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Ferromagnetic resonance of compensated ferromagnetic/antiferromagnetic bilayers

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We report a theoretical study of the ferromagnetic resonance (FMR) frequency $\Omega(H)$ of $Fe/FeF_2(110)$ and $Fe/MnF_2(110)$ uniaxial anisotropy compensated bilayers. We show that under external field perpendicular to the anisotropy axis, the uniform mode of the Fe-film becomes soft at an external field strength ($H^* = H_A^F - H_{int}^{\perp}$) smaller than the Fe anisotropy field. For strong interface exchange coupling, there is a gap in the FMR spectrum. In this case, $\Omega(H)$ is a monotonically increasing function of the external field strength and for any value of the external field strength $\Omega(H) > \Omega(0)$. The value of the effective interface field downshifts ($H_{int}^{\perp}$) and the value of $\Omega(0)$ may be used to estimate the interface exchange energy. © *2012 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4757032]

I. INTRODUCTION

There is continuing interest in the study of interface effects in ferromagnetic/antiferromagnetic bilayers (F/AF) consisting of a ferromagnetic thin film, or nanoelement, exchange coupled to an antiferromagnetic substrate. These systems have become a key part of a number of magneto-electronic devices[1–4] ever since the invention of the spin valve.[5]

One key parameter of F/AF bilayers is the interface exchange energy. Current applications require it to be large enough to hold the ferromagnetic layer in a single domain uniform state.[1]

The interface exchange energy is most commonly investigated from the exchange bias shift of the hysteresis loops. However, magnetization measurements sample large areas of the interface and thus average out the interface field strength.[6]

Interface pinned domain wall resonance,[7,8] magnetic thermal hysteresis,[9] and magnetic heat capacity[10] have been proposed as local probes of the interface exchange energy.

Ferromagnetic resonance (FMR) has also been reported as an efficient means of getting information on the interface energy of exchange coupled magnetic bilayers. The interface field appears in the ferromagnetic resonance frequency, allowing a simple way to investigate the strength of the interface exchange energy. Previous reports have used FMR to investigate ferromagnet/antiferromagnet bilayers,[11–13] as well as exchange spring systems,[14,15] consisting of two ferromagnetic exchange coupled layers.

In this paper, we investigate interface effects on the FMR curves, $\Omega(H)$, of compensated uniaxial F/AF bilayers, under external field H perpendicular to the easy axis.

An external field applied along the direction perpendicular to the easy axis of an unbiased F-film leads to reorientation (alignment of the magnetization along the external field) when the external field strength reaches the value of the anisotropy field (H_A^F). At this point, the FMR frequency drops to zero ($\Omega = 0$, for $H = H_A^F$).

We have found that the external field dependence of the FMR frequency of compensated bilayers may be investigated using an effective field ($H + H_{int}^{\perp}$), where $H_{int}^{\perp}$ is the effective interface field. $H_{int}^{\perp}$ scales with the inverse Fe-film thickness and is calculated as a function of the interface exchange energy.

We show that for weak interface exchange energy, the FMR frequency $\Omega(H)$ of compensated uniaxial $Fe/FeF_2(110)$ bilayers is similar to that of an unbiased Fe-film, except that the interface field leads to a down-shift of the critical field value (H^*) required for reorientation. We show that $H^* = H_A^F - H_{int}^{\perp}$.

If the interface exchange energy is strong enough to produce reorientation in the absence of external field, $\Omega(H)$ is a monotonically increasing function of the external field strength, starting, at $H = 0$, with a value that depends on the interface field strength.

At low temperatures, compensated F/AF bilayers may exhibit a frustration of the interface exchange coupling if both materials have uniaxial magnetic anisotropy and the easy directions are parallel.[9,10,16–20] 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. Yet, the F-exchange field is parallel to the interface AF spins of one sublattice and opposite to those of the other sublattice.

If the interface exchange coupling is strong enough, the magnetic energy of the F/AF bilayer may be minimized if the magnetization of the F film aligns perpendicular to the easy axis, and the interface AF spins turn slightly (transverse deviation off the uniaxial axis direction by small angles), exhibiting a liquid moment in the perpendicular direction.[19]

The rearrangement of the magnetic structure resolves the interface exchange energy frustration and leads to a non-zero exchange coupling between the F film and the AF substrate, as shown schematically in Fig. 1.

