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Threshold for reorientation of the magnetization in F/AF bilayers

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Abstract

We study reorientation of magnetization of a ferromagnetic film grown on a compensated antiferromagnetic substrate and propose a method to determine a lower bound of the interface exchange coupling strength. For uniaxial ferromagnetic films, we show that the frustration induced by the interface exchange leads to a reorientation of the magnetization only if the strength of the interface field is beyond a threshold value. For ferromagnetic films with fourfold crystalline anisotropy the reorientation of the magnetization occurs for any value of the interface exchange field strength. We use a self-consistent two spin mean field model and apply the theoretical model to Fe/FeF₂ and Fe/MnF₂ bilayers. For these systems the reorientation of the magnetization produces minor changes in the antiferromagnetic arrangement of the spins near the interface, allowing a simple analytical formula which relates the threshold value of the interface exchange coupling to the magnetic parameters of the antiferromagnetic substrate and to the anisotropy and thickness of the ferromagnetic film.

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1. Introduction

A considerable amount of research effort has been dedicated to the study of interface effects in

magnetic bilayers consisting of a ferromagnetic (F) thin film grown on an antiferromagnetic (AF) substrate [1–5].

A key parameter of F/AF bilayers is the interface exchange coupling, which may contribute to either enhancing the coercivity or shifting the hysteresis curve. Although the interface bias phenomenon was observed over 40 years ago [6],

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models relating the observed bias to the actual interface exchange coupling are still the subject of current discussions [2,7,3,8]. Theoretically, the effective interface field is several orders of magnitude larger than the field bias, of the order of the anisotropy field H_A , observed from hysteresis curve measurements [3].

In addition to the exchange bias field, other physical phenomena are affected by interface effects and can be used to study the magnetic coupling. The modification of the spin flop field [3] of the AF substrate is produced by the exchange coupling with the F film. On the other hand, changes in the frequency of spins waves [9] have been proposed as an alternative way of studying the interface exchange coupling.

In this paper we explore another interface phenomenon, the reorientation of the magnetization of the F film, and propose an alternative method to study the magnetic coupling. This reorientation of the magnetization occurs in compensated F/AF bilayers. In this case the interface AF plane contains equal numbers of magnetic moments from both sublattices.

In compensated F/AF bilayers the reorientation of the magnetization of the F film is a magnetic phase transition that may occur below the Néel temperature of the substrate [10]. For flat interfaces it is a genuine interface phenomenon and is an intrinsic property of the bilayer. It has been called perpendicular coupling and has been observed in compensated Fe/FeF₂ bilayers [5]. Similar effects were also observed in permalloy films grown on FeMn substrates [11], and attributed to partial compensation due to interface roughness, and in Fe₃O₄/CoO superlattices [12].

The reorientation results from the frustration of the interface exchange coupling if both materials have uniaxial magnetic anisotropy and the easy directions are parallel. In this case below the Néel temperature of the AF substrate the interface spins of the F film are subjected to exchange field of opposite directions produced by the spins in the unit cell of the AF plane. Conversely, the interface AF spins are under the action of the interface exchange field produced by the spins of the F film. Within the AF magnetic unit cell the interface exchange field is parallel to the interface AF spins

of one sublattice and opposite to those of the other sublattice.

For weak interface exchange coupling the bilayer stays in the aligned phase with no change in the intrinsic magnetic order of each material (Fig. 1a). In this phase the magnetic moments of each material are parallel to the easy axis. However if the interface exchange coupling is strong then a reorientation of the magnetization of the ferromagnet occurs leading to a structure in which the magnetization of the F film is perpendicular to its easy axis direction and the interface AF spins are slightly canted with respect to the AF easy axis (Fig. 1b). This reorientation of the magnetization was proposed by Hinchey and Mills [4] in a study of the magnetic phases of superlattices consisting of compensated AF thin films and F thin films.

