The strain-induced magnetic anisotropy of $Ni_{81}Fe_{19}/W_{90}Ti_{10}$ multilayers

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Abstract: The magnetic anisotropy results of $Ni_{81}Fe_{19}$ multilayers, prepared by DC sputtering in ultra high vacuum, were described on the basis of existing models. It is shown that magnetoelastic anisotropy energies K_{me} of the $Ni_{81}Fe_{19}/W_{90}Ti_{10}$ multilayers which have fcc (111) perfectly flat interfaces can be expressed with biaxial modulus, magnetostriction and lattice mismatch. In the incoherent state, the residual strain gives rise to a magnetic anisotropy which is proportional to the reciprocal of the magnetic layer thickness. The influence of roughness would decrease the anisotropy contribution.

Keywords: Multilayers; Magnetoelastic anisotropy; Roughness.

I. Introduction

The magnetic properties of metallic multilayered films are of great interest both from fundamental and technological viewpoints [1-4]. Especially, magnetic perpendicular anisotropy of multilayered films has been attracting much attention in relation to magnetic and magneto optical recording media [5, 9]. As has been reported in several systems, Co/Pd [5, 6], Co/Au [7] and Co/Pt [8], a large positive uniaxial magnetic anisotropy was observed when the magnetic layer thickness is smaller than a few monolayers. The origin of this anisotropy has been generally believed to be a change in the magnetic anisotropy of the interface atoms as a consequence of the reduced symmetry in their surrounding, first pointed out by Néel [9]. Nevertheless, some studies [10] indicate that perpendicular anisotropy cannot be explained only by the Néel's surface anisotropy. Moreover, strain and atomic mixing at magnetic-nonmagnetic interfaces have been also suggested as possible causes, especially for the samples obtained by sputtering [11]. The purpose of this paper is to calculate the strain-induced magnetic anisotropy energy by using a relatively simple model.

II. Experimental details

$Ni_{81}Fe_{19}/W_{90}Ti_{10}$ multilayers were grown by DC sputtering in ultrahigh vacuum under controlled conditions. The initial pressure in the chamber, before the deposition, was roughly at 2×10^{-7} Torr, while the sputter gas (ultra high purity argon - 5 nines) pressure was kept constant at 6 mTorr. The NiFe-layer thickness t_{NiFe} was varied from 10 to 100Å and t_{WTi} were kept fixed at 20 Å. Samples were deposited onto water-cooled Si(001) substrates at 300 K. All the samples were grown on 100Å thick WTi buffer layer. In all cases the first and the last layer was WTi. 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 showed the existence of fcc NiFe (111) peak [12]. Magnetization M_S was measured using a vibrating sample magnetometer (VSM) with a precision better than ±5% under magnetic fields up to 15kOe [12]. We calculated the effective magnetization $4\pi M_{eff}$ from the FMR spectra at 9.8 GHz using a Bruker EPR spectrometer.

III. Results and discussion

To study the anisotropy of $Ni_{81}Fe_{19}/W_{90}Ti_{10}$ multilayers, some series of these were prepared by DC sputtering in high-vacuum onto water-cooled Si(001) substrates. Previous work [13] has shown that the perpendicular anisotropy field (excluded the demagnetization term) can be written as:

$$H_K = 4\pi M_{eff} - 4\pi M_S \,, \qquad (1)$$

I.e

$$H_K = H_U + \frac{2H_S}{t_{NiFe}} \qquad (2)$$

The perpendicular anisotropy field $H_K = 2K_1/M_S$ includes two terms, a volume anisotropy $H_U = 2K_U/M_S$, and a surface-induced one $H_S = 2K_S/M_S$.

Thus Eq. (2) can be written as

$$K_{eff} = K_V + \frac{2K_S}{t_{NiFe}} \qquad (3)$$

K_{eff} and K_V are the effective perpendicular anisotropy energy and the effective volume anisotropy energy. Figure 1 shows the plot of the product H_K as a function of NiFe layer thickness (t_{NiFe}). From the intercept and the slop of linear fits to the data, we can get the interface and volume anisotropies for $Ni_{81}Fe_{19}/W_{90}Ti_{10}$ multilayers as listed in Table 1.

