Enhanced coercivity of exchange-biased Fe/MnPd bilayers

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We present detailed studies of the enhanced coercivity of exchange-bias bilayer Fe/MnPd, both experimentally and theoretically. We have demonstrated that the existence of large higher-order anisotropies due to exchange coupling between different Fe and MnPd layers can account for the large increase of coercivity in Fe/MnPd system. The linear dependence of coercivity on inverse Fe thickness are well explained by a phenomenological model by introducing higher-order anisotropy terms into the total free energy of the system.

Exchange coupling at the interface between a ferromagnetic (FM) layer and an antiferromagnetic (AF) layer can cause exchange-biasing, i.e., a shift of the hysteresis loop of the FM layer along the field axis characterized by an exchange-bias field H_{ex}, which is often described as an in-plane unidirectional anisotropy[1]. Although it has been extensively studied, the physics of FM/AF exchange coupling remain poorly understood[2-4]. It is now generally believed that both the exchange-bias field and coercivity are the results of the interfacial exchange coupling of AF and FM layer, which related to the actual spin distribution and arrangement among the FM layer and AF sublattice at the interface which, however, still remains unclear so far.

Although several models assuming the AF spins at AF/FM interfaces fixed or not can yield correct order-of-magnitude results of exchange-bias fields,[2-6] however, they can not account for the increased coercivities of the exchange-biased films which was also found to be dependent on the thickness of FM and AF layers[7-9].

It was found that the interfacial roughness might influence the interfacial interaction by causing local spin dispersion resulting local additional anisotropies. These anisotropies competing with demagnetization field serve as an energy barrier to domain wall motion leading to the increasing of coercivity[10]. However, it is also found that in epitaxially grown structures like Fe_3O_4 interfaces[5] and Fe/FeF_2 interfaces[6] where the interfacial roughness is quite smaller, large enhancement of coercivity can still be found due to the spin arrangement at interfaces. Apart from the spin arrangement at the interface, higher-order anisotropies which comes from the exchange interaction between AF and FM layers is also found to have strong influence on coercivity.[11, 12]

In this Letter we present detailed studies of the enhanced coercivity of exchange-bias bilayer Fe/MnPd. By setting up a phenomenological model, we have also for the first time indicated that the enhanced coercivity in exchange-bias system can be caused by higher-order anisotropies which come from the exchange interaction from Fe and MnPd layers.

The samples were grown in MBE system by coevaporation using e-gun for Fe, Pd and an effusion cell for Mn. Pressures during growth were ~10^{-9} mbar and growth rate were 0.1 Å/s for Fe, Pd and 0.2 Å/s for MnPd, respectively. Wedge shaped samples were grown at room temperature with the structure $Si/SiO_2/Fe$ (t_F)/MnPd (200Å)/Pd (20Å) with Fe thickness t_{Fe} varying from 20 Å to 160 Å. During growth a magnetic field of 50 Oe was applied along the surface of samples. A wedge shaped polycrystalline pure Fe layer was also produced with Fe thickness varying from 20 to 100 Å for comparison. *In situ* Auger was used to monitor the composition of Mn and Pd of MnPd layer. The crystallography of the films was studied by X-ray diffraction with Cu K_α radiation and magnetic properties were measured by Magneto-optic Kerr effect (MOKE) at room temperature.

Our previous studies of Fe/MnPd exchange-bias structure found that the antiferromagnetic fct phase of MnPd layer can be obtained at room temperature which leads to profound exchange-bias effect in Fe/MnPd sysem[13].

Fig. 1 presents the typical easy direction hysteresis loops of wedge shaped sample $Si/SiO_2/Fe$ (t_{Fe})/MnPd(200Å)/Pd(20Å) (t_{Fe}=20 Å~160 Å) at different Fe thickness of 30 Å, 50 Å, 70 Å, 90 Å and 110 Å, respectively. All the hysteresis loops were measured by longitudinal MOKE with the applied magnetic field parallel to the fields applied during growth. By scanning the laser beam over the wedge shaped sample, the thickness dependence of exchange-bias field (H_{ex}) and coercivities (H_c) can be studied with only one sample. Before scanning the sample the magnetic field was cycled several times to avoid possible ambiguities related to the training effect[14]. As one can see, the hysteresis loops shifted to left from H=0 Oe exhibiting exchange-bias coupling in the system. The thickness dependence of easy

direction exchange-bias fields H_{ex} and coercivities H_c for the sample are shown in Fig. 2 a. The exchange-bias field H_{ex} varied from about 50 Oe to 5 Oe with increasing Fe thickness from 20 Å to 160 Å. The dependence of H_{ex} on the inverse Fe thickness which is shown in the inset of Fig. 2 a indicates that the exchange coupling is an interface phenomenon.

It is also evident that the coercivity of the structure is largely increased compared with pure Fe layer (about 14 Oe found in our study) at all Fe thickness, which is the same as other observations[15]. In our study, the linear dependence of H_c on the inverse Fe layer thickness was also found as shown in the inset in Fig. 2 a.