As proposed earlier the magnetic energy of the F/AF bilayer may be minimized when the magnetization of the F film aligns perpendicular to the easy axis of the AF substrate. This arrangement resolves the frustration of the interface exchange coupling and leads to a non-zero coupling between the liquid magnetic moment of the AF interface plane and the magnetic moments of the F film at the interface.

However an energy balance is involved in the formation of the reoriented state and the strength of the interface exchange energy is a decisive

Fig. 1. Schematic configuration of the magnetic moments in the interface planes. The upper panels represent the interface plane F spins and the lower panels represent the corresponding AF spins. (a) For $J_{INT} < J_{INT}^*$ the spins of both materials are along the uniaxial axis. (b) For $J_{INT} \geq J_{INT}^*$ the F film is in the reoriented state and the AF spins are deviate slightly from the AF easy axis.

factor. Compared to the aligned state, in the reoriented state there is an increase of the F film uniaxial anisotropy energy which is proportional to the F film thickness. Also, the interface AF spins are subjected to an interface field which is perpendicular to the easy axis of the antiferromagnet. Spins from both sublattices turn in the same direction leading to an increase of both the anisotropy energy and the intrinsic exchange energy of the antiferromagnet. Thus, the intrinsic magnetic energy of both materials increase. The reoriented state forms if the interface exchange coupling energy is large enough to compensate the increase in the magnetic energy of the F film and of the AF substrate.

Previous work explored the critical temperature of the transition for the reoriented state [10]. Differently we analyze the effect of the strength of the AF substrate magnetic anisotropy and of the symmetry of the magnetic anisotropy and thickness of the F film. We present the theoretical model and calculate the threshold value for the strength of the interface exchange energy J_{INT}^* using a numerical algorithm based on a self-consistent local field theory.

2. Threshold for reorientation

The effect of the interface exchange energy is twofold. On one hand, the effective field acting on the F interface spins is proportional to the interface exchange energy J_{INT} . On the other hand, the transverse component of the magnetic moment per unit cell of the interface AF plane is proportional to $J_{\text{INT}}/|J_{\text{AF}}|$, where J_{AF} is the intrinsic exchange energy of the AF substrate. This transverse component is a result of the deviation of the uniaxial axis of the structure of the AF substrate. Thus, the interface exchange energy is proportional to $-J_{\text{INT}}^2/|J_{\text{AF}}|$. The energy barrier to be overcome is due to the changes in the AF order of the substrate and to the increase in the anisotropy energy of the F film. Therefore it is larger than the anisotropy energy of the F film $t_{\text{F}}K_{\text{F}}$, where K_{F} is the anisotropy energy per atom in the F film and t_{F} is the number of planes in the F film. Thus the magnitude of the interface

exchange coupling required to stabilize the reoriented state is larger than $\sqrt{t_{\text{F}}K_{\text{F}}|J_{\text{AF}}|}$.

Since the AF exchange field H_{E} and the coercive of the F film H_{c} are proportional to J_{AF} and K_{F} , respectively, one is lead to the conclusion that if reorientation is observed in a F/AF compensated bilayer then the effective interface field acting on the F film must be larger than $\sqrt{t_{\text{F}}H_{\text{c}}H_{\text{E}}}$.

In order to calculate the threshold value of the interface coupling energy it is necessary to examine the magnetic phase of the bilayer at low temperature, with the AF spins saturated. At high temperatures the thermal value of the AF spins is reduced. Thus a larger value of the interface exchange energy is required to produce the reorientation. The values of the energies of anisotropy of both materials and intrinsic exchange energy of the substrate are relevant parameters. These parameters control the degree of canting of the AF interface spins as well as the magnitude of the energy barrier. This is a point of special interest because the features closely related to the anisotropy field can be checked experimentally.