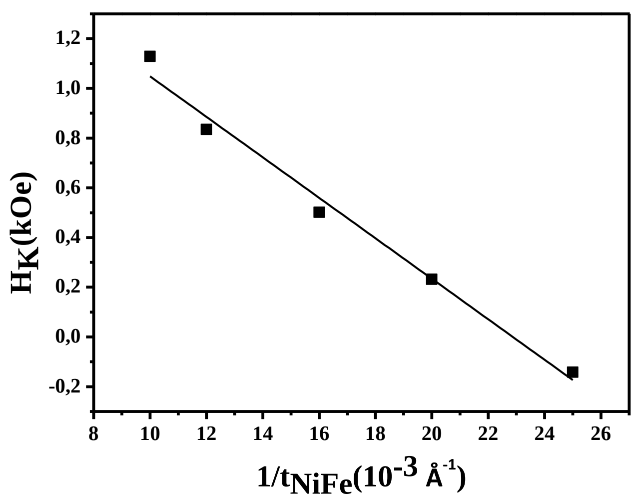

Figure 1: Variation of H_K versus $1/t_{NiFe}$ for $Ni_{81}Fe_{19}/W_{90}Ti_{10}$ multilayers at 300 K.

Volume anisotropy energy K_V is generally written as $K_V = K_d + K_{mc} + K_{me}$, where the first term K_d is the demagnetization energy which is the shape contribution, $K_d = -2\pi M^2$ where M is the saturation magnetization ($-2\pi M^2 = -3.80\times10^5$ J/m^3) and K_{mc} the magnetocrystalline energy of the $Ni_{81}Fe_{19}$ ($K_{mc} = 0$ J/m^3), and the last magnetoelastic energy (K_{me}) is the contribution due to stress (σ) and the related magnetostriction (λ).

Table 1: The interface, volume and strain-induced magnetic anisotropy energies of $Ni_{81}Fe_{19}/W_{90}Ti_{10}$ (111) textured multilayers.

Multilayers	K_S (J/m^2)	K_V (10^5 J/m^3)	K_{me} (10^4 J/m^3)
$Ni_{81}Fe_{19}/W_{90}Ti_{10}$	-0.016	-3.15	6.5

The magnetoelastic anisotropy can have various origins. For example, thermal stress arises from difference in thermal expansion coefficients between films and substrate, or between the different kinds of layers. Since the thermal expansion coefficient differs usually very little, thermal stress is of minor importance in most cases. Another source of magnetoelastic anisotropy in multilayers is coherency

strain due to the lattice mismatch between the adjacent layers. Tow regimes should be distinguished. If the lattice mismatch between the lattice parameters is not too large, minimizing the total energy leads to a situation whereby, below a critical thickness t_{NiFe}^{crit} the misfit can be accommodated by introducing a tensile strain in one layer and a compressive strain in the other such that ultimately the two materials NiFe and NM adopt the same in-plane lattice parameter. This regime is called the coherent regime; the lateral planes are in full lattice registry. The critical thickness t_{NiFe}^{crit} in symmetric multilayers is given by [14]:

$$t_{NiFe}^{crit} \approx \frac{2Gb}{\eta E_{NiFe}}, \quad (4)$$

where $\eta = (a_{NM}-a_{NiFe})/a_{NiFe}$ is the lattice mismatch, b is the Burgers vector (b≈2.5Å), G is the shear modulus (G = 1.86 10^{10} N/m^2) and E_{NiFe} is the biaxial elastic modulus $E_{NiFe} \approx 2\times10^{11}$ J/m^3 [15] and from Eq.(4) we deduce t_{NiFe}^{crit} (Table 2).