Another interesting phenomenon in our sample is that the right coercivity H_{c1} of the hysteresis loops remains almost constant with varying Fe thickness, while the left coercivity H_{c2} increases with increasing Fe thickness, as one can see from Fig. 1. Here, the right coercivity H_{c1} and H_{c2} is defined as the field at which the magnetization is zero in increasing and decreasing branch of the hysteresis loop, respectively. Fig. 2 b also present the thickness dependence of H_{c1} and H_{c2}, which clearly shows that the increase of coercivity with decreasing Fe thickness of our sample is mainly due to the increase of left coercivity H_{c2}. No clear results about FM layer thickness dependence of the left and right coercivity can be obtained in references for NiFe/FeMn and other systems.

It is believed that the interfacial roughness may be a cause for the enhanced coercivity since interfacial roughness can provide more interfacial area and spin dispersion causing a higher coercivity[10]. This, however, is much more related with the microstructures of the films that may vary with different samples. From our study we believe that there are some more intrinsic properties due to exchange coupling that can produce higher coercivity in exchange-bias system. It has been recently shown by micromagnetics calculation that the spin-flop exchange coupling in CoO/Co system can induce uniaxial anisotropy in FM/AF system, which in turn causes the large coercivities in the exchange-biased system.[16] Induced uniaxial and four-fold anisotropies by the exchange coupling of FM and AF layers in NiFe/NiO [17] and NiFe/CoO [9] systems were also found and believed to account for the increased coercivity of the system. It was also found from our previous studies of Fe/MnPd system[13] that the unidirectional, uniaxial and four-fold anisotropies of Fe/MnPd structure are largely increased compared with pure Fe layer. All these enhanced in-plane anisotropies have an interfacial character, which come from the exchange coupling from Fe and MnPd layers. These anisotropies may have strong effect on the coercivity of the exchange-bias system.

To properly understand the enhanced coercivities in our samples, we propose a model based on the idea of Mauri[2] by introducing additional higher-order anisotropies.

Here we include higher-order anisotropy energy in the total free energy δ of the interface of FM/AF structure in units of $2\sqrt{AK}$ in Eq. 1 below, which is simply an extension of Eq. 2 of Ref. 2:

$$\delta = (1-\cos\alpha) + \lambda[1-\cos(\alpha-\beta)] + \mu\cos^2\beta + \kappa(1-\cos\beta) + \eta\cos^2\beta\sin^2\beta \qquad (1)$$

The first term is the energy of the domain wall; the second term is the exchange energy with $\lambda=A_{12}/\xi 2\sqrt{AK}$ where A_{12} the exchange stiffness at the interface and ξ the interface thickness, A and K are the exchange stiffness and crystalline anisotropy in the antiferromagnet; the third term is the uniaxial anisotropy with $\mu=K_F t_{FM}/2\sqrt{AK}$ where K_F the anisotropy constant; the fourth term is magnetostatic energy with $\kappa=HM_S t_{FM}/2\sqrt{AK}$ where H external field, M_S the saturation magnetization of FM layer, t_{FM} the thickness of FM layer; and the last term is a four-fold energy with $\eta=K_H/2\sqrt{AK}$ where K_H the effective anisotropy constant comes from the interaction between different layers of AF and FM. α and β are the directions of AF spin vectors at interface and FM layer magnetizations respect to the easy direction, respectively.

By finding the angle α and β for which δ is at minimum of Eq.1, one can obtain the magnetization curves of the films. The exchange-bias fields H_{ex} and coercivities H_c can thus be determined.

Fig. 3 a presents calculated magnetization curves in the easy direction for η=0, 0.3, 0.6, 0.9 with μ=-0.25, λ =0.5. One can find that due to higher-order anisotropies in the system, while the right coercivity changes slightly, the left coercivity of magnetization curves are substantially increased with increasing η, causing a increase of both

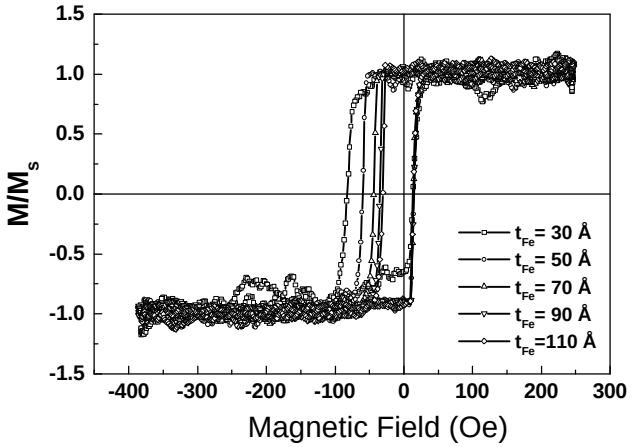

Fig. 1 Easy direction hysteresis loop for a polycrystalline sample for wedge shaped polycrystalline sample $Si/SiO_2/Fe(t_{Fe})/MnPd(200Å)/Pd(20Å)$ at different Fe thickness t_{Fe}=30 Å , 50 Å, 70 Å, 90 Å and 110 Å.