We study compensated bilayers with the Fe/FeF₂(1 1 0) and Fe/MnF₂(1 1 0) stacking patterns. The normal to the surface is in the y -axis direction, the easy axis of both materials are along the z -axis direction and the spins are confined in the planes parallel to the surface of the bilayer. In the AF substrate the magnetic moments from a given sublattice in the same plane are considered equivalent. We do not consider any temperature effects. Thus the magnetic moments have the saturation value $g\mu_{\text{B}}S$ and the magnetic structure is represented by the angles that each magnetic moment makes with the z -axis, $\{\theta_n(1), \theta_n(2), n = 1, \dots, N_{\text{AF}}\}$. $\theta_n(1), \theta_n(2)$ are the angles with respect to the easy axis, for magnetic moments of sublattices 1 and 2 at the n th-plane (as shown in Fig. 1b to the interface layer of the AF substrate) and N_{AF} is the number of (1 1 0) planes in the AF substrate. The F film, with N_{F} planes, is represented in a similar manner. Thus the magnetic structure is described in terms of two interacting linear chains with $2(N_{\text{AF}} + N_{\text{F}})$ magnetic moments.

We use a self-consistent effective field method developed earlier and applied to the study of

magnetic multilayers and AF films. Here we briefly outline the main points. The equilibrium pattern is found by requiring each magnetic moment to be parallel to the local effective field. We use an iterative procedure seeking to find a structure (spin profile) in which each one of the two spins per atomic plane is in equilibrium with the local field produced by the other spins. The method is an extension of the theory applied earlier to transition metal multilayers and AF superlattices [3,13,15].

The magnetic energy per unit cell of the interface is given by

$$E = \sum_{nm} -J_{nm} \vec{S}_n \cdot \vec{S}_m - \sum_n \frac{K_n}{2} S_{nz}^2. \quad (1)$$

The first term represents the intrinsic exchange interaction between nearest-neighbor spins. K_n is the uniaxial anisotropy constant for the two magnetic moments in the magnetic unit cell of the n th-plane. In the F and AF subsystems the exchange couplings are, respectively, J_F and J_{AF} , the uniaxial anisotropy constants are, respectively, K_F and K_{AF} and the spin quantum numbers are, respectively, S_F and S_{AF} . We have chosen the values of these quantities so as to represent either Fe/FeF₂(110) or Fe/MnF₂(110) bilayers. The exchange coupling across the interface is J_{INT} . We use the same local coordination of the magnetic moments of the substrate throughout the bilayer. The magnetic moment belonging in one of the linear chains in plane n has four nearest neighbors in the other chain at the same plane and two nearest neighbors in each of the planes $n \pm 1$.

For comparison purposes we also consider bilayers in which the F film has fourfold anisotropy. In this case we substituted the uniaxial anisotropy energy in Eq. (1) by $(K_c/S^4)S_{nz}^2 S_{nx}^2$ for the magnetic moments in the F film.

We have chosen $J_F = 10J_{AF}$. Judging from the ratio between the Curier temperature of bulk Fe and the Néel temperature of either bulk FeF₂ or MnF₂, a factor of around 10 should be used. The ordering temperature of both materials are affected by finite size effects and the interface coupling [15]. However these changes are out of the scope of this paper. For our present purpose it suffices that the choice of $J_F/J_{AF} = 10$ represents

the fact that in the reorientation of thin F films there is no appreciable change in the F alignment in the film.

The parameters used in the calculation are as follows. For FeF₂ the spin $S_{AF} = 2$, the exchange field $H_E = 434$ kG and the anisotropy field is given by $H_A = 149$ kG, while for MnF₂ the spin $S_{AF} = 2.5$, the exchange field $H_E = 465$ kG and the anisotropy field is given by $H_A = 7$ kG. These values are mean field parameters and do not exactly match up with those measured through AF resonance. They give, in the mean field approach, the correct Néel temperatures and reproduce correctly the ratio between the anisotropy and exchange fields [15]. The exchange and anisotropy parameters are given by the expressions $J_{AF} = g\mu_B H_E / 8S_{AF}$ and $K_{AF} = g\mu_B H_A / S_{AF}$. For the Fe film we use $S_F = 2$ and the uniaxial and fourfold anisotropies fields are 0.1 and 0.5 kG, respectively [14,5].

