Ferromagnetic resonance studies of exchange-biased Permalloy thin films

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Ferromagnetic resonance (FMR) spectra of Permalloy thin films exchange-coupled to iron-manganese films are analyzed. Studies were made on bilayer, ferromagnetic-antiferromagnetic (FA) and trilayer (AFA) structures, as a function of both F and A layer thicknesses in the range 20–800 Å. Data are presented at a frequency of 9.3 GHz for both in-plane and perpendicular directions of the applied field, and at 34.1 GHz, in-plane. Analysis of these data enables extraction of the magnetization, gyromagnetic ratio, and an exchange shift due to spin-wave stiffness and perpendicular-surface anisotropy, as a function of layer thickness. The azimuthal dependence of the in-plane resonance is used to determine the magnitude of the exchange anisotropy (bias field). The magnetization and gyromagnetic ratio show little dependence on the thickness of either the F or A layer down to 50 Å, implying that the interfaces are sharp on a scale of a few lattice constants. Within this interfacial region the magnetization is reduced as a result of interaction with the antiferromagnet. We suggest that the perpendicular-surface anisotropy is created by exchange coupling to the antiferromagnet whose easy axes are not in the plane of the interface. Finally, we suggest a model for exchange anisotropy in which the antiferromagnetic domain pattern is not totally locked, but adjusts in response to the ferromagnetization. Such a model qualitatively explains the bias field exerted by the antiferromagnetic layer deposited before the ferromagnet, the field-training effect, the FMR linewidth, and the magnitude of the bias field.

I. INTRODUCTION

The phenomenon of exchange anisotropy was discovered by Meiklejohn and Bean approximately 30 years ago.[1] It occurs as a result of the interaction of a ferromagnetic material with an antiferromagnet, and can be described, phenomenologically, in terms of an exchange interaction between magnetic moments on each side of the interface between the two materials.[1–3]

Experimentally it is convenient to study exchange anisotropy in a layered geometry[4–11] (see Fig. 1). In this study the ferromagnetic layer is Permalloy ($Ni_{0.8}Fe_{0.2}$) and the antiferromagnetic layer is manganese-iron ($Mn_{0.5}Fe_{0.5}$). In order to observe exchange anisotropy it is customary to deposit the Permalloy first in the presence of a uniform field. The antiferromagnetic layer is then grown in contact with the magnetized Permalloy and the sublattice magnetization direction of the first few atomic planes is defined by the exchange with the ferromagnet.

Exchange anisotropy is characterized by the following experimental observations:[1–3]

(1) A hysteresis loop, $M(H)$, displaced along the field (H) axis by an amount H_B, known as the unidirectional or exchange anisotropy, or simply as the "bias field;" in the layered geometry, H_B is inversely proportional to the thickness of the ferromagnetic material, t_F.

(2) A torque which varies as $\sin\phi$, where ϕ is the azimuthal angle of the applied magnetic field in the plane of the film, measured from the orientation of the field in which the film was grown.

(3) Rotational hysteresis which, unlike unbiased ferromagnetic layers, onsets at large applied fields.[3]

(4) A training effect in which the hysteresis loop of a freshly prepared sample shrinks and shifts as the field is cycled along the axis of unidirectional anisotropy.[7]

(5) An in-plane ferromagnetic resonance field which exhibits a $\cos\phi$ azimuthal behavior.[10]

(6) A temperature dependence of H_B going to zero approximately linearly,[6]

$$H_B = H_B^0(1 - T/T_B) , \tag{1}$$

where the blocking temperature $T_B \le T_N$, the Néel temperature of the bulk antiferromagnet.

Many of these observations can be explained in terms of a model in which the sublattice magnetization of the

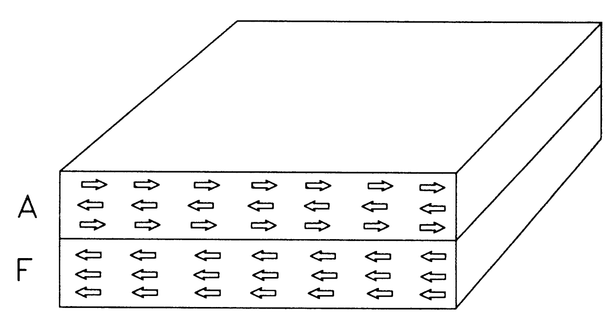

FIG. 1. Schematic view of an exchanged-biased layer structure. The antiferromagnetic upper layer (A) exerts a torque on the ferromagnetic lower layer (F) as a result of the exchange interaction across the interface between the two materials.

