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The exchange coupling of a NiO/FeNi bilayer with interdiffused interface

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Abstract

A series of NiO(110 Å)/FeNi(t_F Å)/Cu(24 Å)/FeNi(t_F Å) spin-valve-structure samples were fabricated using ion beam sputtering. The exchange bias H_E of the pinned FeNi layer increases as the FeNi thickness t_F decreases. For $t_F < 70$ Å, however, H_E decreases with the decrease of t_F. The coercivity H_{Cp} varies as $1/t_F$ at room temperature. The M–H loops show that the magnetic moment of the pinned FeNi layer is smaller than that of the free FeNi layer, indicating that an FeNi layer of about 20 Å is interdiffused with the NiO layer leading to a drop of the magnetic moment of the pinned FeNi layer. The interdiffusion between the FeNi and NiO layers may account for the decrease of the exchange bias H_E for $t_F < 70$ Å.

1. Introduction

Exchange coupling was first discovered as a new type of magnetic anisotropy in partially oxidized Co fine particles [1, 2]. The term 'exchange anisotropy' refers to the phenomenon of the magnetic behaviour associated with the interfacial interaction between a ferromagnet (FM) and an antiferromagnet (AFM), which induces a shift of the hysteresis loop away from its original location, as a so-called 'exchange bias'. The important application of exchange bias in information storage technology has stimulated considerable interest in both fundamental and applications research on this effect in recent years [3–6].

Unidirectional anisotropy and exchange bias can be qualitatively understood using an intuitive model [3]. According to this model, the exchange bias H_E is inversely proportional to the thickness of the FM layer (t_F), but the magnitude predicted by this model is several orders larger than the experimental results. To account for this discrepancy, different approximations of the energy equation have been used to model this phenomenon [3]. Such studies attempt to account for different important parameters that have not been considered in the basic formula. These include the effect on the AFM layer, grain size contributions, induced thermoremanent magnetization in the AFM layer, non-collinearity of AFM–FM spins at the interface, random

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anisotropy in the AFM layer, uncompensated surface spins, etc. The models have attained different degrees of agreement with existing experiment results. But these models all neglected the interdiffusion of the AFM and FM layers, which is inevitable in multilayers deposited using the sputtering technique. In this paper, we report studies of the ferromagnetic layer thickness dependence of the exchange bias and coercivity in NiO/FeNi bilayers.

2. Experimental details

A series of NiO(110 Å)/FeNi(t_F Å)/Cu(24 Å)/FeNi(t_F Å) ($Fe_{21}Ni_{79}$) spin-valve-structure samples were fabricated on glass substrates using ion beam sputtering. A magnetic field of about 50 Oe was applied parallel to the substrate surface to induce a uniaxial anisotropy and the exchange bias during the sample preparation. The NiO layer was first deposited using reactive sputtering. The argon pressure was 2.0×10^{-2} Pa; the oxygen partial pressure was the same as that of argon. The substrate temperature was 100 °C with a deposition rate of about 5.3 Å min^{-1}. After the deposition of the NiO layer, the oxygen was withdrawn and the bottom FeNi layer was deposited. After completion of the pinned FeNi layer, the samples were heated to 260 °C, above the Néel temperature ($T_N = 250$ °C [7]) of NiO, for 2 min, and then cooled in the magnetic field to room temperature. The Cu and top FeNi layer were deposited sequentially. The magnetization hysteresis loops were measured using a vibrating-sample magnetometer (VSM, LakeShore Cryotronics, Incorporated) at room temperature.

3. Results and discussion

Figure 1 shows the magnetization curves for the NiO(110 Å)/FeNi(t_F Å)/Cu(24 Å)/FeNi(t_F Å) samples. The exchange bias H_E, the coercivity H_{Cp} of the pinned FeNi layer, and H_{Cf} for the free FeNi layer can be obtained as shown in figure 1(a). We have drawn a horizontal line at the half-height in the M–H loop of the pinned FeNi layer; there are two intersections: H_{Cp1} and H_{Cp2}. H_{Cp1} and H_{Cp2} are defined as the right coercivity and left coercivity respectively. H_E is defined as $\frac{1}{2}(H_{Cp1} + H_{Cp2})$, while H_{Cp} is defined as $\frac{1}{2}|H_{Cp2} - H_{Cp1}|$. The same method was used to get the coercivity H_{Cf} of the free FeNi layer. Figure 2 shows H_E, H_{Cp}, and H_{Cf} as functions of the FeNi layer thickness t_F. It is clear that H_E first increases with decreasing t_F up to 70 Å, showing a $1/t_F^{1.1}$ behaviour. However, with further decreasing t_F, H_E decreases with decreasing t_F. Meanwhile, H_{Cp} increases with decreasing t_F, showing a $1/t_F$ power law. For the free FeNi layer, H_{Cf} increases with decreasing t_F to about 40 Å, and then drops abruptly with further decrease of t_F. H_{Cf} shows a $1/t_F^{1.4}$ behaviour for $t_F > 40$ Å.