In order to prove that there is a threshold value of the interface exchange coupling (J_{INT}^*), beyond which the reorientation of the magnetization of the F film occurs, we follow Koon [2] and calculate the magnetic energy as a function of the angle (θ) of the magnetic moments of the free surface of the F film with the uniaxial axis of the AF substrate. The magnetic equilibrium pattern of the bilayer is calculated for each value of the angle θ and then the magnetic energy is calculated. The reorientation occurs when the magnetic energy displays a minimum for $\theta = 90^\circ$.

We choose to represent the energy values in the curves without dimensions and multiplied by a factor (10^5) to facilitate the understanding. To construct the level curves shown in Fig. 2, we vary the angle θ of the free surface of the F film and the strength of the interface coupling, J_{INT} , for a Fe/FeF₂ (110) bilayer with $N_F = 10$ and $N_{AF} = 11$. The magnetic energy is written in units of the intrinsic exchange energy per atom of the AF substrate, $E_{AF} = 8J_{AF}S_{AF}^2$, and it is measured from the energy of the aligned state. The number by the curves indicate the values of $\varepsilon = (E - E_0) / E_{AF} \times 10^5$. Where E_0 is the magnetic energy of the aligned state of the bilayer. The constant energy curves, shown in Fig. 2, represent the locus of points for which ε is constant. Curves for positive

Fig. 2. Level curve of the magnetic energy (ε) of a Fe/FeF₂(110) bilayer as a function of the orientation of the F films magnetic moments and the strength of the interface exchange energy, J_{INT} . The curves are for (a) bilayers with uniaxial anisotropy F films and (b) bilayers in which the F film has fourfold crystalline anisotropy energy.

and negative values of ε were chosen to pinpoint the existence of a threshold value of J_{INT} .

Notice from Fig. 2a that in order to have a negative value of ε in $\theta = 90^\circ$ for uniaxial bilayers it is necessary to have $J_{\text{INT}}/J_{\text{AF}} > 0.4$. In other words, the energy of the reoriented state [$E(\theta = 90^\circ)$] only is lower than that of the aligned state when the interface coupling is greater than a threshold value, J_{INT}^* .

In contrast in Fig. 2b it is seen that for $\theta = 90^\circ$ and any non-zero value of J_{INT} the magnetic energy, ε , is negative. For bilayers with F films with fourfold crystalline anisotropy the configuration with $\theta = 90^\circ$ corresponds to a minimum of energy. In this case, in the absence of interface coupling, the $\theta = 90^\circ$ state of the F film is degenerate with any of the other three uniform states (0° , 180° and 270°) where the magnetization is along one of the easy directions set by the fourfold anisotropy. Thus any finite value of the interface exchange energy, J_{INT} , will favor the F spins arranged perpendicular to the easy axis of the AF substrate.

We have found that the threshold value of the interface exchange depends on the thickness of the

F film as well as on the ratio of the anisotropy to exchange field of the AF substrate. In order to examine these features we have calculated the equilibrium pattern initializing all spins in the aligned state, as appropriate for low values of the interface exchange coupling, and by increasing the value of J_{INT} we have found the value which produces the reorientation.

The curves in Fig. 3 show the magnetic energy of the bilayer (ε) with the same choices of origin and units as used in Fig. 2. To produce these curves we use the self-consistent effective field method commented previously. By this iterative method, the angles (θ) that each magnetic moment makes with the z -axis have been calculated, including those of the free surface of the F film. We observe that the magnetic moments of the F film remains parallel to the easy axis (z direction) for weak J_{INT} . When $J_{\text{INT}} > J_{\text{INT}}^*$ there is a phase transition to the reoriented state. In Fig. 3 the value of J_{INT}^* is that which makes the energy of the reoriented state lower than that of the aligned state, i.e., $\varepsilon < 0$.