antiferromagnet is fixed in direction by an anisotropy energy K_A, while the magnetization M of the ferromagnet is acted on by the external magnetic field H, a uniaxial anisotropy K_F, and the interfacial exchange interaction $K_{AF}\cos(\phi_F-\phi_A)$.[1-3] In order to reverse the ferromagnetic magnetization, the Zeeman energy, HM per unit volume, must exceed the interfacial exchange energy K_{AF} per unit area. Thus,

$$H_B = K_{AF}/Mt_F \ . \tag{2}$$

The angular dependence of the ferromagnetic resonance field can also be understood in terms of a unidirectional surface anisotropy. Speriosu *et al.*[10] have shown that the $K_{AF}\cos(\phi_F-\phi_A)$ term induces a surface pinning of the rf component of the magnetization such that the wave vector for the main resonance, k, is nonzero and can be written as

$$k_E^2 = \frac{K_{AF}}{2At_F}\cos\phi \tag{3}$$

(A is the spin-wave stiffness of the ferromagnet) and the in-plane resonance field is shifted by an amount

$$\delta H_\parallel = 2Ak_E^2/M = (K_{AF}/Mt_F)\cos\phi \ . \tag{4}$$

Thus the coefficient of the azimuthal variation is precisely the unidirectional bias field.

Unfortunately there are difficulties in understanding the microscopic origin of the interfacial exchange anisotropy, and the simple model outlined above fails to explain the experimental observations numbered (4) and (6) above. A simple estimate of the magnitude of the bias field H_B, using this model, gives a much larger value than is experimentally observed in the Permalloy–manganese-iron system. Assuming that the interfacial exchange arises as the result of pairwise interactions of atoms across a perfectly flat interface, one can estimate the interfacial exchange energy of the random alloys to be

$$J_{AF} = (1-p_F)(1-p_A)J_{\rm NiMn} + (1-p_F)p_A J_{\rm NiFe} + p_F(1-p_A)J_{\rm MnFe} + p_F p_A J_{\rm FeFe} \ , \tag{5}$$

where $p_{F,A}=0.2$, 0.5 is the concentration of iron atoms in the ferromagnetic (antiferromagnetic) material, and the exchange interactions have been estimated by Menshikov *et al.*[12] on the basis of neutron scattering studies of the spin-wave stiffness in ternary fcc (γ-phase) Ni-Mn-Fe alloys:

$$J_{\rm NiNi} = 52 \text{ meV} \ ,$$

$$J_{\rm FeNi} = 38 \text{ meV} \ ,$$

$$J_{\rm MnNi} = 44 \text{ meV} \ ,$$

$$J_{\rm FeFe} = -8 \text{ meV} \ ,$$

$$J_{\rm FeMn} = 17 \text{ meV} \ ,$$

$$J_{\rm MnMn} = -285 \text{ meV} \ .$$

The result is $J_{AF}=34$ meV, or $K_{AF}=J_{AF}/a^2 \sim 10$ erg/cm^2, where $a=2.4$ Å is the lattice spacing. Experimentally,[5] one observes $H_B \simeq 20$ Oe for a Permalloy film thickness of 400 Å, or $K_{AF}=H_B M t_F \sim 0.06$ erg/cm^2. Thus there is a discrepancy of more than 2 orders of magnitude.

The situation is rather different if one assumes an atomically rough surface. In this case the ferromagnetic spins are as likely to have antiferromagnetic neighbors in the A sublattice as in the B. Thus, naively, one expects the net interfacial exchange to average to zero for any macroscopic sample.

The simple model also has difficulty explaining the temperature dependence of H_B. Since the ferromagnet is far below its Curie point, the temperature dependence would have to be that of the antiferromagnet sublattice magnetization $K_{AF} \sim M_A(T)$. M_A vanishes at the Néel temperature with a critical exponent β, according to

$$M_A = M_A^0(1-T/T_N)^\beta \ , \tag{6}$$

where $\beta=0.5$ in mean-field theory, and is certainly much less than unity [cf. Eq. (1)]. In the Permalloy–manganese-iron system, the blocking temperature is $T_B \simeq 150\,^\circ$C, considerably below the Néel temperature (210 °C) of bulk MnFe.[5] Finally the "field-training" effect cannot be explained in a model which postulates a unique orientation for the equilibrium antiferromagnet sublattice magnetization.

In a recent paper Malozemoff[13(a)] has addressed the issue of the magnitude of the bias field. He postulates that for a rough surface the antiferromagnet will break up into domains of characteristic size $L \simeq \pi a\sqrt{J_A/K_A}$ resulting in a nonzero exchange anisotropy of $K_{AF} \sim J_{AF}/aL$ which is of the same order of magnitude as found experimentally. In a more recent paper Malozemoff[13(b)] has considered the temperature dependence of L for the case of cubic anisotropy and finds that the exchange bias varies linearly with temperature in agreement with experiment. He also describes how the field-training effect can arise from reorganization of the antiferromagnetic domain pattern.

