Magnetization study of Ni/Ag multilayers

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The magnetic properties of Ni/Ag multilayers, prepared by evaporation in ultrahigh vacuum under controlled conditions, have been systematically studied by magnetic measurements. A spin-wave theory has been used to explain the temperature dependence of the magnetization and the approximate values for the bulk exchange interaction J_b and surface exchange interaction J_S for various Ni layer thicknesses have been obtained.

Keywords: Ni/Ag multilayers; Magnetization; Exchange interactions

I. INTRODUCTION

Magnetic multilayers with suitable magnetic properties would offer improvements over conventional magnetic materials for applications in high density magnetic recording, both as recording media [1] and as heads [2]. One of the main requirements for perpendicular recording and magneto-optic recording is a high perpendicular magnetic anisotropy, which can be achieved in magnetic multilayers.

Compared with the corresponding bulk materials, ultrathin films exhibit drastic differences in their magnetic properties. Long-range ferromagnetic order in solids is a collective phenomenon depending strongly on the coordination number, which is effectively diminished in films consisting of only one or a few monolayers. In addition, the lowered dimensionality of thin films in relation to the bulk leads to important changes in the shape of the magnetization as a function of temperature and in the critical exponents.

The magnetic properties of multilayers are strongly dependent on their detailed structure and composition, which are determined by the growth conditions used during fabrication [3-5]. For example, the degree of mixing between adjacent layers determines the amount of Ni able to contribute to the magnetic properties of the film, and the degree of crystallographic texture within the layers, combined with any surface anisotropy present determines the overall anisotropy of the multilayers.

The fact that Ni is ferromagnetic, a study of the magnetic properties of this system also can bring additional information on the state of the interface. Therefore, we have undertaken such a study and describe our results here. We calculate the thermal variation of the magnetization as a function of Ni layer thickness and compare it qualitatively and quantitatively with experimental results.

II. EXPERIMENTAL

Ni/Ag multi-layered films were synthesized by sequential evaporation of Ni and Ag in an ultra high vacuum using several electron guns. The pressure during evaporation was in the $5x10^{-9}$ Torr range. The rate of evaporation and the thickness were controlled by quartz oscillators. Water cooled glass and Si substrates were used. In all the cases the first layer was Ag. The total number of layers (N) was adjusted to get a total Ni layer thickness of about 1000Å. The Ag layer thickness t_{Ag} was kept constant at 50 Å and t_{Ni} varied between 10 and 100 Å. Low angle x-ray diffraction of all the samples revealed peaks typical of the modulated structure and the x-ray diffraction in the high angle range $35°<2\theta<50°$ showed the existence of fcc Ni(111) peak. Magnetization M was measured using a vibrating sample magnetometer under magnetic fields up to 1T and in the temperature range 5 to 300 K.

III. RESULTS AND DISCUSSION

The low-temperature magnetization was studied in detail for a few samples. Plots of the magnetization, for different thicknesses of Ni layers, versus temperature were made for the Ni/Ag multilayers (Fig. 1).

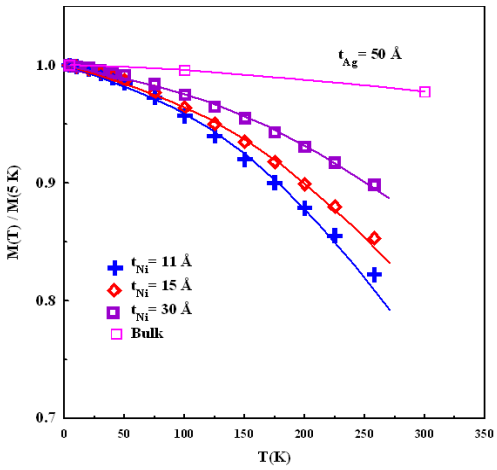

Fig. 1. Calculated (continuous line) and measured (symbols) temperature dependence of the normalized magnetization of Ni/Ag multilayers with varying Ni layer thicknesses.