Fig. 3. Magnetic energies of Fe/FeF₂ (110) and Fe/MnF₂(110) bilayers with $N_{\text{AF}} = 11$ and $N_{\text{F}} = 10$. The uniaxial anisotropy constant of the Fe film is given by $K/8J_{\text{AF}} = 0.001$ and interface exchange is written in units of the FeF₂ exchange parameter.

The gradual decrease of energy for values of J_{INT} larger than J_{INT}^* results from the increase in the absolute value of the interface coupling which is due both to the increase in J_{INT} and to the larger deviation of the uniaxial axis of the structure of the AF substrate. This deviation is restricted to the spins in a few planes near the interface. Furthermore, we observe from our numerical results that J_{INT}^* is a increasing function of the thickness of the F film.

In Fig. 3 we examine the effect of the strength of the anisotropy field of the AF substrate on J_{INT}^* . We have found that bilayers with low anisotropy have a lower value of the threshold of the interface exchange energy. In the figure we show the results for Fe/MnF₂(1 1 0) and Fe/FeF₂(1 1 0) bilayers. It is clear that for MnF₂ substrates the threshold value of the interface exchange energy is smaller than that for FeF₂ substrates. These materials have similar values of the intrinsic exchange coupling but the anisotropy energy of MnF₂ is much smaller than that of FeF₂. Therefore for a given value of the interface field, produced by the F film on the interface AF spins, the deviations of the uniaxial axis induced in the MnF₂(1 1 0) substrate is larger than that in the interface AF spins for a FeF₂(1 1 0) substrate, since for the MnF₂(1 1 0) substrate the cost of AF anisotropy energy is smaller. Thus the MnF₂(1 1 0) substrate couples more efficiently with the F film and requires a smaller value of J_{INT} to stabilize the reoriented state.

Our results confirm that J_{INT}^* is a function of the magnetic parameters of the F and AF subsystems as well as of the thickness of the F film. In the next section, we obtain a simple formula for J_{INT}^* that confirms the predictions of the above numerical results, and may be used to estimate a lower bound of the value of the interface exchange interaction for compensated F/AF bilayers.

3. Analytic estimate of the threshold interface field strength

The effect of a magnetic field perpendicular to the easy axis of a two-sublattice antiferromagnet is to produce a canting of spins from both sublattices in the direction of the external field. In the bulk the deviation θ from the anisotropy axis is given by

$\sin \theta = H/(2H_E + H_A)$, where H_E , H_A and H are the intrinsic exchange and anisotropy fields of the antiferromagnet and the external field, respectively. For FeF₂ the ratio between the anisotropy and exchange fields is $H_A/H_E = 0.34$. Then for $H = H_E$ one has $\theta \cong 25^\circ$. Due to the smaller anisotropy energy the canting of spins for MnF₂ tends to be larger. For this material the ratio between the anisotropy and exchange fields is $H_A/H_E = 0.015$. Then for $H = H_E$ one has $\theta \cong 29.7^\circ$. In the canted state produced by the reorientation of the F film only the AF interface moments are subjected to the transverse interface field. As a result the deviations from the substrate AF order in the reoriented state of a compensated bilayer are much smaller and restricted to the spins in the near interface region [7].

In the reoriented state the spins of the Fe film are along the x -axis direction $\{\theta_n(1) = \theta_n(2) = \pi/2\}$ for $n = 1, \dots, N_F$ and the magnetic structure of the AF substrate is represented by the angles that each magnetic moment makes with the z -axis, $\{\theta_n(1), \theta_n(2), n = 1, \dots, N_{\text{AF}}\}$. $\theta_n(1), \theta_n(2)$ are the angles for the spins of the two sublattices in the n th plane from the interface. Due to the symmetry imposed by the transverse field acting on the AF interface moments we have found that the angles that determine the magnetic order of the AF spins are given by $\theta_n(1) = \theta_n$ and $\theta_n(2) = \pi - \theta_n$. We notice that the deviations from the AF order (θ_n) are rather small and restricted to the spins in the substrate planes near the interface.