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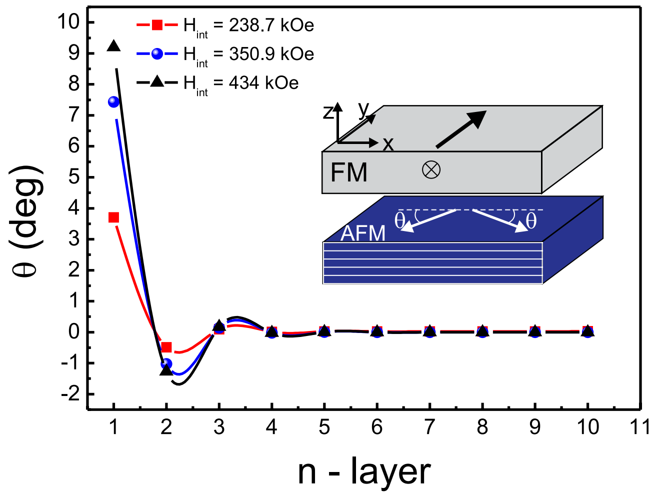

FIG. 1. Deviations (θ_n) from the AF order in the perpendicular state for a Fe(4 nm)/FeF_2(110) bilayer. The numbers by the curves indicate the values of the interface effective field strength. Notice that the deviations from the AF order are restricted to the AF interface layer.

This perpendicular coupling state has been observed in Fe/FeF_2(110) bilayers,[21] in permalloy films on FeMn substrates,[22] and in Fe_3O_4/CoO superlattices.[23]

In this paper, we investigate the interface effects on the FMR frequency $\Omega(H)$ in two regimes: Either the interface energy is below the reorientation threshold value, requiring an external field to produce the perpendicular state, or the interface exchange energy is strong enough to produce reorientation in the absence of external field.

For both regimes, in the reoriented phase, the liquid moment of the interface AF-spins is perpendicular to the easy axis and leads to an interface exchange field ($H^{\perp}_{int}$) parallel to the external field.

We have found that the modification of the magnetic order in the substrate decays rapidly from the interface. It is restricted to the AF-spins at the interface plane. As a result, the energy balance to produce the reorientation may be handled in a rather simple manner, allowing the calculation of a simple expression relating the interface exchange energy to the modifications in the FMR curves $\Omega(H)$, in both regimes of strong and weak interface exchange energy.

We note that for a given pair of F-AF materials, the regimes of strong and weak interface effects are controlled by the thickness of the F-film, since the interface energy scales with the inverse F-film thickness. Thus, it is possible to tailor the composition of the bilayer in order to observe both behaviors of the FMR frequency $\Omega(H)$.

II. THEORETICAL MODEL

We study compensated bilayers with the Fe/FeF_2(110) stacking pattern. Both materials are uniaxial and both have the easy axis along the x-axis direction. The AF substrate is a stacking of AF planes containing moments from the two sublattices. Magnetic moments from a given sublattice in the same plane are considered equivalent and to each plane, we assign two magnetic moment variables. The coordination number is $Z = 8$, and each magnetic moment has four nearest neighbors in the same plane and two nearest neighbors in the two adjacent planes. The normal to the surface is in the z-axis direction. The Fe-film is represented in a similar manner, except for the much stronger exchange energy, coupling nearest neighbors parallel to each other.

We use spin variables $\vec{S}_{i,j}$ to represent the magnetic moment of the i-th atomic plane of the ferromagnetic film and antiferromagnetic substrate and $j = 1,2$ represents the sublattices per plane. The magnetic energy is

$$\begin{aligned} E = {} & \sum_{i=1}^{N}\sum_{l=i-1}^{i+1}\sum_{j\neq k=1}^{2} J_{i,l}\{(S^{\tilde{x}}_{i,j}S^{\tilde{x}}_{l,k}+S^{\tilde{y}}_{i,j}S^{\tilde{y}}_{l,k}) \\ & \times\cos(\theta_{i,j}-\theta_{l,k}) - (S^{\tilde{x}}_{i,j}S^{\tilde{y}}_{l,k}+S^{\tilde{y}}_{i,j}S^{\tilde{x}}_{l,k}) \\ & \times\sin(\theta_{i,j}-\theta_{l,k})+S^{\tilde{z}}_{i,j}S^{\tilde{z}}_{l,k}\} \\ & -\sum_{i=1}^{N}\sum_{j=1}^{2}\{K_i[\cos^2\theta_{i,j}(S^{\tilde{x}}_{i,j}) + \sin^2\theta_{i,j}(S^{\tilde{x}}_{i,j})^2 \\ & - 2\cos\theta_{i,j}\sin\theta_{i,j}S^{\tilde{x}}_{i,j}S^{\tilde{y}}_{i,j}] \\ & - g\mu_B H(\sin\theta_{i,j}S^{\tilde{x}}_{i,j} - \cos\theta_{i,j}S^{\tilde{y}}_{i,j})\} \\ & + \sum_{i=F}\sum_{j=1}^{2} 2\pi(g\mu_B)^2(S^{z}_{i,j})^2, \end{aligned} \tag{1}$$

where $\theta_{i,j}$ is the equilibrium value of the in-plane angle between $\vec{S}_{i,j}$ and the easy axis ($\hat{x}$ direction). $S^{\tilde{x}}_{i,j}$, $S^{\tilde{y}}_{i,j}$, and $S^{\tilde{z}}_{i,j}$ are the components of $\vec{S}_{i,j}$ along the local equilibrium direction at the site (i, j).

