Antiferromagnetic thickness dependence of exchange biasing

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A theory for a ferromagnetic/antiferromagnetic (FM/AF) exchange coupled bilayer of finite thickness is presented. Calculations based on this theory describe the reversible and irreversible transitions of the magnetic moments in this FM/AF system. A description of the exchange bias effect is offered that explains the observed phenomena of enhanced coercivity and rotational hysteresis. The theory also explains the AF thickness dependence of the exchange field and the coercivity.

Currently, there is a great deal of interest in the physics and materials involved in the so-called exchange bias effect, which was discovered in partially oxidized Co particles more than 40 years ago.[1] As a result of interfacial exchange coupling, the hysteresis loop of a ferromagnet (FM) in contact with an antiferromagnet (AF) is displaced in an applied magnetic field relative to that of an isolated FM film by an amount termed the exchange field H_e. Despite extensive experimental studies[2,3] and numerous theoretical efforts,[4–7] the mechanism of the FM/AF exchange coupling is not well understood. This effect is of great practical value since it is critical for the operation of recording heads based on giant magnetoresistance (GMR), as well as for magnetic random access memories (MRAM).

From hysteresis loop measurements, an increased coercivity H_c is always observed in an exchange biased FM relative to a single FM film. Most of the previous models dealing with the exchange bias effect do not address this coercivity enhancement. Qian *et al.*[8] associated this enhancement with an interfacial uniaxial anisotropy induced by higher order exchange coupling terms. However, there is no direct evidence to support the existence of such higher order terms. The existence of an interfacial spin flop state in the AF layer can result in an enhanced uniaxial anisotropy in the FM and give an enhanced coercivity according to Schulthess and Butler.[7] However, spin flop does not lead to exchange bias in FM/AF bilayers.

The AF thickness dependence of exchange bias on the thickness of the AF is shown in Fig. 1 for $Ni_{81}Fe_{19}/Pt_{10}Mn_{90}$. Notice that when the AF thickness decreases to a certain value, the exchange field H_e drops abruptly to zero. At the same time, the coercivity H_e increases and a large rotational hysteresis loss appears. These results have also been observed by others.[9] In principle, the coherent rotation model of Meiklejohn and Bean[1] can account for such a sharp change of exchange field with AF thickness. However, Parkin and Speriosu[10] found that a calculation of the torque based on this coherent rotational model does not give an abrupt decrease with AF thickness. The rotational hysteresis loss gives a clue that the presence of moment rotation in the AF (Refs. 5 and 6) may play a role. In this paper, a simple model for an exchange coupled FM/AF is presented. Based on this idea, the exchange field and the coercivity can both be derived from this model, and the AF thickness dependence of the exchange bias and rotational hysteresis loss can be obtained. While Neel[5] found that rotation of the magnetization in the AF could lead to irreversible behavior, he did not relate this to the exchange bias.

We shall assume that the FM layer is isotropic in the film plane. A theoretical study[11] has shown that there is no helical structure, for example, along the thickness direction in a thin ferromagnetic layer, e.g., $Ni_{80}Fe_{20}$ with thickness up to 500 Å, exchange coupled with a ferromagnetic, ferrimagnetic or antiferromagnetic film at the interface. Furthermore, Parkin *et al.*[12] have observed a uniform magnetization distribution throughout the thickness of a 400 Å $Ni_{80}Fe_{20}$ layer coupled with a $Fe_{50}Mn_{50}$ layer. Therefore, we assume the FM moments rotate uniformly in the presence of an applied field. For a FM/AF bilayer with a single-crystal AF layer and an uncompensated interface, the total energy per area unit of the bilayer includes the volume energy of the AF layer and the interfacial exchange coupling energy

$$E=\int_0^{t_{\mathrm{AF}}}\left[A_{\mathrm{AF}}\left(\frac{d\varphi}{dz}\right)^2+K_{\mathrm{AF}}\sin^2\varphi\right]dz-J_E\cos(\varphi-\alpha)|_{z=0}, \tag{1}$$

where A_{AF} and K_{AF} are exchange coupling constant and uniaxial anisotropy constant of the AF layer with finite thickness t_{AF}, respectively. The FM magnetization $\mathbf{M}_F$ is assumed to make an angle α with the AF easy axis. The direction of the AF moments varies spatially with z as described by $\varphi(z)$. The moments of the FM and AF layers are coupled

