Magnetic and non magnetic thickness effect on the exchange integrals in Co/Pt multilayers

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Abstract: In this paper, we report a theoretical study of elementary magnetic excitation properties of $Co(t_{Co})/Pt(t_{Pt})$ multilayers. We establish the corresponding spin hamiltonian by including exchange interactions, surface anisotropy and dipolar interactions. This hamiltonian is treated by Green's function method. The calculated magnetization for various values of the magnetic layer thickness (t_{Co}) as well as those of the non-magnetic one (t_{Pt}) according to the temperature is in good agreement with the experimentally measured one for these thicknesses and temperature . The deduced exchange integral values are satisfactory in agreement with the values known for 3d transition metals like cobalt.

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I – INTRODUCTION

Several works about the $Co(t_{Co})/Pt(t_{Pt})$ system showed that the easy axis magnetization is perpendicular to the film plane. This favorates a wide use in the magnetism field such as magneto optic recording, the perpendicular magnetic recording (allowing a big storage capacity by unit surface), and the construction of the magnetic components used in the electromechanical systems [1-3].

Theoretical studies as well as experimental ones showed that quasi two-dimensional systems (2D) have some magnetic properties different of that of three-dimensional one (3D). In particular the main role of the magnetocrystalline anisotropy existence in the magnetic state stability, the existence of a dimensionality crossover where the magnetic interactions pass from 3D behavior (magnetization varies in $T^{3/2}$) for low temperatures compared to gap energy value to another behavior characteristic of the (2D) systems (magnetization varies in TlogT) for high temperatures compared with the gap energy value without neglecting , as we shall see in this work, the appearance of other interactions which are essentially dipolar interactions and surface anisotropy and their important role in the stability magnetic when the temperature increases[4-12]. So, this work is constituted by two parts, the first one consists of a theoretical study in which we emphasize the surface anisotropy and dipolar interaction effects on the magnetization per spin. The second part contains an application of our calculation model on experimental results of the $Co(t_{Co})/Pt(t_{Pt})$ system for various thicknesses $t_{C}o$ and t_{Pt} values. The adjustment allowed us to deduce the exchange integral values.

II- MATHEMATICAL FORMULATION

We consider a ferromagnetic system with localized spin made up of N planes. The easy axis magnetization is confused with (Oz) axis. While the film plane is the (xy) plane. The corresponding hamiltonian can be represented by:

$$\mathcal{H} = -J_{//}\sum_{<ij>}(S_i^x S_j^x + S_i^y S_j^y + \delta S_i^z S_j^z) - J_{\perp}\sum_{<ii'>}(\vec{S_i}\vec{S_{i'}}) - \alpha\sum_i{}'(S_i^z)^2 + \frac{g^2\mu_B^2}{2}\sum_{<ij>}\frac{1}{r_{ij}^3}\left\{\vec{S_i}\vec{S_j} - 3\frac{(\vec{S_i}\vec{r_{ij}})(\vec{S_j}\vec{r_{ij}})}{r_{ij}^2}\right\} \quad (1)$$

$J_{//}$ is the nearest neighbors exchange integral in the same plane. $J_{\perp}$ is the nearest neighbors exchange integral between planes. $\delta>0$ and $\alpha>0$ are magnetocrystalline anisotropies where Σ' acts only on the surface planes. The last term represents dipolar interactions. The application of linear spin wave theory [13] and Fourier transform[14], allowed us to obtain the following hamiltonian expression:

$$\mathcal{H} = \sum_{l,m}^{N}\sum_{k_{//}}\left\{A_{lm}(k_{//})a_{k_{//},l}^{+}a_{k_{//},m} + \frac{1}{2}B_{lm}(k_{//})\left(a_{k_{//},l}^{+}a_{-k_{//},m}^{+} + a_{k_{//},l}a_{-k_{//},m}\right)\right\} \quad (2)$$

Where $k(k_{//},k_{\perp})$ is the wave vector . A_{lm} ($k_{//}$) and B_{lm} ($k_{//}$) are the matrix elements expressed according to the various parameters occurring in the equation (1). The treatment of the Hamiltonian matrix representation so obtained is made by Green's function method[15].