The first term in Eq. (1) is the intrinsic exchange energy coupling spins either in the same plane or in adjacent planes. At the interface, the exchange energy ($J_{i,l}$) may be either the intrinsic exchange energy, J_F—coupling F-spins in the same atomic plane, J_{AF}—coupling AF spins in the same plane, or the interface exchange energy, J_{int}—coupling F-spins to AF-spins across the interface. The second term is the uniaxial anisotropy energy, and the third term is the Zeeman energy, for an external field H applied perpendicular to the easy axis. The last term is the demagnetizing energy, used only in the domain of F-spins.

Local axes are defined from the equilibrium pattern ($\{\theta_{i,j}\}, i = 1,\ldots,N$, and $j = 1, 2$) as $\hat{x} = -\hat{\tilde{y}}_{i,j}\sin\theta_{i,j} + \hat{\tilde{x}}_{i,j}\cos\theta_{i,j}$, $\hat{y} = \hat{\tilde{y}}_{i,j}\cos\theta_{i,j} + \hat{\tilde{x}}_{i,j}\sin\theta_{i,j}$, and $\hat{z} = \hat{\tilde{z}}$. In the equilibrium configuration, all the spins are contained in the layers and $S^{\tilde{x}}_{i,j} = S$, $S^{\tilde{y}}_{i,j} = 0$ and $S^{\tilde{z}}_{i,j} = 0$.

The effective field at a given spin is found from the energy using the usual relation $\vec{H}_{eff} = -(1/g\mu_B)\nabla_{\vec{S}}E$. The equilibrium pattern is found by requiring each magnetic moment to be parallel to the local effective field. We obtain the equilibrium profile ($\{\theta_{i,j}\}, i = 1,\ldots,N$, and $j = 1, 2$) using a self-consistent effective field method developed earlier and applied to the study of magnetic multilayers and AF films.[24–26]

We start the calculation at large magnetic fields, above the threshold value of the external field strength required for alignment of the magnetization of the Fe-film along the external field direction.

For each value of the external field, the self-consistent procedure is initialized with the magnetic state corresponding to the equilibrium state of the previous value of the external field.

Proceeding this way, we find the metastable equilibrium state nearest to the preceding one, as appropriate to checking the stability of the reoriented state. Convergence is checked to guarantee a maximum torque of 10^{-24} J in any one of the spins.

The excitation spectrum is obtained from the Landau-Lifshitz equations without damping, using the above system of coordinates with the local axes ($\{\hat{\tilde{x}}_{i,j}\}, i=1,2,N$, and $j=1,\ 2$) along the equilibrium direction of the spin representing the sublattices at each atomic layer.

In the long wavelength limit, we assume the fluctuations out of equilibrium to be of the form $S^{\tilde{y}}_{i,j}(t)=S^{\tilde{y}}_{i,j}e^{i\Omega t}$ and $S^{\tilde{z}}_{i,j}(t)=S^{\tilde{z}}_{i,j}e^{i\Omega t}$, where $S^{\tilde{y}}_{i,j}$ and $S^{\tilde{z}}_{i,j}$ are layer dependent amplitudes. We obtain the system of 4N coupled equations

$$
\begin{aligned}
&i\frac{\Omega}{\gamma}\vec{S}^{\tilde{y}}_{i,j}-\left[\frac{J_{i,i}S_{i,k}}{g\mu_B}\cos(\theta_{i,j}-\theta_{i,k})+\frac{J_{i,i\pm1}S_{i\pm1,k}}{g\mu_B}\cos(\theta_{i,j}-\theta_{i\pm1,k})+\frac{2K_iS_{i,j}}{g\mu_B}\cos^2\theta_{i,j}+H\sin\theta_{i,j}+4\pi g\mu_B S_{i,j}\right]S^{\tilde{z}}_{i,j}+\frac{J_{i,i}S_{i,j}}{g\mu_B}S^{\tilde{z}}_{i,k}\\
&\quad+\frac{J_{i,i\pm1}S_{i,j}}{g\mu_B}S^{\tilde{z}}_{i\pm1,k}=0,\\
&i\frac{\Omega}{\gamma}\vec{S}^{\tilde{z}}_{i,j}+\left[\frac{J_{i,i}S_{i,k}}{g\mu_B}\cos(\theta_{i,j}-\theta_{i,k})+\frac{J_{i,i\pm1}S_{i\pm1,k}}{g\mu_B}\cos(\theta_{i,j}-\theta_{i\pm1,k})+\frac{2K_iS_{i,j}}{g\mu_B}\cos(2\theta_{i,j})+H\sin\theta_{i,j}+4\pi g\mu_B S_{i,j}\right]S^{\tilde{y}}_{i,j}-\frac{J_{i,i}S_{i,j}}{g\mu_B}S^{\tilde{y}}_{i,k}\\
&\quad-\frac{J_{i,i\pm1}S_{i,j}}{g\mu_B}S^{\tilde{y}}_{i\pm1,k}=0,
\end{aligned}
\tag{2}
$$

where for each sublattice ($j=1,2$) of the i-th atomic plane ($i=1,\ 2,\dots,\ N$) and k represents spins in the other sublattice, either in the same plane or in the nearest neighbor planes.