In the coherent case ($t_{NiFe} \leq t_{NiFe}^{crit}$), the strain anisotropy $K_{me} = -3/2\ \lambda\sigma$ for magnetic layers can be shown to be:

$$K_{me}^{coh} = -\frac{3}{2}\lambda_{111} E_{NiFe}\eta, \quad (5)$$

where λ_{111} is the magnetostriction coefficient of (111) plane ($\lambda_{111}=-3\times10^{-6}$). Table 2 summarizes the strain-induced anisotropy energies of $Ni_{81}Fe_{19}/W_{90}Ti_{10}$ multilayers.

Table 2: Lattice mismatch, critical thickness and coherent strain anisotropy.

Multilayers	η	t_{NiFe}^{crit} (Å)	K_{me}^{Coh} (10^5J/m)
$Ni_{81}Fe_{19}/W_{90}Ti_{10}$	0.107	4.34	9.65

In general, it is not an easy task to calculate the strain in the incoherent regime ($t_{NiFe} > t_{NiFe}^{crit}$). In the special case of single magnetic layer on rigid substrate it has been shown [11], by minimization of the sum of the elastic energy and the energy due to dislocations, that the residual strain ε, which is assumed to be uniform within the layer, can be written as:

$$\varepsilon = \eta \frac{t_{NiFe}^{crit}}{t_{NiFe}}, \quad (6)$$

The magnetoelastic anisotropy energy constant, which is essentially generated in the volume,
can be calculated using the formula (for the incoherent growth regime):

$$K_{me}^{incoh} = -\frac{3}{2}\lambda_{111} E_{NiFe}\eta \frac{t_{NiFe}^{crit}}{t_{NiFe}}, \quad (7)$$

Figure 2 shows the dependence of the strain-induced magnetic anisotropy energies on t_{NiFe} for $Ni_{81}Fe_{19}/W_{90}Ti_{10}$ (111) textured multilayers. Since the magnetostriction constant of NiFe is much smaller than the lattice mismatch, we can evaluate K_{me}^{incoh} with Eq.(7). Figure 2 illustrates the transition between the coherent and incoherent regime and the resulting effect observed in the magnetic anisotropy.

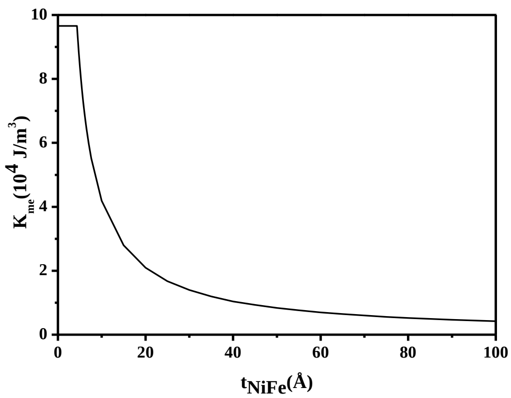

Figure 2: Strain-induced magnetic anisotropy energies K_{me} of $Ni_{81}Fe_{19}/W_{90}Ti_{10}$ (111) textured multilayers calculated by Eqs. (5)-(7).

In the incoherent regime, the residual strain gives rise to a magnetic anisotropy which is proportional to the reciprocal of the magnetic layer thickness.

The calculations show that magnetoelastic anisotropy energies of $Ni_{81}Fe_{19}/W_{90}Ti_{10}$ multilayers decreases with increasing of the magnetic layer thickness and it should be larger than K_{me} value found from H_K measurement. The raison for this disagreement may be sought in some origins as follows [16]: (1) the strains may be relaxed through the introduction of interfacial dislocation and (2) the surface roughness may reduce K_{me} because the strain of magnetic layers in $Ni_{81}Fe_{19}/W_{90}Ti_{10}$ multilayers may be tensile not only in the plan direction but also in the perpendicular direction.

IV. Conclusion

In conclusion, it is not an easy task to calculate the strain in the incoherent regime. The models used allow an estimate of the magnetoelastic anisotropy. The K_{me} in the incoherent region is proportional to the reciprocal of the magnetic layer thickness. We have shown the strain-induced magnetic anisotropy energies of the multilayers which have fcc (111) perfectly flat interfaces are larger than the K_{me} obtained from K_{eff} measurement. This result indicates that the interfacial roughness reduces considerably K_{me}.

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