III - EXCITATION SPECTRUM

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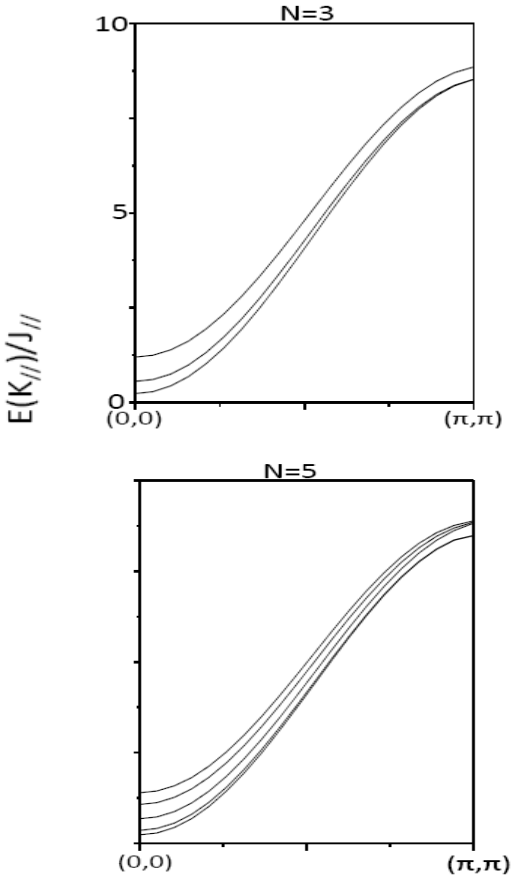
The excitation spectra are obtained by the diagonalization of the hamiltonian (2). This diagonalization is made by Green's function method. So we consider the following Green's functions:

$$G_{lm} = \left\langle\left\langle a_{k_{//},l}, a^{+}_{k_{//},m} \right\rangle\right\rangle \quad \text{and} \quad G'_{lm} = \left\langle\left\langle a^{+}_{k_{//},l}, a^{+}_{k_{//},m} \right\rangle\right\rangle \tag{3}$$

The motion equations associated with these functions allow us to obtain a set of coupled equations represented by the following matrix form:

$$\begin{pmatrix} \underline{A}-E & \underline{B} \\ -\underline{B} & -\underline{A}-E \end{pmatrix} \begin{pmatrix} \underline{G} & 0 \\ \underline{G}' & 0 \end{pmatrix} = \frac{-1}{2\pi} \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} \tag{4}$$

Where A and B are N order matrices, their elements $A_{lm}(k_{//})$ and $B_{lm}(k_{//})$ is given by the equation (2).
The elementary excitation energies $E_l(k_{//})$ are obtained from the poles of the matrix $\begin{pmatrix} G & 0 \\ G' & 0 \end{pmatrix}$ as being the eigenvalues of the matrix $M = \begin{pmatrix} A & B \\ -B & -A \end{pmatrix}$ and their calculation is done as in our previous studies [9-12].
On the figure 1, we present the obtained excitation spectra $E(k_{//})$ from equation (4) for N=3, 5 and 10



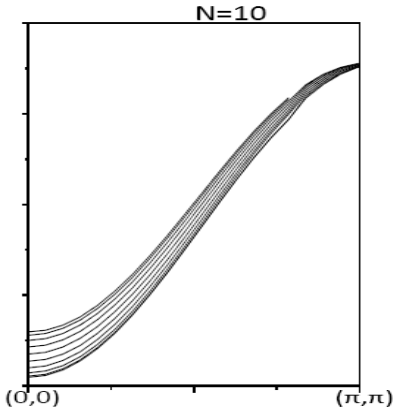


Fig. 1: Excitation spectra for N= 3, 5 and 10 monatomic planes.

