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Coercivity induced by random field at ferromagnetic and antiferromagnetic interfaces

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Abstract

In the presence of random fields at an interface between a ferromagnetic and an antiferromagnetic layer, the domain walls in the ferromagnetic layer are pinned by local minimum energy. To move the domain walls, an applied magnetic field must be large enough to overcome statistically fluctuating energy. We have calculated this energy and found that the coercivity can be as large as a few kOe for a thin ferromagnetic layer. It is also found that the coercive field at low temperature scales as $1/t^{3/2}$ where t is the F layer thickness, and the coercive field decreases strongly with temperature.

Keywords: Coercivity; Exchange bias

The nature of the magnetic interaction at the interface between a ferromagnet and an antiferromagnet is a long debated issue. Experimentally, there are two distinct features in the magnetic hysteresis loop. First, the hysteresis loop is offset from zero applied magnetic field if the bilayer film (ferromagnetic and antiferromagnetic layers) is field cooled from temperature above the Néel temperature of the antiferromagnetic layer; this has been termed the exchange bias [1]. The second effect is that the coercivity of the ferromagnetic layer is much larger than that without the underlying antiferromagnetic layer.

Up till now most of the theoretical studies have been focused on understanding the first phenomenon, the exchange bias. Mauri et al. [2] considered a perfect 'uncompensated' interface where the moments of the first layer of the antiferromagnet in contact with ferromagnetic layer are ferromagnetically aligned. Koon [3] investigated a 'compensated' interface where there are no net moments on the first layer of the antiferromagnet. Both theories predict domain formation in the antiferromagnetic layers and give the right order of magnitude of the exchange bias in comparing with experimental values. However, the above theories which are based on the 'ideal' nature of the interfaces have two significant drawbacks. First, the structure of AF layer and F layer of experimental interfaces are usually not matched and far away from simple perfect uncompensated or compensate interfaces. It seems from vast experiments that the exchange bias does not require perfection of the interface. The more serious problem is that the theories do not address the phenomenon of the enhanced coercivity observed experimentally.

The present study follows the idea that experimental interfaces are not perfect and interactions at the interface between F and AF layers are random as first proposed by Malozemoff [4,5]. The presence of the random interaction leads to an energy term which competes with other energies in the system. As a result, the antiferromagnetic layer breaks into domains with finite sizes. Within each domain, the ferromagnetic layer receives a statistically net field from the antiferromagnetic layer, i.e., an exchange bias is induced by the random interaction [4,5]. Here, we examine the role of this random interaction on

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the coercivity, and determine the correlation between exchange bias and the enhancement of the coercivity in the ferromagnetic–antiferromagnetic bilayer system.

Let us consider a domain wall in the ferromagnetic layer. The domain wall width and length are W and L with its center coordinates x_0 and y_0; the thickness of the ferromagnetic layer is t, which is assumed to be small so that the magnetization does not vary along the direction perpendicular to the film plane. The domain size L will be determined later. In a magnetic field H, the equilibrium position of the domain wall satisfies the following equation:

$$2M_s H\delta V = \gamma(y_0 + \delta y) - \gamma(y_0), \tag{1}$$

where the left-hand side represents the energy gain due to external field as the domain wall moves along the y-direction by δy and by $\delta V = Lt\delta y$ in volume, M_s is the saturation magnetization per unit volume, the right hand is the energy difference of the domain wall after and before the move, and $\gamma(y_0)$ is the total energy of the wall, i.e.,

$$\gamma(y_0) = \int \gamma(x, y)\, \mathrm{d}x\, \mathrm{d}y, \tag{2}$$

where the integration is limited to the wall region, $|x - x_0| < L/2$ and $|y - y_0| < W/2$. The energy density of the wall $\gamma(x, y)$ is assumed to be independent of z since the ferromagnetic layer is thin so that the magnetization is uniform along the z-direction. By taking the limit $\delta y \to 0$, Eqs. (1) and (2) result in

$$2M_s HLt = \frac{\mathrm{d}\gamma(y_0)}{\mathrm{d}y_0} = \int_{x_0 - L/2}^{x_0 + L/2} \mathrm{d}x[\gamma(x, y_0 + W/2) - \gamma(x, y_0 - W/2)]. \tag{3}$$

The wall energy density consists of number of energies in the film; they are exchange energy, uniaxial anisotropy, demagnetization energy and random field energy from the antiferromagnetic film. The exchange energy and uniaxial anisotropy are usually uniform within a film, thus they do not contribute to the motion of the wall, Eq. (3). The demagnetization field varies spatially and it gives rise to the coercivity. Here we are neglecting this, since this effect exists for films without the antiferromagnetic layer and we are interested in the *enhancement* of the coercivity in the presence of the antiferromagnetic layer. We are focusing solely on the effect of random fields on the coercive force below.