The magnetic profile of the AF substrate is determined by minimizing the magnetic energy. This amounts to requiring that $(\partial E / \partial \theta_n = 0, n = 1, 2, \dots)$. In order to find a simple formula for the threshold value of the interface exchange field we consider that in the reoriented state the spins in the F films are aligned along the x -axis direction and assume that the deviations from the AF order of the substrate spins are restricted to the interface plane. Taking the energy of the aligned state as reference, the magnetic energy of the reoriented state is given by

$$\delta E = z[J_{\text{AF}}S_{\text{AF}}^2(\cos(2\theta) - 1) + K_{\text{AF}}S_{\text{AF}}^2(1 - \cos^2 \theta) + t_F K_F S_F^2 + 2J_{\text{INT}}S_F S_{\text{AF}} \sin \theta, \quad (2)$$

where t_F is the thickness of the F film, z is the coordination number of a spin in the AF substrate and $\theta = \theta_1$. In Eq. (2) the first two terms are the increase of the exchange and anisotropy energy of the substrate, the third term is the F film anisotropy barrier and the last term is the interface exchange coupling between the interface F spins and the magnetic moment of the spins of the AF interface plane.

Minimizing the energy δE with respect θ , we find

$$\sin \theta = \frac{-J_{\text{INT}} S_F}{2z|J_{\text{AF}}| + K_{\text{AF}} S_{\text{AF}}}. \quad (3)$$

Therefore, from Eq. (2) we get

$$\delta E = t_F K_F S_F^2 - \frac{J_{\text{INT}}^2 S_F^2}{2z|J_{\text{AF}}| + K_{\text{AF}}}. \quad (4)$$

The threshold value of J_{INT} is obtained from Eq. (4), imposing $\delta E = 0$. We get

$$J_{\text{INT}}^* = \sqrt{t_F K_F (2z|J_{\text{AF}}| + K_{\text{AF}})}. \quad (5)$$

The first contribution to J_{INT}^* represents the balance between the F film anisotropy barrier and the interface exchange coupling and the second term is due to the increase in the AF anisotropy energy. If the AF anisotropy energy is a small fraction of the AF exchange energy, as in the case of Fe/MnF₂ bilayers, and considering that $\sqrt{z}$ is of the order of one, we get J_{INT}^* of order of $\sqrt{t_F K_F |J_{\text{AF}}|}$, as mentioned previously. The AF anisotropy energy term in Eq. (5) explains the difference between the threshold values of the interface field for FeF₂ and MnF₂ substrates as seen in Fig. 3.

In Fig. 4 we compare the result got with Eq. (5) with the results of numerical calculations. Eq. (5) reproduces the results of the numerical calculation for thin F films. However, there is a small difference for thick F films. The balance of energy leading to Eq. (5) fails to account for the small increase in substrate anisotropy energy, due to the deviations from the AF order for spins of other than the interface plane. Although these contributions per AF plane are rather small, the total effect may lead to the differences seen in Fig. 4 for thick films.

These differences do not impact our results since the prediction of Eq. (5) is smaller than that of the

Fig. 4. The threshold interface exchange coupling as function of the number of atomic layer (t_F) of the F film for a Fe/FeF₂(1 1 0) bilayer with $N_{\text{AF}} = 11$. In the inset we show the results for a Fe/MnF₂(1 1 0) bilayer.

numerical calculation. Thus the analytic relation between the threshold value of the interface field and the magnetic parameters of the bilayer, as in Eq. (5), can be used to estimate a lower bound for the interface field strength.