We so notice that for studied three values of N, the number of the obtained modes is equal to the number of monatomic planes engaged in every super-lattice. This important result is probably due to the effect of the symmetry break transversely to the planes.
Besides, we also notice that more the number N of ferromagnetic planes increases more the separation between the energy modes decreases. This can be due to the surface effect which becomes more and more weak when the size of the super-lattice becomes thick.

IV- Magnetization per spin

4.1 Surface anisotropy and dipolar interaction effects

In this part, we report a numerical study results of surface anisotropy and dipolar interaction effects on the properties of the studied super-lattice. The magnetization per spin expression is given by[16]:

$$\frac{\langle S^z \rangle}{S} = 1 - \frac{1}{S}\frac{1}{N}\frac{s}{(2\pi)^2}\sum_{l=1}^{N}\sum_{n=1}^{N}\int_{BZ}\left[\frac{P_{ln}P_{nl}^{-1} - P_{ln'}P_{n'l}^{-1}}{e^{\beta E_l(k)}-1} - P_{ln'}P_{n'l}^{-1}\right]dk_x dk_z \tag{3}$$

With P(2N,2N) is the passage matrix which allows to diagonalize the Hamiltonian, s is the basic cell surface and $E_l(k_{//})$ are the Hamiltonian energies.
In the presence of dipolar interactions and surface anisotropy, the analytical resolution of this equation becomes complicated when the plane number exceed one. We have resort to a numerical resolution to show the effect of each one of these interactions on the superlattice magnetic stability.
On figure 2, we represented the thermal variation of the normalized magnetization with regard to the case where dipolar interactions and surface anisotropy intervene with the same weight (α =D) in the magnetic order stabilization.

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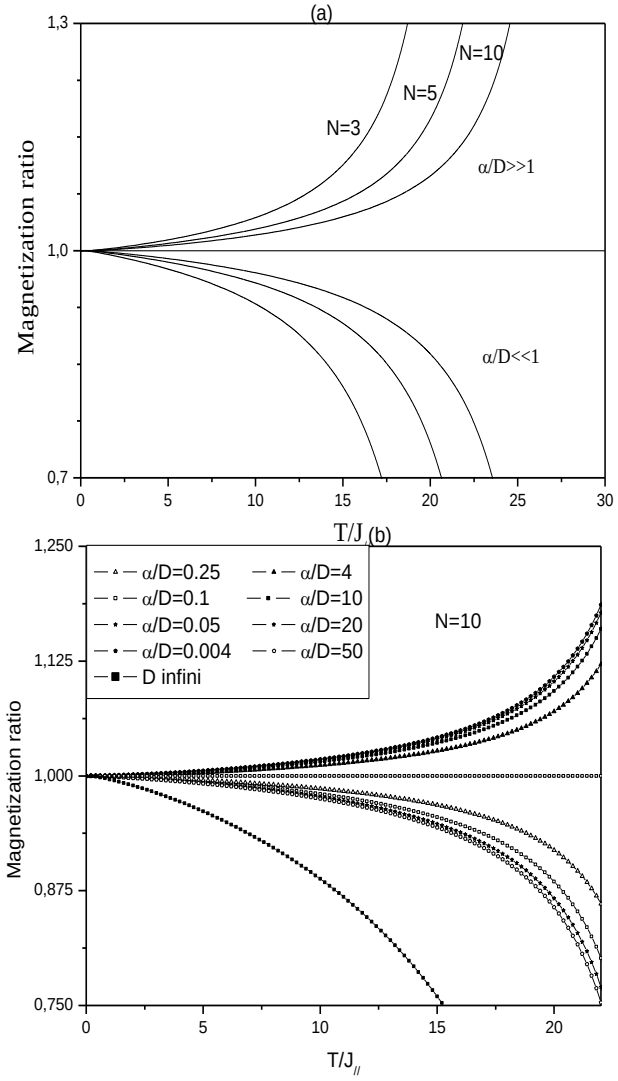