The exchange and uniaxial anisotropy fields are given by $H^E=ZJS/g\mu_B$ and $H^A=2KS/g\mu_B$, respectively. The magnetic parameters used for Fe are $H^A_F=0.55$ kOe and $H^E_F=11639.8$ kOe. For FeF_2, the anisotropy and exchange fields are $H^A_{AF}=149$ kOe and $H^E_{AF}=434$ kOe. For MnF_2, the anisotropy and exchange fields are $H^A_{AF}=8.8$ kOe and $H^E_{AF}=540$ kOe.

For each value of the external field, the FMR frequency is obtained from the lowest eigenvalue of Eq. (2), corresponding to in phase oscillations (no exchange energy contributions) of the F-spins.

A. Analytical model—reoriented state

In the reoriented phase, the competition between the intrinsic anisotropy and exchange energies of the AF substrate spins and the interface exchange energy may be handled in a rather simple manner. It is thus possible to calculate the liquid moment of the AF-spins at the interface plane as well as the value of the effective interface exchange field $H^{\perp}_{int}$ in the perpendicular direction.

Two features of the magnetic phase have been explored. The modification of the magnetic order in the substrate decays rapidly from the interface, it is restricted to the AF-spins at the interface plane. Also, spins from both sublattices in the interface plane deviate from the AF order by the same amount (θ). As a result, the interface exchange field is along the external field direction.

The effects of the interface exchange energy on the external field dependence of the FMR frequency $\Omega(H)$ may be investigated using an effective field $(H+H^{\perp}_{int})$, where $H^{\perp}_{int}$ is the interface exchange field along the external field direction. $H^{\perp}_{int}$ scales with the inverse Fe-film thickness and is calculated as a function of the interface exchange energy.

$\Omega(H)$ is the frequency of the uniform mode of an uniaxial ferromagnetic film, with magnetization parallel to the film surface, subjected to an effective field $H+H^{\perp}_{int}$ applied in the plane of the surface and perpendicular to the F-film uniaxial direction. It is given[27] by

$$\Omega=\gamma\sqrt{(H^{\perp}_{int}+H+4\pi M_S)(H^{\perp}_{int}+H-H^A_F)},\tag{3}$$

where

$$H^{\perp}_{int}=H_{int}\sin\theta/N_F\tag{4}$$

and $H_{int}=2J_{int}S_{AF}/g\mu_B$ is the interface field acting on F-spins at the interface plane and N_F is the number of atomic layers in the iron film. θ is the deviation from the AF order for the interface layer spins, γ is the iron gyromagnetic ratio, and M_S is the iron saturation magnetization.

We have found that for a wide range of interface exchange energy strength, ranging from small values up to the value of the intrinsic exchange energy of the AF-substrate, the deviations from the antiferromagnetic order at the interface layer are of the order of 10^{-1} rad, while the deviations at the second atomic plane are one order of magnitude smaller, as shown in Fig. 1.

These small values may be anticipated from the following simple argument. For a bulk antiferromagnet, the deviation θ_B from the anisotropy axis, in response to an external field (H_{ext}) perpendicular to the easy axis, is given by[27] $\sin\theta_B=H_{ext}/(H^E_{AF}+H^A_{AF})$. For fields of the order of the iron anisotropy field, the deviation from the antiferromagnetic order of FeF_2 spins is of the order of 10^{-4} rad. Only for external field strength of the order of the exchange field, there is an appreciable deviation from the AF order. For $H_{ext}=H^E_{AF}$, one has $\theta_B\approx 0.85$ rad.

In this paper, we consider values of the external field strength of the order of the iron anisotropy field. Therefore, the direct effect of the external field on AF-spins is negligible.

In the canted state produced by the reorientation of the Fe film, the AF-spins at the interface atomic layer are subjected to the interface exchange field. The interface exchange field is perpendicular to the uniaxial axis and may be of the order of the intrinsic exchange field of the antiferromagnetic substrate. At first glance, one might expect large values of the deviations as in the bulk.

However, there is a key difference. The AF-spins in the interface layer are exchange coupled to spins from the second AF layer. These are kept quite close to the AF order, pointing almost along the uniaxial axis. As a result, the deviations from the substrate AF order in the reoriented state of a compensated bilayer are rather small and restricted to the spins in the near interface region.

The liquid magnetic moment of the AF-spins at the interface, as well as the effective interface field acting on the F-film interface spins, may be obtained from the minimization of the interface energy.