Recently, Pinettes et al. [6] examine the influence of the anisotropy on the thickness dependence of the spin wave excitation spectra and calculate the thermal variation of the magnetization as a function of film thickness.

The system can be considered as periodic with magnetic cell containing n magnetic planes. We consider that the ferromagnetic thin film is a cubic lattice with uniaxial anisotropy . The thin film is build of a superposition of n atomic planes parallel to the surface of the thin film . The lattice unit vectors ($\vec{e}_x$, $\vec{e}_y$, $\vec{e}_z$) are so that the $\vec{e}_z$ is perpendicular to the surface of the thin film. Any atom can be denoted by jα , where α (α =1,….,n) is the layer ordering number and j the position-vector in the plane of the layer.

The Heisenberg Hamiltonian can be written as :

$$H = -J_S \sum_{\alpha \in \{1,n\}} \sum_{\langle i,j \rangle} S_{i\alpha} S_{j\alpha} - J_b \sum_{\langle \alpha,\alpha' \rangle} \sum_{\langle i,j \rangle} S_{i\alpha} S_{j\alpha} + S_{i\alpha} S_{j\alpha'} - D^{\perp} \sum_{i\alpha} S_{i\alpha}^{Z^2} + D^{//} \sum_{i\alpha} \left(S_{i\alpha}^{X^2} - S_{i\alpha}^{Y^2} \right) \quad (1)$$

where J_b and J_S are the bulk and surface exchange interactions. $D^{\perp}$ and $D^{//}$ are the surface anisotropy parameters for the uniaxial out of plane and in plane components. We denote by < > the summation on the pairs of nearest-neighbours atoms or adjacent layers. $S_{j\alpha}$ is the spin operator of the jα atom.

In the Holstein-Primakoff formulation [7], the creation and annihilation operators ($a_{i\alpha\mu}$ and $a^{+}_{i\alpha\mu}$) for each atomic spin are related to the spin operators by:

$$S^X_{i\alpha\mu} + i\, S^Y_{i\alpha\mu} = (2S)^{1/2} f_{i\alpha\mu}(2S)\, a_{i\alpha\mu}$$

$$S^X_{i\alpha\mu} - iS^Y_{i\alpha\mu} = (2S)^{1/2} a^{+}_{i\alpha\mu} f_{i\alpha\mu}(2S)$$

In the frame work of non interacting spin wave theory, the linear approximation of the Holstein-Primakoff method is sufficient to describe the main magnetic behaviour and the correction terms are quite-small at low temperatures ($T<T_C/3$) [8,9]. So, the value of $f_{i\alpha\mu}(2S)$ is fixed to 1.

We pass from the atomic variables ($a_{i\alpha\mu}$, $a^{+}_{i\alpha\mu}$) to the magnon variables ($b_{k\alpha\mu}$, $b^{+}_{k\alpha\mu}$) after a two-dimensional Fourier transformation; we show that Performing a two-dimensional Fourier transformation :

$$H = H_0 + 2D^{//} S \sum_{k\alpha;\alpha\in\{1,n\}} b_{k\alpha} b_{-k\alpha} + b^{+}_{k\alpha} b^{+}_{-k\alpha} + \sum_{k\alpha;\alpha\in\{1,n\}} A_k\, b^{+}_{k\alpha} b_{k\alpha} + \sum_{k\alpha;\alpha\in[2;n-1]} B_k\, b^{+}_{k\alpha} b_{k\alpha} + \sum_{k\langle\alpha;\alpha'\rangle;\alpha\in[1;n]} C_k\, b^{+}_{k\alpha} b_{k\alpha'} \quad (3)$$

where

$$A_k = (J_s (2n^{//} - (\lambda^{+}_k + \lambda^{-}_k)) + 2 J_b n^{\perp} + 2D^{\perp}) S,$$

$$B_k = (4n^{\perp} + 2n^{//} - (\lambda^{+}_k + \lambda^{-}_k)) J_b S, \quad (4)$$