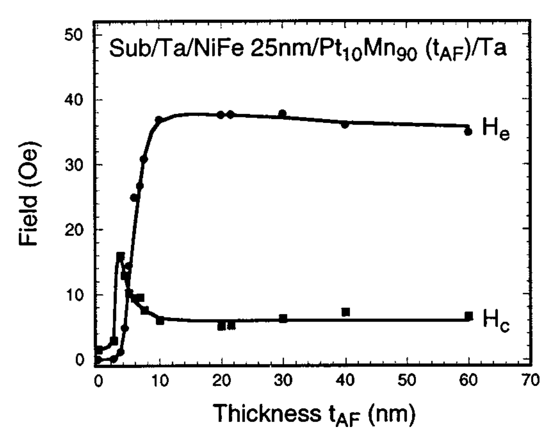

FIG. 1. AF layer thickness dependence of the exchange field H_e and coercivity H_c in the $Ni_{81}Fe_{19}(250\ \text{Å})/Pt_{10}Mn_{90}$ bilayer system.

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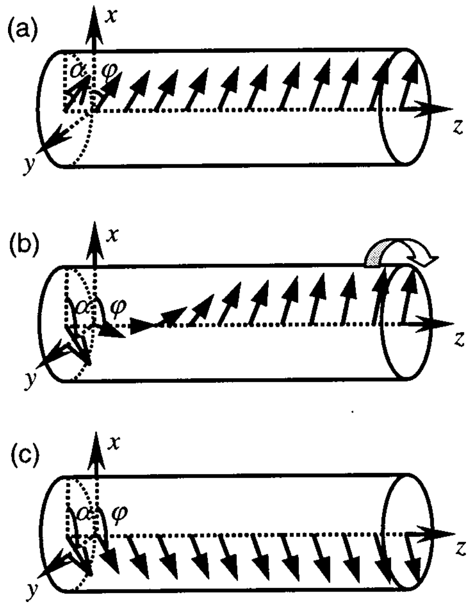

FIG. 2. Schematic representation of the helical structure of AF moments with one end exchange-coupled with the FM magnetization and the other end free to rotate. The FM magnetization rotates away from the AF easy axis x by an angle α. The moments of only one sublattice of the AF layer are shown. (a) a slightly wound-up helical structure, (b) the helical structure before transition, and (c) the helical structure after transition. The curved arrow shows the twisting direction.

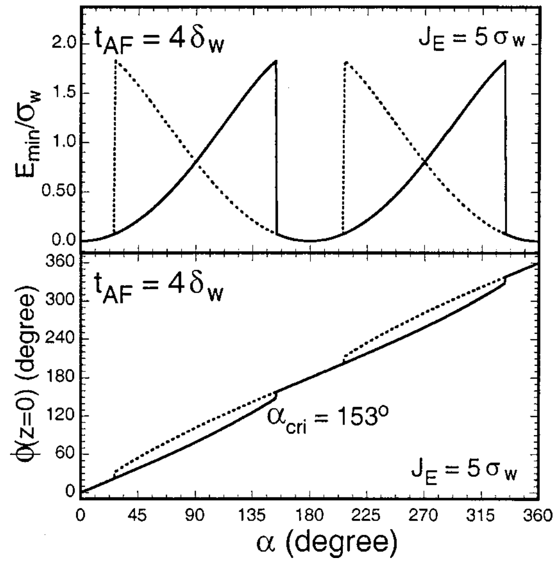

FIG. 3. Minimum energy $E_{\min}$ and the angle φ that the AF interfacial moments make with respect to the AF easy axis in the case of $J_E=5\sigma_w$ and $t_{\mathrm{AF}}=4\delta_w$. The solid lines are for the FM magnetization rotating from 0° to 360°. The dash lines are from 360° back to 0°.