We have found that the interface energy is to a good approximation given by

$$\begin{aligned} E = & -2K_{AF}S_{AF}^2\cos^2\theta + 4J_{AF}S_{AF}^2\cos 2\theta \\ & + 4J_{int}S_F S_{AF}\sin\theta + 2g\mu_B H S_{AF}\sin\theta \\ & + 4J_{AF}S_{AF}^2\cos(\theta-\eta), \end{aligned} \tag{5}$$

where θ and η are the deviations from the AF order for the interface and second layer spins, respectively. The first and the second terms are the anisotropy and exchange energies, the third term is the interface exchange energy, the fourth term is the Zeeman energy, and the last term is exchange coupling between the spins in the first and the second AF layers.

The value of θ is found from the minimization of the interface energy. We have neglected second order terms and found that

$$\sin\theta = \frac{4(H_{int}(S_F/S_{AF}) - H) + \eta H_{AF}^E}{4H_{AF}^A + 5H_{AF}^E}, \tag{6}$$

where $H_{int}(S_F/S_{AF})$ is the effective interface exchange field acting on the interface layer AF-spins.

We have used Eqs. (3) and (6) in order to fit the numerical results. η has been used as a fitting parameter. It turned out that for ultra-thin films, η is of the order of 10^{-2} rad, as shown in Fig. 1 for a Fe(4 nm)/FeF_2(110) bilayer.

However, a good fitting of the numerical results may be achieved neglecting the small deviations of the AF order in the second layer of spins. For ultrathin Fe-film bilayers taking $\eta = 0$ provides a good theoretical prediction of the FMR curves, with error in $\Omega(H)$ smaller than 10%.

III. RESULTS AND DISCUSSIONS

Under in-plane external field H perpendicular to the uniaxial axis, the magnetization of an unbiased ferromagnetic film turns continuously to the field direction, by increasing the external field strength, and the FMR frequency $\Omega(H)$ drops to zero when the external field strength reaches the anisotropy field. This is the critical external field value to produce alignment of the magnetization with the external field ($H^* = H_A^F$). By further increasing the external field strength $\Omega(H)$ increases monotonically, as shown in Fig. 2 for an unbiased 4 nm thick iron film.

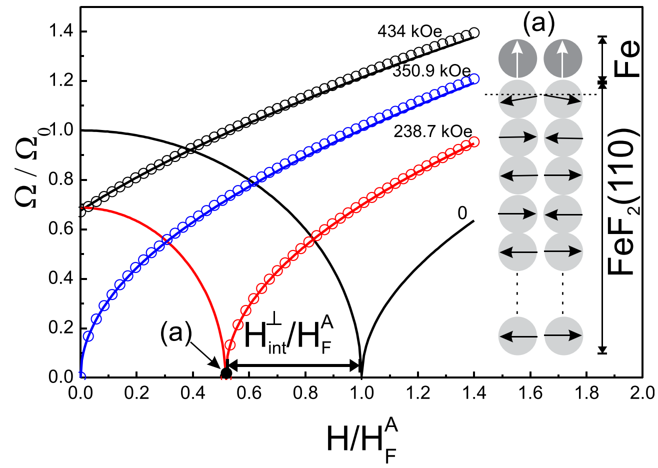

FIG. 2. $\Omega(H)$ of a Fe(4 nm)/FeF_2(110) bilayer. The numbers by the curves are the values of the interface field strength and $\Omega(H)$ is shown in units of $\Omega_0 = \gamma\sqrt{H_F^A(H_F^A + 4\pi M_S)}$. The continuous line curves were calculated numerically, from Eq. (2), and the open symbol curves, from the analytical model—Eq. (3). In the inset, we show the deviations from the AF—order for an external field strength of $H/H_F^A \cong 0.5$ and an interface field strength of 238.7 kOe.

We presently show that interface biasing may lead to relevant changes in this basic picture. Typical results are shown in Figs. 2 and 3 for Fe/FeF_2 bilayers with ultrathin Fe-films, in Fig. 4 for a Fe(13 nm)/FeF_2 bilayer, and in Fig. 5 for a Fe(4 nm)/MnF_2 bilayer.

Starting at large external field values and decreasing the field strength, the critical field is reached at the point for which the FMR mode becomes soft.[28,29]

There are two regimes according to the value of the interface exchange energy. If the interface exchange energy is small, so that $H_{int}^{\perp} < H_F^A$, the critical field is $H^* = H_F^A - H_{int}^{\perp}$.

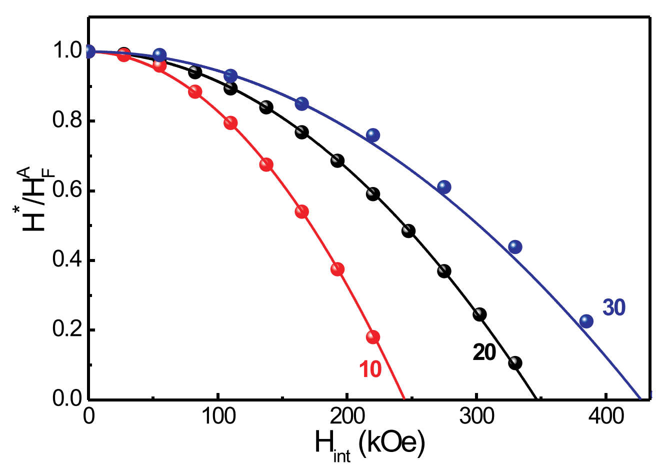

FIG. 3. Critical field H^* in units of H_F^A for a Fe/FeF_2 bilayer. The number by the curves indicate the values of the number (N_F) of Fe atomic layers. The continuous lines correspond to the predictions of the analytical model, and the full symbol curves are from the numerical calculations.