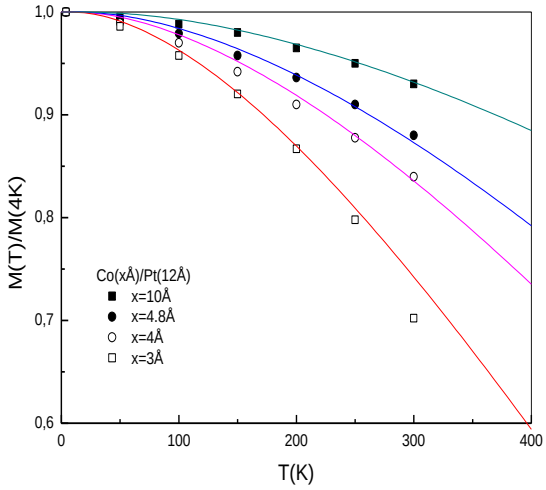
Figure 2: Thermal variation of the magnetization ratio (a) for N=1, 5 and 10, (b) for various value of α/D

We notice that, when the dipolar interactions is dominant (α /D<<1), the magnetization is reduced, while for a dominant surface anisotropy (α/D>> 1), the magnetization increases with regard to the case (α =D) for the three values of the plane number. Indeed, dipolar interactions tend to align the magnetic moments according to the film plane and consequently to reduce the magnetization perpendicularly to the plane, while surface anisotropy tends to align moments perpendicularly to the plane, and consequently to reinforce the magnetization. We also notice, that when the plane number increases, the effect at once of dipolar interactions and of the surface anisotropy decreases suggesting that for very fine thin layers, the effect of these two interactions cannot be neglected.

The fig. 1 b represents the thermal magnetization ratio variation for several values of the ratio α/ D [9-12]. We notice that more the effect of surface anisotropy becomes important compared to dipolar interactions more the increase of the magnetization ratio becomes remarkable. While more dipolar interactions effect becomes important, more the magnetization ratio decreases suggesting the fact that the surface anisotropy tends to align surface moments perpendicularly to the plane and consequently to reinforce the magnetization. While dipolar interactions tend to align moments in the plane and consequently to decrease the magnetization perpendicularly to the film plane.

4.2 Comparison with results of an experimental study

The comparison of our calculation results of reduced magnetization thermal evolution $m_{th}(T)=M(T)/M(4K)$ (solid line) with those of experimental measurements $m_{ex}(T)$ (symbols) made on the $Co(t_{Co})/Pt(t_{Pt})$ system for various thicknesses of the Co magnetic layer (fig. 3 a) and of the non-magnetic layer (fig. 3 b) show a good concordance. This allows us to estimate the $J_{//}$ and $J_{\perp}$ exchange integral values presented on tables 1 and 2. These values are in agreement with those found generally for 3d transition metals as Co.



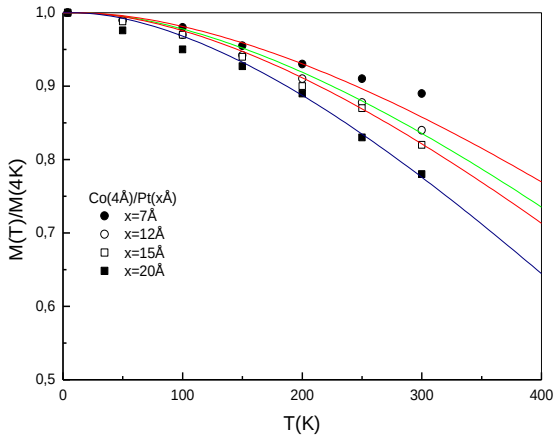


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Figure 3 : Adjustment of our calculation (solid line) with experimental results(symbols).
a- Co thickness is variable and t_{Pt} is fixed.
b- Pt thickness is variable and tCo is fixed.