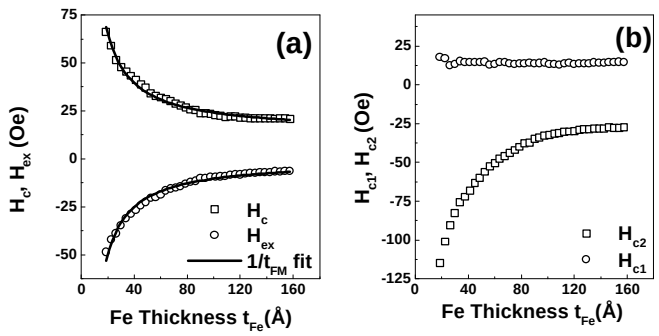

Fig. 2 Wedge shaped sample $Si/SiO_2/Fe(t_{Fe})/MnPd(200Å)/Pd(20Å)$, t_{Fe}=20 Å~160 Å, (a) Thickness and inverse thickness (inset) dependence of exchange-bias field H_{ex} and coercivity H_c; (b) Thickness dependence of left coercivity H_{c2} and right coercivity H_{c1}.

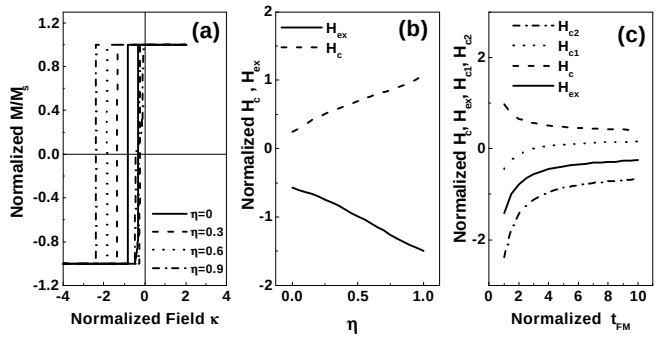

Fig.3 (a) Calculated hysteresis loops with different four-fold anisotropy contribution η=0, 0.3, 0.6, 0.9 with μ=-0.25 and λ =0.5. (b) Calculated exchange-bias field H_{ex} and coercivity H_c dependence on the four-fold anisotropy contribution η with μ=-0.25 and λ =0.5. (c) Calculated FM thickness dependence of exchange-bias field H_{ex} and coercivity H_c with η=0.9, μ=-0.25 and λ =0.5.

exchange-bias field and coercivity. The round edge in magnetization curve at η=0 which was found in Marui's calculation and also here is modified by square loop with increasing η to 0.6. When η=0.9, however, the round edges appear again but at M=0 in ascending branch of the hysteresis loop. The effect of higher-order anisotropies on exchange-bias field H_{ex} and coercivity H_c is summarized and shown in Fig. 3 b. Other than the nearly unchanged coercivity and exchange-bias field with increasing the exchange coupling strength λ form 0 to 10 calculated by Mauri, the coercivity H_c and exchange-bias field H_{ex} obtained at η=1 are three to four times larger than those at η=0, suggesting a very strong effect on the exchange-bias coupling structure due to higher-order anisotropies.

The thickness dependence of H_c and H_{ex} are also computed. The linear dependence of H_c and H_{ex} on inverse Fe thickness is obtained and presented in Fig. 3 c, which is the same as experimental results here and other observations[7-9]. In the calculation, η=0.9, μ=-0.25, and λ =0.5 are used. The calculated left and right coercivities are also presented in Fig.3 c. We found that although the calculated right coercivities slightly increase with increasing the FM layer thickness, exhibiting differently from those shown in Fig.2 b, the increase of the left coercivities are nearly three times larger than the increase of the right coercivity from t_{FM}=1 to 10, still confirming that the enhanced coercivities are mainly due to the left coercivities in our model. However, more realistic models are needed to get a more clear picture of the enhanced coercivities of FM/AF system.

From Eq. 1, if we suppose that the exchange coupling of the FM/AF bilayers are very strong, i.e. $A_{12}/\xi 2\sqrt{AK} >> 1$, then one can assume that α and β change coherently, i.e. α=β. For external field H applied in the easy direction of the film, the magnetization curve is square and one obtains:

$$H_{ex} = (H_{C1} + H_{C2})/2 = -2\sqrt{AK}/M_S t_{FM}, \qquad (2)$$
$$H_C = (H_{C1} - H_{C2})/2 = (2K_H - 2K_F t_{FM})/M_S t_{FM}$$

It is obvious that the exchange-bias field H_{ex} predicted by this model is still the same as the result of Mauri[2]. But the coercivity is different now. The linear dependence of H_c on reverse FM layer thickness as revealed by Eq. 2 can be clearly seen in the inset in Fig. 3. According to Eq. 2 the coercivity can be separated into two parts. One is the coercivity of the unbiased FM layer that equals to $-2K_F/M_S$, the other is $2K_H/M_S t_{FM}$ which can be attributed to exchange coupling effect. By fitting the experimental data, one obtains $H_C \cong 14$ Oe for unbiased Fe layer, which is almost the same as we have obtained for the pure Fe layer.

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