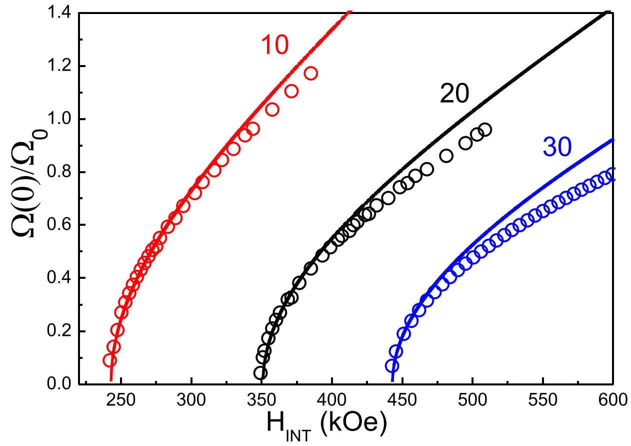

FIG. 4. $\Omega(0)/\Omega_0$ for Fe/FeF$_2$(110) bilayers. The numbers by the curves indicate the numbers of atomic layers in the Fe-film. The open symbol curves and the continuous lines are from the numerical results and the analytical model, respectively.

In this case, the FMR curves are similar to those of an unbiased film, except for a down-shift of the critical field and also a reduction of the value of $\Omega(0)$.

For interface field strength above a Fe-layer thickness dependent value,[19] the bilayer is reoriented for $H = 0$. The smallest value of the interface field strength corresponds to having a down-shift equal to the F-film anisotropy ($H_{int}^{\perp} = H_A^F$). In this case, $\Omega(0) = 0$.

For larger values of the interface field strength $\Omega(0)$ is an increasing function of the interface field strength, given by

$$\Omega(0) = \gamma\sqrt{(H_{int}^{\perp} + 4\pi M_S)(H_{int}^{\perp} - H_F^A)}. \tag{7}$$

Thus, it is possible to investigate the interface exchange energy in both regimes of the interface exchange energy (either for weak coupling or strong coupling).

In Figs. 1 and 2, we consider a Fe(4 nm)/FeF$_2$(110) bilayer, with 20 atomic layers in the Fe-film and 10 atomic layers in the AF substrate, for interface field strengths of 434 kOe, 350.9 kOe, and 238.7 kOe.

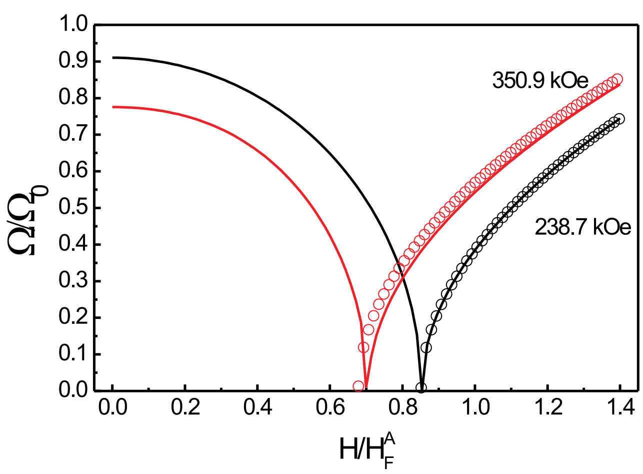

FIG. 5. $\Omega(H)/\Omega_0$ for a Fe(13 nm)/FeF$_2$(110) bilayer for $H_{int} = 238.7$ kOe and 434 kOe. The open symbol curves correspond to the predictions of the analytical model and the continuous lines are from Eq. (2).

As shown in Fig. 1, for the chosen values of the interface field strength, at $H = 0$ the deviations from the AF-order are restricted to the interface AF-spins. Except for the spins in the interface layer and for a small deviation of the order of 10^{-2} rad at the second atomic layer, the AF-spins are in the antiferromagnetic arrangement along the uniaxial axis.

This picture is valid with no appreciable changes along the interval of external field strengths shown in Fig. 2, corresponding to the reoriented state ($H > H^*$). The external field strength is two orders of magnitude smaller than the intrinsic exchange field of FeF$_2$. Therefore, in the chosen external field interval, the substrate magnetic pattern and the interface exchange perpendicular field $H_{int}^{\perp}$ do not change.

