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Modeling of magneto-transport properties for giant magneto-resistance and tunneling magneto-resistance structures

M. NEGOITA*, J. NEAMTU, VIOREL-CIPRIAN ONICA
INCDIE ICPE-CA, Bucharest, 313,Splaiul Unirii, sector 3, Romania

When we refer to transport, we take into consideration the transport of electrons in the lattice and the scattering processes, but also the tunneling of electrons. We calculated through computerized models the magnetic properties of the layers. This should help us in a better implementation of electronic devices based on the magnetic properties of the elements that make those devices.

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1. Introduction

Since its discovery 20 years ago [1], the giant magneto-resistive effect was considered a big step in what concerns the future of electronics. New types of read heads and memories for the storage of information with larger capacities, witch relies on this effect, have been created in order to improve the computer's performances [2].

In what concerns this effect, it is taking into account also the spin of the electron [3], not only his charge, witch provides a new degree of freedom needed for the manipulation of the electrons inside the solid materials in order to obtain best results from the transport properties of the materials.

The effect represents the change in resistance for successive layers of magnetic and non-magnetic materials when we apply an external magnetic field [4]. But there are different results in what concerns this effect: the magnetic layers can be aligned parallel or anti parallel, resulting in a ferromagnetic configuration or anti-ferromagnetic configuration [5].

Transport in layered materials has been subject of intensive theoretical investigations, in particular the discovery of the giant magneto-resistance in metallic multilayer. Most of the measurements were reported for the current-in-plane geometry [6] since the current-perpendicular-to-plane geometry presents greater experimental results [7]. On the other hand, from the theoretical point of view, the current-perpendicular-to-plane differs from the current-in-plane in several aspects: the high-symmetry of the current-perpendicular-to-plane geometry makes its theory easier, it is better suited for testing of theoretical models [8, 9, 10, 11, 12], and it gives larger value of the giant magneto-resistive effect as compared to the current-in-plane geometry. Last but not least, the current-perpendicular-to-plane transport is also closely related to the tunneling through a nonmetallic spacer and to the ballistic transport [13].

Alternative theoretical approaches applicable to the current-perpendicular-to-plane transport are based either on a non-equilibrium Green function method [14] or on a transmission matrix formalism implemented within an empirical tight-binding method based on surface Green functions [15].

In this paper we will use this approach based on Green functions with the Hamiltonian for a tight-binding model in order to calculate giant magneto-resistance and tunneling magneto-resistance for some multilayer.

2. Model

We assumed that the system consists of on random semi-infinite left and right leads sandwiching a sample consisting of a left and a right magnetic slab separated by a non-magnetic spacer. Alternatively, a multilayer consists of a set of nonmagnetic and magnetic layers such that a ferromagnetic and an anti-ferromagnetic configuration can be formed.

If we consider the transport problem as a scattering one, the electrons are injected into the scattering region by the incident wave, where they are transmitted or reflected. We have treated this problem considering semi-infinite scattering leads, where we have taken into account the coupling between them and the hopping mechanism.

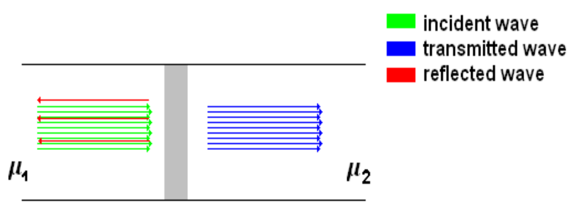

Fig. 1. The scattering region.

We have started by considering the intensity of the flux of electrons as a function of chemical potentials. For example, considering two leads:

$$I = \frac{e}{h}(\mu_1 - \mu_2) \tag{1}$$

And with the relationship between the voltage and the chemical potential, the conductance can be written as:

$$I = \frac{e}{h}T(\mu_1 - \mu_2) = \frac{e^2}{h}T\Delta V \tag{2}$$

$$\Gamma = \frac{I}{\Delta V} = \frac{e^2}{h}T \tag{3}$$

The magneto-resistance is a function of conductance:

$$MR = \frac{\Gamma_{FM}^{\uparrow} + \Gamma_{FM}^{\downarrow} - 2\Gamma_{AF}^{\uparrow\downarrow}}{2\Gamma_{AF}^{\uparrow\downarrow}} \tag{4}$$

where Γ_{FM}^{σ} is the conductance of a channel in the feromagnetic configuration and $\Gamma_{AF}^{\uparrow\downarrow}$ is the conductance of any type of spin in the antiferomagnetic state.

In order to calculate the transmission coefficients, we can start by calculating the S matrix witch gather the transmission coefficients and the reflected ones from the leads in left but also from right.

$$S = \begin{pmatrix} r & t' \\ t & r' \end{pmatrix} \tag{5}$$

where r, t are the reflected and transmitted coefficients from left and r' and t' the equivalent quantities from right. This coefficients are obtained from the Green functions for the leads.

The Green function is given by the Dyson equation:

$$G(E) = \left[g(E)^{-1} - H_{eff}(E)\right]^{-1} \tag{6}$$

where g(E) is a matrix where the diagonal terms are the Green functions for each lead, left and right, and $H_{eff}(E)$ is the effective Hamiltonian. The Hamiltonian for the tight-binding model is the sum of the atomic orbital energies and the hopping energies, so there are 13 parameters witch describe the total Hamiltonian.