Another interesting phenomenon is the thickness dependence of the right coercivity H_{Cp1} and left coercivity H_{Cp2}. As shown in figure 3, it can be clearly seen that for $t_F > 70$ Å, H_{Cp1} changes slightly with decreasing t_F, and the increase of the coercivity with decreasing t_F is mainly due to the increase of the left coercivity H_{Cp2}, which is consistent with other work [8]. While for $t_F < 70$ Å, the left coercivity H_{Cp2} remains almost unchanged, the right coercivity H_{Cp1} decreases quickly with decreasing t_F and changes sign for $t_F = 40$ Å. The increase of the coercivity for $t_F < 70$ Å mainly comes from the decrease of H_{Cp1}.

The pinned FeNi layer and the free FeNi layer should have equal saturated magnetic moments as they have the equal volumes. It can be clearly seen in figure 1, however, that the saturated magnetic moment of the pinned FeNi layer is smaller than that of the free FeNi layer as the thickness of both FeNi layers, t_F, is small. It is well known that the interdiffusion will not only weaken the exchange coupling between the AFM and FM layers, but also decrease the saturated magnetic moment of the FM layer. From figure 1(d) one can see that the hysteresis

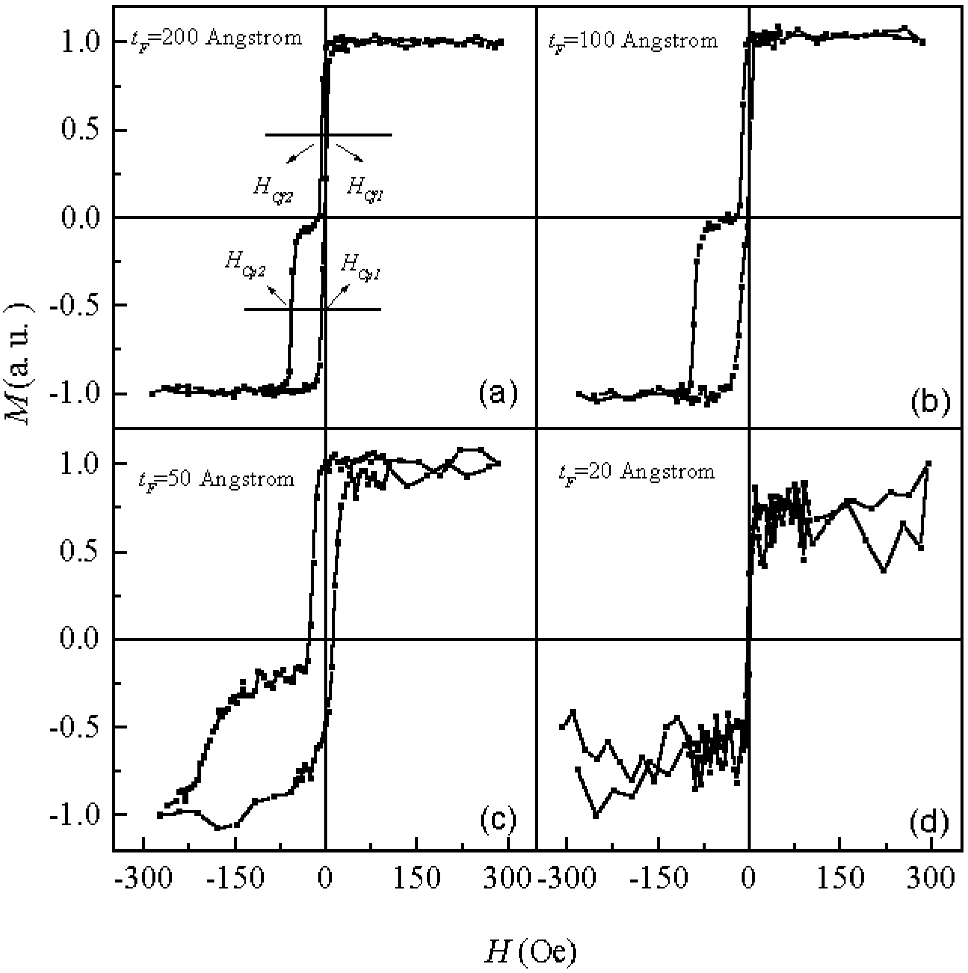

Figure 1. The dependence of the M–H loops for NiO(110 Å)/FeNi(t_F Å)/Cu(24 Å)/FeNi(t_F Å) spin-valve-structure samples on t_F. (a) t_F = 200 Å; (b) t_F = 100 Å; (c) t_F = 50 Å; (d) t_F = 20 Å.

