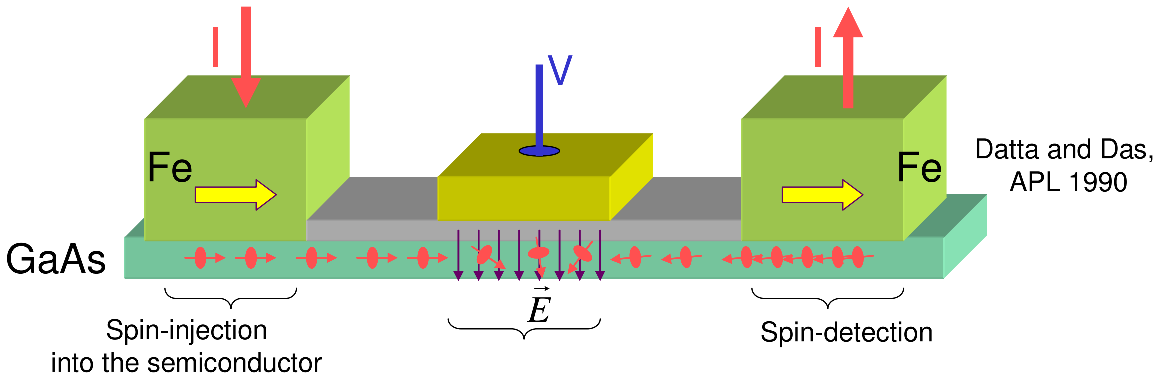
**- Slonczewski and effective field terms in magnetic tunnel junctions.**

In magnetic tunnel junctions, the effective field term is significantly larger than in metallic stack being of the order of 30% of Slonczewski's torque term. This difference between MTJ and metallic stack mainly originates from the momentum selection imposed by the tunneling (mainly electrons with momentum perpendicular to plane can tunnel resulting in a lesser angular averaging on all possible incidences than in the case of metallic pillars).

## 4. Spin-injection in semiconductors

**- experimental results:**

The concept of Datta and Das transistor proposed in 1990 [20] stimulated a strong interest in spintronics. The working principle of this transistor involves the injection of spin into a semiconductor from a magnetic material at the emitter, their manipulation (here by Rashba effect) during their drift in the semiconductor channel, and their spin dependent collection at the collector.




Several experimental attempts have been made to inject spin polarized electrons from a magnetic metal into a semiconductor but these attempts remained first unsuccessful. It was then realized that because of the very large difference in density of states between the magnetic metal and the semiconductor, such injection could not be efficient unless a thin Schottky barrier or a tunnel barrier is placed between the magnetic metal and the semiconductor.

**- Impedance mismatch or mismatch of density of states at Fermi level.**

This impossibility of injecting spin polarized electrons from a magnetic metal directly into a semiconductor was pointed out by Schmidt et al [21]. A. Fert and H. Jaffres latter extended this calculation to derive conditions for injection and collection of spin polarized electrons at both ends of the transistor [22].

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