at the interface by an exchange coupling constant J_E. Using the variational method to minimize the total energy, the AF moment structure is given by the differential equation for $\varphi(z)$:

$$2A_{\mathrm{AF}}\left(\frac{d^2\varphi}{dz^2}\right)-K_{\mathrm{AF}}\sin(2\varphi)=0, \tag{2}$$

with the boundary conditions

$$\left(\frac{d\varphi}{dz}\right)\bigg|_{z=0}=\frac{J_E}{2A_{\mathrm{AF}}}\sin(\varphi-\alpha)\quad\text{and}\quad\left(\frac{d\varphi}{dz}\right)\bigg|_{z=t_{\mathrm{AF}}}=0. \tag{3}$$

As the AF thickness t_{AF} approaches infinity, then the total energy reduces to that of Mauri *et al.*[5] In our case, the finite AF layer has moments at one end coupled with $\mathbf{M}_F$ and moments at the other end free to rotate. To perform the numerical calculations, we transform Eqs. (2) and (3) into a discrete form with step size of $10^{-3}\delta_w$, where $\delta_w=\sqrt{A_{\mathrm{AF}}/K_{\mathrm{AF}}}$. Our results are independent of step size in this regime. Figure 2 describes the moment configuration in the AF layer along the thickness direction with the FM defining an angle α at the interface. In the following, we will present our numerical results for the AF thickness normalized by the characteristic domain wall length δ_w and J_E normalized by the domain wall energy parameter $\sigma_w=2\sqrt{A_{\mathrm{AF}}K_{\mathrm{AF}}}$. It turns out that this system shows different behavior depending upon whether J_E is larger or smaller than σ_w.

Let us consider the response of the FM layer in the presence of a reverse applied field. Assume that $\mathbf{M}_F$, ferromagnetically coupled with the AF moments at the interface, lies along the AF easy axis. In coherent rotation $\mathbf{M}_F$ rotates away from the easy axis, and the AF moment structure twists as shown in Fig. 2(a). This helical structure develops further as the AF moments at the interface try to follow the rotating $\mathbf{M}_F$. Let us assume that J_E is larger than σ_w, in particular, $J_E=5\sigma_w$. When the AF moments at the interface reach or pass through the AF hard axis we find that the helical structure becomes unstable when the angle of $\mathbf{M}_F\alpha$ reaches a critical value α_{cri}. The AF structure ''springs'' forward, settling down in a new stable state which still contains some twist (see Figs. 2(b) and 2(c)). Finally, when $\mathbf{M}_F$ has completed its rotation to the opposite direction, the AF structure has also rotated by 180°. This irreversible motion of the AF moments was first obtained by Neel[5] in 1967 and recently applied by Stiles and McMichael.[13] Neel concluded that when the AF thickness is great than $2\delta_w$, the irreversible transition occurs at a critical angle in the range from 90° to 180°. Stiles and McMichael attribute the experimentally observed ''rotatable anisotropy'' in ferromagnetic resonance (FMR) measurements[14] to this irreversible motion of the AF spin structure. Our calculations show explicitly how the critical transition angle α_{cri} is dependent on J_E and t_{AF}. When J_E is greater than σ_w, such a transition always occurs and α_{cri} approaches 180° with increasing J_E and t_{AF}.

To clarify the behavior of $\mathbf{M}_F$, we have computed the total energy as a function of the angle α of $\mathbf{M}_F$ from Eq. (1) using the $\varphi(z)$ from Eqs. (2) and (3). Figure 3 shows the α-dependent $E_{\min}$ as well as the angle $\varphi(z=0)$ of the interfacial AF moments which are coupled to $\mathbf{M}_F$ in the case $J_E=5\sigma_w$ and $t_{\mathrm{AF}}=4\delta_w$. As $\mathbf{M}_F$ rotates from 0° to 180°, an irreversible transition occurs at $\alpha=153°$. At this point, the total energy drops abruptly as a result of the ''unwinding'' of the AF moment structure. The AF moments totally recover when $\alpha=180°$. For that part of the cycle where $\mathbf{M}_F$ rotates from 180° to 360°, a new AF helical structure develops just as it did from 0° to 180°. There is an energy loss associated with this magnetization process and the energy difference at