t_{Co} (Å)	$J_{//}/k_B$ (K)	$J_{\perp}/k_B$ (K)
2 planes	95	4.75
3 planes	124	6.2
4 planes	140	7
7 planes	190	9.5

Table 1: The exchange integral values J deduced from the adjustment of $m_{th}(T)$ and $m_{ex}(T)$ according to t_{Co} thikness.

t_{Pt} (Å)	$J_{//}/k_B$ (K)	$J_{\perp}/k_B$ (K)
7	135	6.75
12	124	6.2
15	118	5.9
20	103	5.15

Table 2: The exchange integral values J deduced from the adjustment of $m_{th}(T)$ and $m_{ex}(T)$ according to t_{Pt} thikness.

We notice that more the magnetic layer is thick more the exchange interaction is reinforced (table 1). This fact can be due to an increase of bulk effect and then the number of Co nearest neighbor atoms of a given Co site increases too when t_{Co} increases. While more the t_{Pt} increases more the magnetic exchange is reduced. Indeed, the number of Co nearest neighbor of a given Co decreases when t_{Pt} increase.

V- Dynamics of the created magnon population

An approach to the relaxation of magnon created population can be estimated based on the fact that the contribution of the exchange to the of magnon frequency and therefore to the mixture potential of cobalt 'd' and 's' bands corresponding to this creation V_{sd}^{mag} is related to the electronic contribution in a ratio of ten[17]; we have:

$$V_{sd}^{mag} = \frac{m_e^*}{m_{mag}^*} V_{sd}^{ele} \approx 10^{-1} V_{sd}^{ele} = 0.014 eV$$

where $V_{sd}^{el} = 0.14\ eV$ [18 ; 19].

The magnon relaxation time can then be written as:

$$\tau_{mag}^{-1} = \frac{2\pi}{\hbar} |V_{sd}^{mag}|^2 \mathcal{D}_d(E_F)$$

$\mathcal{D}_d(E_F)$ is the state density at Fermi level. For cobalt $\mathcal{D}_d(E_F) = 4.16\ (eV^{-1})$ [18]. The mixture potential V_{sd}^{mag} measures also the gap energy E_g of creating these magnons. The values of E_g, defined as being the lowest eigenvalues of the hamiltonien (1), were calculated for different thicknesses t_{Co} and t_{Pt} . The obtained values of E_g are in agreement with the mixture potential $V_{sd}^{mag} = 0.014\ eV$ as shown on the two following tables (tables 3 and 4) giving the energy gap E_g and the magnon relaxation time τ_{mag} values for different thicknesses studied.

t_{Co}(Å)	3	4	4.8	10
E_g (eV)	0,01	0.136	0.015	0.02
$\tau_{mag}(10^{-13}\ s)$	2.294	1.34	1.056	0.573

Tables 3: Energy gap E_g and the magnon relaxation time τ_{mag} according to t_{Co} thikness.

t_{Pt} (Å)	7	12	15	20
E_g (eV)	0,015	0.136	0.013	0.011
$\tau_{mag}(10^{-13}\ s)$	1.136	1.34	1.487	1.952

Tables 4: Energy gap E_g and the magnon relaxation time τ_{mag} according to t_{Pt} thikness.

The decrease of relaxation time $\tau_{mag}(t_{Co})$ is consistent with the tendency of the exchange effect with the magnetic layer thickness.

VI-Conclusion

In this work, we find that the surface anisotropy and dipolar interactions that occur because of reduced dimensionality play an important role when the temperature increases, the magnetic stability of 2D systems.
The experimental result fit performed on the Co(tCo)/Pt(tPt) system showed that the exchange integrals increase with increasing of the magnetic layer thickness and consequently the magnetic order also increases.

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