loop of the pinned FeNi layer disappears when t_F decreases to 20 Å, indicating that there may be about a 20 Å FeNi layer interdiffused with the NiO layer in the above samples. Recently, Yu *et al* [9] have studied the NiO/FeNi interface using x-ray photoelectron spectroscopy (XPS). The results show that there are two reactions at the NiO/FeNi interface: $NiO + Fe = Ni + FeO$ and $3NiO + 2Fe = 3Ni + Fe_2O_3$; the thickness of the chemical reaction as estimated by angle-resolved XPS is about 1–1.5 nm, which is consistent with our results. On the other hand, the interdiffusion and the interface roughness will make a $t_F < 70$ Å FeNi layer imperfect, with many pinholes. With further decreasing t_F, the pinholes will expand and become larger, which makes the real contact area of the FeNi and NiO layers smaller, leading to a net uncompensated pinned moment decrease and thus affecting the strength of the exchange coupling.

To study how the interdiffusion influences the exchange coupling of FeNi and NiO, the model proposed by Mauri *et al* [10] is used. The interface exchange coupling energy is $2JS_1S_2/a^2$, where J is the interface exchange parameter, S_1 and S_2 are the spins at the interfaces of the FM and AFM layers respectively, and $1/a^2$ is the number of coupling FM and AFM

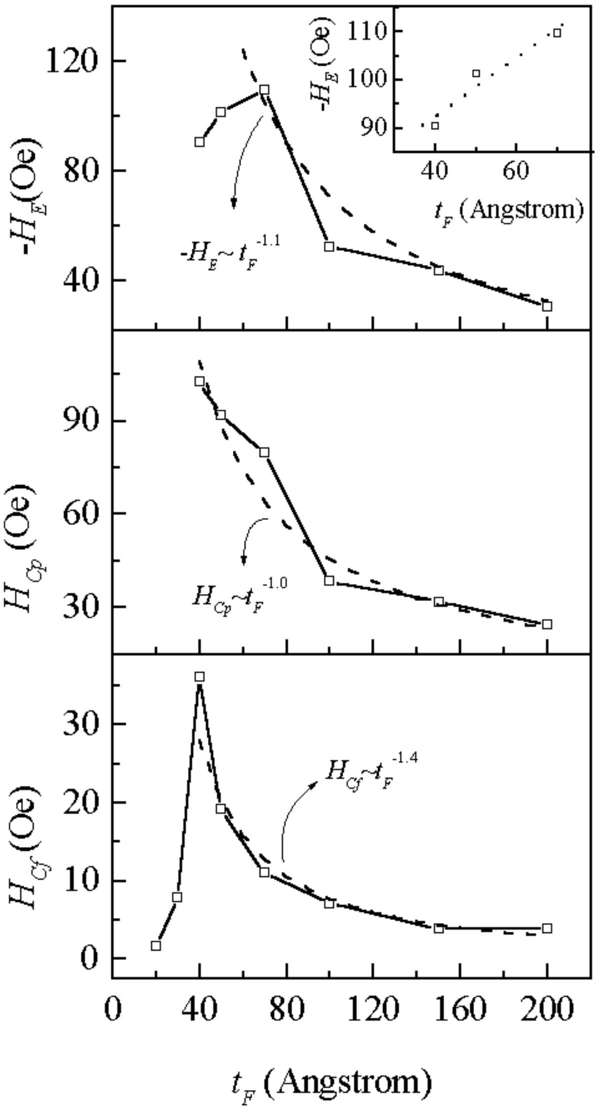

Figure 2. H_E, H_{Cp}, and H_{Cf} as functions of the FeNi layer thickness t_F. The solid lines are guides to the eyes. The dashed lines are the best fits of the data. We assume an x^n-relation in advance. The inset shows the linear fit of the variation of H_E with t_F for $t_F < 70$ Å.