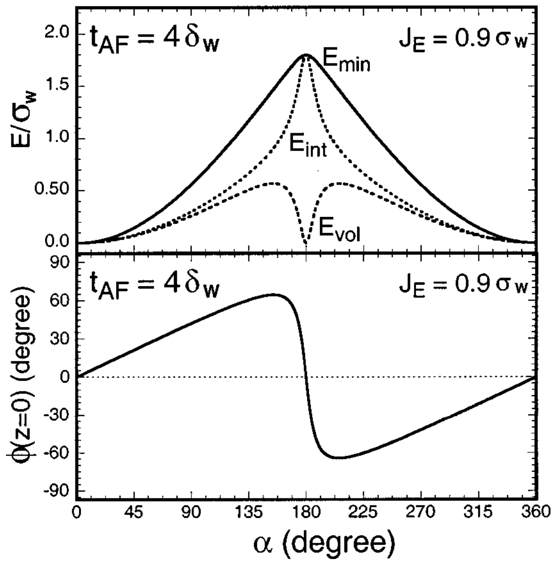

FIG. 4. Minimum energy E_{min} and the angle φ that the AF interfacial moments make with respect to the AF easy axis in the case $J_E = 0.9\sigma_w$. The minimum energy E_{min} is the sum of the volume energy of the AF layer E_{vol} and the interfacial exchange coupling energy E_{int}. The AF thickness is $4\delta_w$.

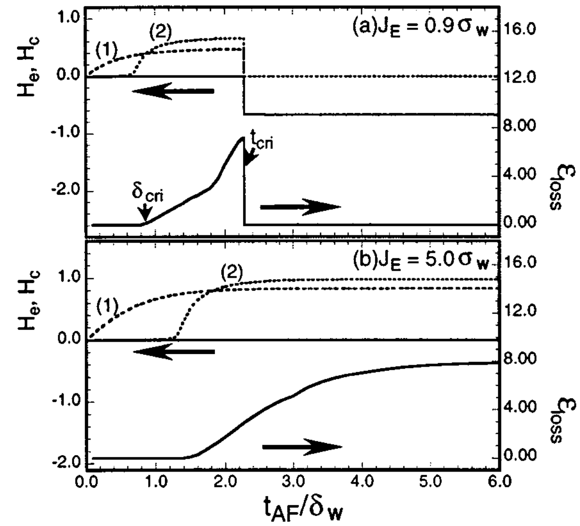

FIG. 5. AF thickness dependence of the exchange field, coercivity, and hysteresis energy loss in the cases of (a) $J_E = 0.9\sigma_w$ and (b) $J_E = 5\sigma_w$. Note that the exchange field and coercivity are normalized by $\sigma_w / M_F t_F$, and the rotational hysteresis energy loss per unit area $\varepsilon_{\mathrm{loss}}$ is normalized by σ_w. Thickness-dependent exchange fields and coercivities are shown by solid and dash lines, respectively. Curves (1) and (2) for coercivity are obtained from Eqs. (5) and (4), respectively.

the critical angle accounts for this loss. This result is similar to that given by Koon,[5] but by calculating the magnetizing process, we can see that there is no exchange bias in the system, and the coercivity is due to the irreversible process.

When J_E is less than σ_w, the results are different. Figure 4 shows the resulting numerical calculation for the case of $J_E = 0.9\sigma_w$. When t_{AF} is equal to $4\delta_w$, no irreversible transition occurs in the system and there is only a single stable state as the FM magnetization rotates. As $\mathbf{M}_F$ rotates from 0° to 180°, the AF moments at the FM/AF interface follow this rotation as a result of the interfacial exchange coupling. When $\mathbf{M}_F$ rotates beyond a certain angle which is greater than 90°, e.g., 168° in the case of $J_E = 0.9\sigma_w$, further winding of the structure generates a wall energy that can not be sustained by the interfacial coupling. As a result, the AF moments at interface rotate back and the AF moments return to their original positions when $\alpha = 180°$.