In Fig. 2, we show the FMR frequencies $\Omega(H)$ of an unbiased 4 nm thick iron film and Fe(4 nm)/FeF$_2$(110) bilayers for three values of the interface field strength. In the reoriented phase, the $\Omega(H)$ curves corresponding to interface fields of 238.7 kOe, 350.9 kOe, and 434 kOe were fitted with values of $\eta = 0.012, 0.017$, and 0.025, respectively.

Notice that a 50% downshift of the critical field requires an interface field of 238.7 kOe, which amounts to 55% of the intrinsic exchange field of the FeF$_2$ substrate.

An interface field of 350.9 kOe is required for reorientation at $H = 0$. This value represents 80.8% of the intrinsic exchange field of the FeF$_2$ substrate.

For larger values of the interface field strength, the bilayer is reoriented in the absence of external field and $\Omega(0)$ increases as predicted by Eq. (7). For an interface field strength of the same magnitude as the intrinsic exchange field of FeF$_2$ (434 kOe), $\Omega(0) \sim 0.7\Omega_0$.

Notice that for large values of the interface field strength, the spectrum of the long wavelength FMR mode is qualitatively different from that of an unbiased Fe-film. There is a gap in the spectrum, the minimum value of frequency is that given by Eq. (7).

In Fig. 3, we show H^*/H_F^A of Fe/FeF$_2$ bilayers for three values of the F-film thickness, $N_F = 10$, 20, and 30 atomic layers, corresponding to thicknesses of 2 nm, 4 nm, and 6 nm, respectively. The results from Eq. (2) were fitted using $\eta = 0$ in the analytical model.

Using Eqs. (4) and (6) with $\eta = 0$, the critical field $H^* = H_A^F - H_{int}^{\perp}$ may be written

$$H^* = \frac{H_F^A N_F(4H_{AF}^A + 5H_{AF}^E) - 4H_{int}^2(S_F/S_{AF})}{N_F(4H_{AF}^A + 5H_{AF}^E) - 4H_{int}}. \tag{8}$$

Notice that the error in neglecting the small deviations from the AF order of the AF-spins in the second atomic layer is smaller than 1%. Thus, Eq. (8) may be used to obtain the interface exchange energy.

There is a clear impact of the F-film thickness on the interface effects. As shown in Fig. 3 for an interface field strength of 220 kOe, the down-shift of the critical field varies from $0.8H_A$ for a 2 nm thick Fe-film to $0.25H_A$ for a 6 nm thick Fe-film.

Notice also that in ultrathin Fe-film bilayers, there is a strong dependence of the critical field on the value of the interface exchange field. For a Fe(2 nm)/FeF$_2$(110) bilayer, corresponding to the $N_F = 10$ curve in Fig. 3, a reduction in

50% in the interface field (from 200 kOe to 100 kOe) leads to a change of the critical field from $0.2H_A$ to $0.8H_A$.

In Fig. 4, we show how the interface field strength affects the value of $\Omega(0)/\Omega_0$ for Fe/FeF$_2$(110) ultrathin bilayers with 10, 20, and 30 iron atomic layers, corresponding to thicknesses of 2 nm, 4 nm, and 6 nm, respectively. As in Fig. 3, we have used $\eta = 0$ in Eqs. (4), (6), and (7). As seen in Fig. 4, this leads to a satisfactory fitting of the numerical results, with error smaller of 10%.

Notice that values of the interface field of 242 kOe, 350 kOe, and 440 kOe are required to produce reorientation. Furthermore, for an interface field strength equal to the intrinsic exchange field of FeF$_2$ (434 kOe), we find that the minimum frequency for the 2 nm Fe/FeF$_2$(110 bilayer is 40% larger than Ω_0), whereas for the 3 nm Fe/FeF$_2$(110 it is smaller than Ω_0).

In Fig. 5, we show the FMR frequencies $\Omega(H)$ of a Fe(13 nm)/FeF$_2$(110) bilayer, for two values of the interface field strength. Notice that, as compared to the Fe(4 nm)/FeF$_2$(110) bilayer, the interface effects are much smaller.

For an interface field strength of 238.7 kOe, the down-shift $(H^* - H_A^F)$ is only $0.14H_F^A$. Also, for an interface field of 350.9 kOe, which is enough to reorient the thinner bilayer in the absence of external field, the down-shift is only of $0.3H_A$. $\eta = 0.02$ and $\eta = 0.12$ have been used to fit the numerical results corresponding to interface field strengths of 238.7 kOe and 350 kOe, respectively.

The liquid magnetic moment induced in the interface layer of the AF-substrate depends on the anisotropy and exchange energies of the AF-substrate. MnF$_2$ has a smaller value of the anisotropy energy than FeF$_2$. Therefore, the reorientation of a Fe/MnF$_2$(110) bilayer involves an energy balance with a smaller contribution from the AF-spins anisotropy energy, as compared to the FeF$_2$(110) substrate. As a result, in comparison with a Fe/FeF$_2$(110) bilayer, a given interface effect requires a smaller value of the interface field (in units of the AF-spins intrinsic exchange field).