$$C_k = -J_b S \lambda'_k .$$

H_0 is a constant term, the coefficients λ^{+}_k , λ^{-}_k and λ'_k depend on the crystallographic structure of the magnetic layer. $n^{//}$ represent the number of nearest-neighbours sites in the same atomic plane, while $n^{\perp}$ is the number of nearest–neighbours in the adjacent plane in the magnetic layer. For our case we have a fcc(111) ($n^{//} = 6$ and $n^{\perp} = 3$) with the lattice constant a:

$$\lambda^{+}_k = \lambda^{-}_k = 4\cos(ak_x\sqrt{6}/4)\cos(ak_y\sqrt{2}/4) + 2\cos(ak_y\sqrt{2}/2), \quad (5)$$

$\lambda'_k = 4\cos(ak_x\sqrt{6}/12)\cos(ak_y\sqrt{2}/4)+2\cos(ak_x\sqrt{6}/6).$

The secular equation that results from the Heisenberg equation of motion is given by (2n x 2n) matrix :

$$W = \begin{pmatrix} U & V \\ -V & -U \end{pmatrix}$$

the two (n x n) matrices U and V are given by:

$$U = \begin{pmatrix} A_k & B_k & & & & & \\ B_k & C_k & B_k & & & & \\ & \cdot & & & & & \\ & & \cdot & & & & \\ & & & \cdot & & & \\ & & & & \cdot & & \\ & & & & & \cdot & \\ & & & & & B_k\ C_k\ B_k & \\ & & & & & & B_k\ A_k \end{pmatrix} \quad \text{and}$$

$$V = \begin{pmatrix} 2D^{//}S & 0 & \cdots & \cdots & 0 \\ 0 & 0 & & & \cdot \\ \cdot & & 0 & & \cdot \\ \cdot & & & \cdot & \cdot \\ \cdot & & & & \cdot \\ \cdot & & & & \cdot \\ \cdot & & & & \cdot \\ \cdot & & & & \cdot \\ \cdot & & & & \cdot \\ \cdot & & & 0 & 0 \\ 0 & \cdots & \cdots & 0 & 2D^{//}S \end{pmatrix} \qquad (6)$$

The reduced magnetization m(T) versus temperature is computed numerically from:

$$m(T) = 1 - \frac{1}{N_k nS} \sum_{k,r} \frac{1}{\exp\left(\frac{\omega_k^r}{k_B T}\right) - 1} \qquad (7)$$

The coefficient N_k indicates the number of k points taken in the first Brillouin zone.

Using Eq. (7), satisfactory fits were obtained for the M(T) data for all of the Ni/Ag films. The theoretical curves M(T) obtained from the fits for the t_{Ni} = 11, 15 and 30Å films are shown in Fig. 1. It is seen that the experimental points align well with the calculated curves. The values of J_b and J_S obtained from the fits are listed in Table I for all films (taken S = 0.3 , $D^{\perp}$ =0.03 K and $D^{//}$ = 0). The derived bulk exchange interaction constants all consistently fall in the range expected for the exchange interaction of bulk Ni [10]. Compared to the bulk exchange interaction, the surface exchange interaction is weak and J_S is still less than about 0.3 J_b. Our results would indicate that the interface is diffuse due to the structural imperfection effects (diffusion, island structure, disorder etc.).

t_{Ni} (Å)	J_b/k_B (K)	J_S/k_B (K)
11	235	72
15	234	71
30	218	67

Table I. The fitting results from Eq. (7) for Ni/Ag. J_b is the bulk exchange interaction between neighbouring Ni atoms and J_S is the surface exchange interaction .

IV. CONCLUSION

In conclusion, we have prepared Ni/Ag multilayers by evaporation. The thermal variation of magnetization in ferromagnetic multilayer films is calculated using spin wave theory. A simple model has allowed us to obtain numerical estimates for the exchange interactions for various Ni layer thicknesses.

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