For a bilayer system with $J_E < \sigma_w$, there is a critical thickness t_{cri}, below which an irreversible transition of the AF moments occurs. This thickness characterizes the AF thickness dependence of the exchange field H_e, the coercivity H_c and the hysteresis energy loss per unit area $\varepsilon_{\mathrm{loss}}$. When the AF thickness is larger than this critical value, the motion of $\mathbf{M}_F$ is reversible and a nonzero value of H_e is found. H_e is obtained as the magnitude of an applied field H_a at which $\mathbf{M}_F$ becomes perpendicular to the easy axis, corresponding to $M = 0$ in a hysteresis loop measurement. Therefore, H_e is given as

$$H_e = H_a|_{M=0} = \left(\frac{1}{M_F t_F}\right)\left(\frac{dE_{\mathrm{min}}}{d\alpha}\right)\bigg|_{\alpha=\pi/2}, \tag{4}$$

where t_F is the FM layer thickness. The results for H_e are shown in Fig. 5. For our example case $J_E = 0.9\sigma_w$, in the reversible regime, i.e., $t_{\mathrm{AF}} < t_{\mathrm{cri}}$, H_e increases slightly with increasing AF thickness although this small effect is difficult to show in this figure. As the AF thickness gets very large, the value of H_e approaches $0.67\sigma_w / M_F t_F$, which is equal to our calculation result for a bilayer with infinite AF thickness.[15] H_e shown in Fig. 5 with a minus sign means that the hysteresis loop of the FM magnetization shifts toward negative fields.

When the system enters the irreversible regime, i.e., $t_{\mathrm{AF}} < t_{\mathrm{cri}}$, the irreversible transition occurring in the magnetization process results in an unshifted hysteresis loop which has a coercivity with a magnitude also given by Eq. (4) since the irreversible jump in the AF always occurs for $\alpha > 90°$. In this regime there is no exchange biasing, i.e., the exchange field H_e is equal to zero. In addition to the irreversible transition, there is another mechanism contributing to the coercivity. To force $\mathbf{M}_F$ away from the stable state of $\alpha = 0°$, requires a field H_r with a magnitude that is equal to or greater than the value of the second derivative of $E_{\mathrm{min}}/M_F t_F$ with respect to α. This coercivity is given by

$$H_c = \left(\frac{1}{M_F t_F}\right)\left(\frac{d^2 E_{\mathrm{min}}}{d\alpha^2}\right)\bigg|_{\alpha=0}. \tag{5}$$

The values derived from Eqs. (4) and Eq. (5) for the coercivity are shown in Fig. 5. The larger value will be the coercivity for the nonbiased hysteresis loop. The shape of the hysteresis loop also changes with the AF thickness. A critical thickness of $2.28\delta_w$ is found for $J_E = 0.9\sigma_w$. As we mentioned before, irreversible motion of the AF moments always occurs when the interfacial exchange coupling J_E is larger than σ_w. So, there is no critical thickness when $J_E = 5\sigma_w$.

Hysteresis energy loss is expected when the AF thickness t_{AF} is smaller than t_{cri} where the irreversible motion occurs. The difference of the minimum energy E_{min} at the transition accounts for the hysteresis loss. However, no energy loss occurs if t_{AF} is too small. For an AF layer with a thickness thin enough, the irreversible transition occurs at $\alpha_{cri}=90°$. This results in a single energy state for the FM magnetization and a zero hysteresis energy loss. The AF thickness δ_{cri} at which the rotational hysteresis loss disappears, is about $0.8\delta_w$ and $1.4\delta_w$ for $J_E=0.9\sigma_w$ and $5\sigma_w$, respectively. δ_{cri} increases with increasing interfacial exchange coupling J_E. For the case that J_E is larger than σ_w, the thicker the AF layer, the closer the critical angle for the irreversible transition is to 180°. A nearly 180° AF domain wall develops and the hysteresis energy loss per unit area approaches $8\sigma_w$ when t_{AF} goes to infinity. This is also shown in Fig. 5.

In reality, the interface is complicated by defects and roughness, and most of the AF films are polycrystalline. As a result, the interfacial exchange coupling J_E will be modified by the interface morphology, and will generally vary across the interface as we have found in NiFe/CrMnPt$_x$ ($x=3$, 6, and 9) bilayers prepared by substrate bias sputtering.[16] That is, in some regions J_E will exceed σ_w and in others it will be less than σ_w. Therefore, the observed dependence of H_e, H_c, and ε_{loss}, will be a composite of the two general behaviors shown in Fig. 5, which agrees with the observed behavior in Fig. 1. Note that the exchange bias never exceeds the wall energy σ_w.

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