In Fig. 6, we show $\Omega(H)/\Omega_0$ curves of an unbiased 4 nm thick iron film and Fe(4 nm)/MnF$_2$ bilayers. For a 50% downshift of the critical field, an interface field of 254 kOe is required. This corresponds to 47% of the intrinsic exchange field of the MnF$_2$ substrate.

Also, for reorientation at $H = 0$, a field of 405 kOe is required. This value represents 75% of the intrinsic exchange field of the MnF$_2$ substrate. $\eta = 0.055$ and $\eta = -0.045$ have been used to fit the numerical results for interface field strengths of 254 kOe and 403 kOe, respectively.

In the inset, we show details of the relaxation in the near interface region of the MnF$_2$(110) substrate, for an interface field strength of 254 kOe and for $H \approx 0.5H_A^F$. We show the angles $\theta_{1,n}$ and $\theta_{2,n}$ of spins in both sublattices at a given atomic layer (n), starting with $n = 1$ for the AF-interface layer.

Notice that, as in the case of the FeF$_2$(110) substrate (see Figs. 1 and 2), interface effects are restricted to AF-spins at the interface atomic layer. The interface AF-spins have small deviations from the AF order: $\theta_{1,1} \approx 5°$ and $\theta_{2,1} \approx 174.5°$, corresponding to a relative orientation of $\delta\theta(1) = \theta_{1,2} - \theta_{1,1} = 169.5°$. At the second atomic layer, the AF-spins are closer to AF order: $\theta_{1,2} \approx 0.9°$ and $\theta_{2,2} \approx 180.9°$, corresponding to a relative orientation of $\delta\theta(2) = 181.8°$. The AF-spins in deeper layers are along the uniaxial axis and $\delta\theta(n) = 180°$, for $n \geq 3$.

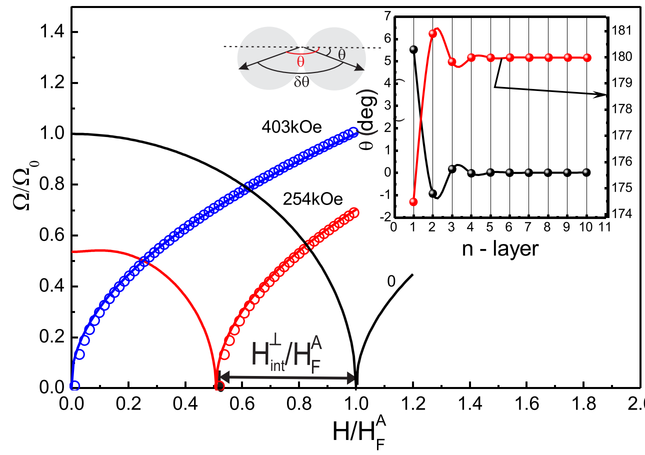

FIG. 6. $\Omega(H)/\Omega_0$ of a Fe(4 nm)/MnF$_2$(110) bilayer. The numbers by the curves are the values of the interface field strength. The continuous line curves were calculated numerically, from Eq. (2), and the open symbol curves, from the analytical model—Eq. (3). In the inset, we show the deviations from the AF—order for an external field strength of $H/H_F^A \cong 0.5$ and an interface field strength of 254 kOe.

In summary, we have reported a study of the frequency of the long wave-length mode of the ferromagnetic layer of a compensated F/AF bilayer. We have focused on the impact of the interface exchange energy on the external field dependence of the frequency, with the external field H applied perpendicular to the easy axis.

We have shown that the FMR spectrum of ultrathin Fe-films bilayers is strongly dependent on the strength of the interface exchange field H_{int}. There are two regimes. For weak interface exchange energy the FMR frequency $\Omega(H)$ is similar to that of an unbiased Fe-film, except that the interface field leads to a down-shift of the critical field value (H^*) required for reorientation as well as a reduction of the $\Omega(0)$ $(\Omega(0)/\Omega_0 < 1)$.

If the interface exchange energy is strong enough to produce reorientation in the absence of external field, $\Omega(H)$ is a monotonically increasing function of the external field strength, starting, at $H = 0$, with a value $\Omega(0)$ that depends on the interface field strength, as given by Eq. (7). In this case, there is a gap in the spectrum. $\Omega(H)$ is a monotonically increasing function of the external field strength, with $\Omega(H) \geq \Omega(0)$. This may turn out to be useful for the determination of the interface exchange energy.

The present discussion may also apply to FeF$_2$ bilayers with twin domains structure.[17] It may also be used to investigate the interface energy in systems with compensation of the interface spin pattern on an average over interface areas of mesoscopic dimensions, provided that the interface magnetic structure is compensated at a length scale smaller than the exchange length of the ferromagnetic material. Two interesting examples are F/AF bilayers with interface energy compensation due to interface roughness[21,22,30] and vicinal bilayers.[20]

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