Introducing a random field $\boldsymbol{h}(x, y)$ acting on the interface of the bilayer, the energy density is written as

$$\gamma(x, y) = -M_s a_0 \hat{m}(x, y) \cdot \boldsymbol{h}(x, y), \tag{4}$$

where a_0 is the monolayer separation, and $\hat{m}(x, y)$ is the unit vector to represent the direction of the local magnetic moment. By placing Eq. (4) into Eq. (3), one has

$$H = -\frac{a_0}{t}\bar{h} - \frac{a_0}{2Lt}\int_{x_0 - L/2}^{x_0 + L/2} \mathrm{d}x[g(x, y_0 + W/2) + g(x, y_0 - W/2)], \tag{5}$$

where we have used $\hat{m}(x, y_0 + W/2) = \hat{e}_x$, $\hat{m}(x, y_0 - W/2) = -\hat{e}_x$ at the domain wall boundaries, and defined $g(x, y_0 \pm W/2) \equiv h_x(x, y_0 \pm W/2) - \bar{h}$ with $\bar{h}$ as the average of the random field. The first term in Eq. (5) represents the exchange bias which has been calculated by Malozemoff [4,5]. $\bar{h} \approx \sqrt{A_{AF}K_{AF}}/2M_s$ where A_{AF} and K_{AF} are the exchange stiffness and anisotropy constant of the AF layer. It is the second term in Eq. (5) which is related to the coercive field. As one changes the applied field, the wall moves back and forth according to the statistically fluctuating field $g(x)$ until a critical field such that the second term reaches maximum. Further increasing the field will lead to irreversible jumps of the wall. Therefore, one can define the coercivity by the maximum value of the second term in Eq. (5). As pointed out by Hoffmann [6,7], the estimation of this quantity can be carried out by evaluating the statistical average of the random field, i.e., one defines the coercivity as

$$H_c = \frac{a_0}{2Lt}\left[\left\langle\left(\int_{x_0 - L/2}^{x_0 + L/2} \mathrm{d}x(g(x, y_0 + W/2) + g(x, y_0 - W/2)\right)^2\right\rangle\right]^{1/2}. \tag{6}$$

Since the random field is not correlated when they are separated by a distance of the domain wall width, the cross term in Eq. (6) is averaged to zero, i.e., $\langle g(x, y_0 + W/2) \cdot g(x, y_0 - W/2)\rangle = \langle g(x, y_0 + W/2)\rangle \cdot \langle g(x, y_0 - W/2)\rangle = 0$. Then we simplify the above equation to

$$H_c = \frac{a_0}{\sqrt{2}Lt}\left[\int \mathrm{d}x_1 \int \mathrm{d}x\, g(x) g(x + x_1)\right]^{1/2}, \tag{7}$$

where we have dropped $y_0 \pm W/2$ variable in the function g. The random function $g(x)$ is usually described by an auto correlation function, i.e., $(1/L)\int \mathrm{d}x g(x) \cdot g(x + x_1) \equiv (J_s/M_s a_0^3)^2 f(x_1)$, where J_s is the average coupling energy of nearest-neighbour F and AF spins at the interface while $f(x_1)$ represents the range of the correlation of the random function. As usual, $f(x_1)$ can be assumed in the form of Gaussian or exponential, and we take the latter form as an example, i.e., $f(x_1) = \exp(-|x_1|/a_0)$ where we have used *white noise* approximation for the random field so that the range of the correlation function is the order of monolayer thickness a_0. With all these plausible simplifications, one can express the coercivity, Eq. (7), as

$$H_c = \frac{J_s}{M_s a_0^2 t}\sqrt{\frac{a_0}{L}}. \tag{8}$$

It remains to determine L, the domain size.