In the end, the transmision and reflection coefficients have the form:

$$t_{hl} \approx G_{hl}\sqrt{\frac{v_h}{v_l}}e^{ik_h l} \tag{7}$$

$$r_{hl} \approx (G_{hl} - \Im)\sqrt{\frac{v_h}{v_l}}e^{ik_h l} \tag{8}$$

in witch we have considered the group verlocityes and the numbers h and l describe the atomic positions in the lattice.

The relation between r and t is sumarized as:

$$\sum r + \sum t = 1 \tag{9}$$

The main difference in what concerns the tunneling magneto-resistive effect with respect to giant magneto-resistive effect is that the current involved is a tunneling current.

In order to calculate the magneto- resistance where the non-magnetic material is very thin, and the transport at the interfaces is made by tunneling through this material, based on the model of Green functions and the scattering matrix S, we have calculated the transmission coefficient considering the density of states for the s, p, d orbital. So, we obtained:

$$T(k_{\parallel}) = \left[1 + \frac{\left[2m_I m_N^2(U_0 - E_F) + 2m_I^2 m_N E_F - k_{\parallel}^2(m_I^2 + m_N^2)\right]^2}{4m_I^2 m_N^2\left[2m_N E_F - k_{\parallel}^2\right]\left[2m_I(U_0 - E_F) - k_{\parallel}^2\right]}\sinh^2\left[\frac{1}{\hbar}\sqrt{2m_I^*(U_0 - E_F) + k_{\parallel}^2 l}\right]\right]^{-1} \tag{10}$$

where l is the length of the non-magnetic material, U_0 the heigth of the potential barrier, m_N the effective mass of the electrons in the metal and m_I is the mass of the insulator.

3. Results

Considering the coefficients presented in the last paragraph, we present the results obtained by simulations:

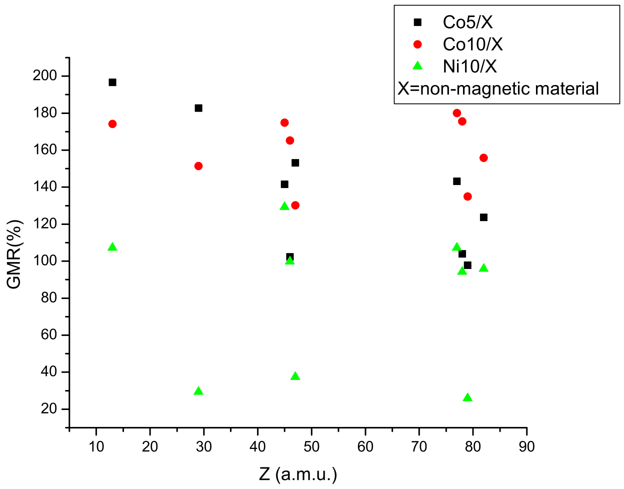

Fig. 2. Variation of GMR as a function of atomic number.

In the case of tunneling magnetoresistance we have calculated the transmission coefficient T and we obtained:

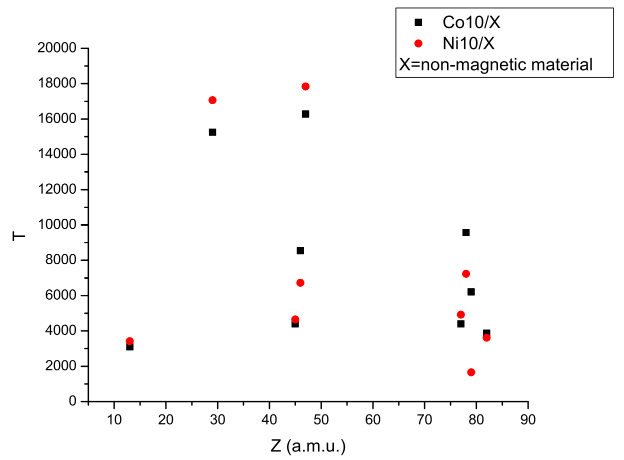

Fig. 3. Variation of transmission coefficient as a function of atomic number.

4. Discussion

For the giant magneto-resistance we observed from calculations that multilayer were the non-magnetic material has a small atomic number, such as Al or Cu, present larger GMR effect, up to almost 200%. This is in according with other models presented in literature [16, 17, 18]

For tunneling, some materials present a large transmission coefficient, but others with small transmission coefficient will present larger magneto-resistive properties, as reported in literature [16, 17, 18].

These results should help us choose witch are the materials to implement in order to obtain the devices needed for our purpose.

5. Conclusions

There are many ways of observing the magneto-resistive effects: the multilayer configurations were the first materials in witch we had noticed this effect on the experiments [19]. It depends very strongly on the thickness of the non-magnetic material.

With the emergence of devices which rely on transport across nano scale interfaces, a clear understanding of scattering events and inter-diffusion in this region is essential. In this study, we have presented some of these materials witch we though that give best results.

The transport in magnetic multilayer is of great scientific and technological interest (sensors, non-volatile memories, magnetic reading heads, etc.). The evaluation of the transport in magnetic multilayer is thus of a great practical importance. In the present paper we have presented a model, particularly suitable for the current-perpendicular-to-plane transport, which allows the evaluation of the sample's magneto-conductance.

The research in this field continues with structures in witch we can apply the giant magneto-resistance and tunneling magneto-resistance effects, where the magnetization of the ferromagnetic layers is fixed with an anti-ferromagnetic layer by exchange anisotropy.

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*Corresponding author: madalina_negoita@icpe-ca.ro