spin pairs per unit area at the interface. For most cases, $2JS_1S_2/a^2$ is very large, and $H_E t_F M_s$ will reach a limit of $2\sqrt{AK}$, which is the energy required per unit area of domain wall in the AFM layer. The expression for the exchange bias is

$$H_E = \frac{-2\sqrt{AK}}{M_s t_F} \tag{1}$$

where A and K are the exchange stiffness and crystalline anisotropy of the AFM, and M_s is the saturated magnetization of the FM. However, for the NiO/FeNi bilayers studied in this paper, there exists apparent interdiffusion between FeNi and NiO at the interface, leading to the

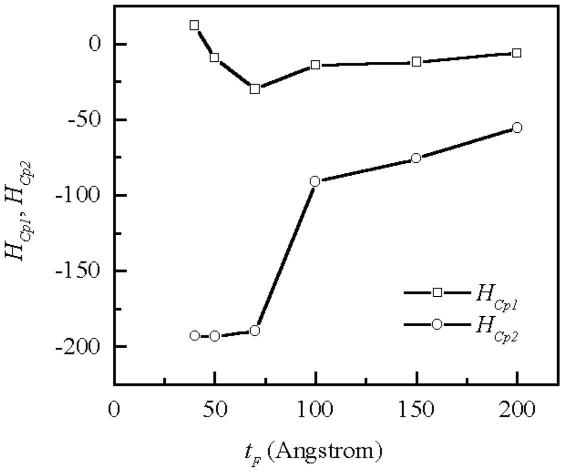

Figure 3. The thickness dependences of the right coercivity H_{Cp1} and left coercivity H_{Cp2}.

exchange constant J decreasing greatly. So $2JS_1S_2/a^2$ is comparable to or even smaller than the domain wall energy $2\sqrt{AK}$, and thus the expression for the exchange bias H_E changes to

$$H_E = \frac{-2JS_1S_2}{a^2M_st_F}. \tag{2}$$

For $t_F > 70$ Å, the FeNi layer is free of pinholes, and $1/a^2$ remains constant, so an approximate $1/t_F$ behaviour was observed, while for $t_F < 70$ Å, there are pinholes in the FeNi layer due to interdiffusion. With decreasing t_F, the pinholes will expand and become larger, so $1/a^2$ decreases with decreasing t_F. Assuming[2] that $1/a^2 = mt_F^2$, where m is a constant, equation (2) changes to

$$H_E = \frac{-2JS_1S_2t_F}{mM_s}. \tag{3}$$

A t_F-dependence of H_E is expected. H_E will decrease with decreasing t_F, which agrees with the experimental observation. The inset of figure 2 shows the linear fit of H_E against t_F for $t_F < 70$ Å. However, the line does not fit the experimental data well, which may be due to the assumption that $1/a^2 = mt_F^2$ being too simple. In fact, the real structure and morphology of the interface is more complex; this needs further study.

4. Summary

A series of NiO(110 Å)/FeNi(t_F Å)/Cu(24 Å)/FeNi(t_F Å) spin-valve-structure samples were fabricated using ion beam sputtering. The exchange bias H_E of the pinned FeNi layer increases with decreasing FeNi thickness t_F. For $t_F < 70$ Å, H_E decreases with decreasing t_F. The coercivity H_{Cp} scales as $1/t_F$. The M–H loops show that the saturated magnetic moment of the pinned FeNi layer is smaller than that of the free FeNi layer, indicating that about 20 Å of FeNi interdiffused with the NiO layer. The interdiffusion between FeNi and NiO may account for the decrease of H_E for $t_F < 70$ Å.

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[2] As area is two dimensional and always proportional to the square of height, it seems appropriate to assume that the real contact area of the FM and AFM is proportional to the thickness t_F due to the pinholes. As the total number of coupling FM and AFM spin pairs at the interface is proportional to the real contact area, one can derive $1/a^2 = mt_F^2$, where m is a constant.

Acknowledgments

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