The domain size L can be derived from the minimization of the competing energies,

$$E = \frac{1}{2} z J_F \left(\frac{\pi a_0}{L}\right)^2 \cdot \frac{t}{a_0} - z' J_s \left(\frac{a_0}{L}\right), \quad (9)$$

where the first and second terms are the exchange energy and the energy from the random field per domain, z and z' are the coordination numbers in the ferromagnetic layer and at the interface, and J_F is exchange constant of the ferromagnetic film. In writing down the first term, we assumed $L \times L$ square domains with linear variation of magnetization from one domain to the next, which is slightly different from the circular domains assumed by Malozemoff [4,5], but the scaling relation that the exchange energy goes as $1/L^2$ is generally valid. The second term comes from statistical average energy of $N = L^2/a_0^2$ spins such that the root mean square of the random energy per site goes down as $J_s/\sqrt{N}$ which results in the second term in Eq. (9). Minimizing the above energy, one finds the domain size is

$$L = \frac{zJ_F}{z'J_s} \pi^2 t. \quad (10)$$

It is noticed that the same line of reasoning has been applied to estimate the size of AF domains, where a similar linear relation between the AF domain size and thickness of the AF layer was previously obtained [4,5].

By placing Eq. (10) into Eq. (8), we arrive at the scaling relation between the coercivity and the thickness of ferromagnetic layers,

$$H_c = \frac{J_s}{\pi M_s a_0^3} \sqrt{\frac{z'J_s}{zJ_F}} \cdot \left(\frac{a_0}{t}\right)^{3/2}. \quad (11)$$

To estimate the order of magnitude of the coercivity from Eq. (11), we need to determine J_s. J_s is expected to depend on the interface roughness; therefore, the coercivity will be different for different growth methods. Unfortunately, the independent measurement of J_s is currently unavailable. Nevertheless, one may assume that J_s and J_F are at the same order of magnitude. Within the mean field approximation, J_F is a fraction of the Curie temperature. If we take $J_F = J_s = T_c/8$ (where T_c is the Curie temperature), $z = 8$, $z' = 4$, and use the bulk magnetization of NiFe, we find that the coercivity is of the order of 1 kOe for the thickness of $t = 50$ Å, which agrees with experiments well. A most important prediction of Eq. (11) is that of the coercivity scales as $1/t^{3/2}$, which is quite in contrast with exchange bias field which scales as $1/t$.

To experimentally examine the magnitude and scaling relation, Eq. (11), we have studied two series of samples: (1) NiFe(t)/CoO/Si and (2) $Ni_{0.5}Co_{0.5}O$/NiFe(t)/MgO. In series (1), a wedged NiFe layer from 50 to 400 Å was grown on a uniform CoO layer of 250 Å, resulted in many individual samples in which the thickness of NiFe was the only variable. In series (2), individual samples with 120 Å of $Ni_{0.5}Co_{0.5}O$ and different NiFe thickness were grown and measured. In the thickness range of our interest, we did not observe any microstructure differences in each of the two sets of the samples. In both series, while the coercivity of the uncoupled NiFe is small (a few Oe at room temperature, and about 20 Oe at 10 K), the coercivity of the exchange-coupled layers increases dramatically for samples with small t to as much as 2 kOe. More importantly, H_c has been observed to vary as $H_c = A/t^n$, and the exponent is $n = 1.51 \pm 0.05$ at $T = 80$ K for the series (1) samples and 1.427 ± 0.05 for the series (2) samples, both in excellent agreement with the theoretical prediction of Eq. (11) with $n = 1.5$, see Fig. 1.

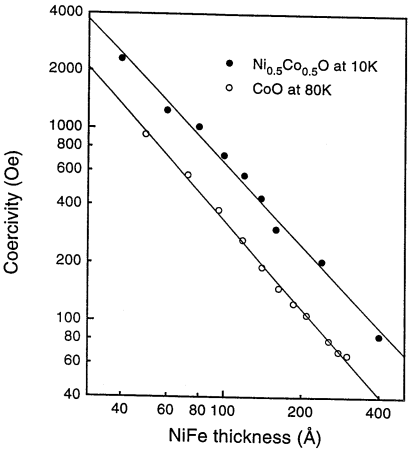

Fig. 1. The values of coercivity as function of NiFe thickness t of exchange-coupled NiFe(t)/CoO at 80 K and $Ni_{0.5}Co_{0.5}O$/NiFe(t) at 10 K showing the $H_c = A/t^n$ dependence with $n = 1.51 \pm 0.05$ and 1.427 ± 0.05, respectively.

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