4. Concluding remarks

We have discussed the effect of the strength of the interface exchange coupling in the magnetic phases of uniaxial compensated F/AF bilayers, assuming the uniaxial axes of both materials to be parallel, as reported for the Fe/FeF₂(1 1 0) bilayer [5]. Assuming full saturation of the AF moments ($T = 0$) we calculated the threshold value of the interface exchange energy (J_{INT}^*) beyond which the magnetization of the F film changes from its easy axis to a perpendicular direction.

We have used a self-consistent two spin local field theory to find the equilibrium structure of the bilayer, assuming that the magnetic structure can be represented by two interacting linear chain of spins, which allows to model the frustration of the

interface exchange coupling and the relaxation of the interface effects away from the interface.

We have applied the theoretical model to the study of Fe/FeF₂ and Fe/MnF₂ bilayers, and have found that J_{INT}^* is an increasing function of the thickness of the Fe film, as expected from simple arguments based on the balance between the anisotropy energy barrier to the interface energy coupling.

We have found that the interface coupling is enhanced in bilayers with low anisotropy AF substrates because the canting of AF interface spins is larger. Thus, the threshold value of the interface exchange energy for low anisotropy bilayers is smaller. These features related to the anisotropy field of the substrate can be checked experimentally since Fe/FeF₂ and Fe/MnF₂ bilayers are amongst the most investigated F/AF bilayers and exhibit a large variation of the anisotropy field. Our results indicate that Fe/FeF₂(110) bilayers have a much larger value of J_{INT}^* than Fe/MnF₂(110) bilayers due to the smaller anisotropy energy of MnF₂.

We have also found that in the reoriented phase indicated in Fig. 1 of the compensated F/AF bilayer essentially only in the vicinity of the interface the AF spins are canted in response to the transverse field imposed by the F interface spins. Taking advantage of this we calculated J_{INT}^* analytically by minimizing the energy of the bilayer in the reoriented state. This produces a formula in which J_{INT}^* is expressed in terms of the constitutive parameters K_{AF} and J_{AF} of the AF substrate and the uniaxial anisotropy constant (K_{F}) and thickness (t_{F}) of the F film.

Looking at Fig. 4 one sees that the value of the threshold field predicted by Eq. (5) is lower than the value obtained from the numerical simulation. However, the difference between the two methods is small, specially for thin F films. In this case one may use the reorientation to estimate a lower bound for the interface exchange coupling.

Only for bilayers with thick F films there is a relevant difference. However, thick F films tend to have fourfold crystalline anisotropy and in this case the reoriented state is the ground state. Thus in this limit one cannot explore the phase transition to study the interface exchange field.

Using Eq. (5) and the magnetic parameters for a Fe/FeF₂ bilayer and assuming that the effective interface field is of the order of the coercive field one concludes that reorientation would not occur even for a monolayer of Fe atoms on the compensated FeF₂ substrate. Also, in order to have the reorientation in a Fe/FeF₂ bilayer with $t_{\text{F}} = 20$, which corresponds to a thickness of 28 Å, a value of $J_{\text{INT}}/J_{\text{AF}} = 0.63$ is required. Thus the existence of reorientation is an indication that the interface exchange energy is of the order of the exchange energy of the substrate.

Eq. (5) may be used from a different stand point, which is more appropriate to the experimentalist. A given bilayer has a certain value of the interface exchange energy J_{INT} . The energy barrier to be overcome is controlled by the thickness of the F film. Thus, one may measure the strength of the interface exchange by finding below what thickness t_{F} the reorientation occurs.

Notice also that interface roughness does not impact our predictions. Interface roughness tends to produce interface areas with a smaller degree of compensation. This tends to inhibit the reorientation, making the threshold value of the interface field larger than that of a compensated interface. Thus the value of threshold interface exchange, as predicted by Eq. (5), may be used also for compensated interfaces with some degree of interface roughness.

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