In an attempt to explore the phenomenology of exchange anisotropy further, and hoping to find additional experimental observations which might help to elucidate the microscopic nature of the interface interaction, we have undertaken a ferromagnetic resonance (FMR) study of exchange-coupled bilayers FA, and trilayers AFA, where the ferromagnetic F layer is Permalloy and the antiferromagnet A layer is manganese-iron. The primary motivation is the fact that the FMR field is sensitive to the magnetization at the interface of the ferromagnetic layer, expressible as a "boundary condition" which defines the allowed modes. By studying the FMR spectra as a function of the thickness of the F and A layers, it is possible to deduce information concerning the abruptness of the interface and the magnetization profile in its vicinity.

Permalloy exchanged-coupled to manganese-iron was used in this work for the same reasons this system was chosen in earlier studies.[8-10] Permalloy has minimal anisotropy and magnetostriction,[14] especially at the 80-20 composition ratio, and therefore has a particularly simple FMR behavior, unaffected to first order, by strain effects which might also occur in thin films. The γ phase of manganese-iron has a relatively high Néel temperature, yielding a convenient blocking temperature of 150 °C, and is quite closely lattice matched to Permalloy. Moreover, the bias fields are in the range 10–100 Oe, which are small compared to the magnetization $4\pi M = 10$ kOe, and the equivalent microwave field $\omega/\gamma = 3.4$ kOe, where ω is the microwave frequency, $2\pi \times 9.3 \times 10^9$ sec^{-1} at X band, and γ is the gyromagnetic ratio.

Section II describes the preparation of the samples and the microwave apparatus used to record the FMR spectra. Section III gives the experimental results on films consisting of bilayers FA, where the thickness of each layer was separately varied, and symmetric trilayers AFA, again with various F and A thicknesses. In Sec. IV we present analysis of the data and the conclusions are summarized in Sec. V.

II. EXPERIMENTAL

The samples were prepared in a high-vacuum dc magnetron sputtering system with four SFI research S guns. The base pressure of the system was typically 10^{-9} Torr prior to film deposition and a large pumping speed was maintained during deposition in a 3.25×10^{-3} Torr argon plasma. By computer control of shutters and substrate platform a series of up to 19 multilayered film structures of arbitrary complexity could be prepared in a single pump down allowing accurate relative changes in film thicknesses within a single series. The absolute film thicknesses were controlled during the deposition process using *in situ* quartz crystal monitors to establish deposition rates to within 5–10% of the nominal 2 Å/sec. *Ex situ* surface profilometry and Rutherford backscattering techniques were used to check deposition rates by measuring thicknesses of thick single layer films grown under the same conditions as the films of interest.

The films were grown on Si(110) substrates which were chemically etched just prior to deposition to provide a clean flat surface. Since direct deposition of Permalloy on Si results in silicide formation and severely modifies the magnetic profile near the interface, a buffer layer of copper was deposited first. In the case of samples with an antiferromagnetic layer below the Permalloy, this Cu layer provides a template to ensure growth of the antiferromagnetic γ phase of FeMn[6]. This method of growth results in highly textured (111) films. A final layer of Cu was deposited to reduce oxidation of the film structures. For convenience, we shall designate film structures of the sequence copper–Permalloy–iron-manganese–copper as "CFAC," and those with copper–iron-manganese–Permalloy–iron-manganese–copper as "CAFAC."

A small magnet (approximately 100 Oe) was secured under each silicon wafer to magnetically order the Permalloy layer during deposition of the FeMn layer so as to establish a net exchange bias field. The FMR experiments were carried out with a Varian E-15 ESR spectrometer which operates at 9.3 GHz (X band) with a rectangular TE_{102} cavity, and with a Bruker ER 200 ESR spectrometer operating at 34.1 GHz (Q band) with a cylindrical TE_{011} cavity.

For the X-band measurements the sample film (typically 2×2 mm^2) was mounted on a two circle goniometer capable of rotation about both horizontal and vertical axes. Thus it is possible to orient the film with the external field H_0 either perpendicular to the sample or at any angle in the plane of the film. For the Q-band measurements, which were done only in-plane, the sample (0.5×0.5 mm^2) was fixed at the flat end of a thin fused quartz rod (diameter 1.5 mm) which is rotatable around its vertical axis. FMR absorption is detected by standard field modulation and lock-in techniques as H_0 is scanned.

To avoid heating of the samples which leads to a decrease of the exchange bias field H_B, the maximum microwave power was limited to 1 mW. To prevent additional heating of the Q-band cavity by the field modulation coils, the cavity was kept at room temperature by flushing with nitrogen gas.

The accuracy of the absolute values of the resonance fields ($\lesssim 30$ G in perpendicular orientation) is mostly determined by the precision of the sample orientation (~ 1–$2°$ about the horizontal axis). Other limits on the accuracy of the field, measured using an NMR gaussmeter, and microwave frequency, using a counter, are 1 part in 10^5 or better.

III. RESULTS

The measured values of the resonance fields are shown in Fig. 2, as a function of the thickness of the F layer for both the CFAC and CAFAC series of samples. The in-plane resonance varies typically with azimuthal angle as

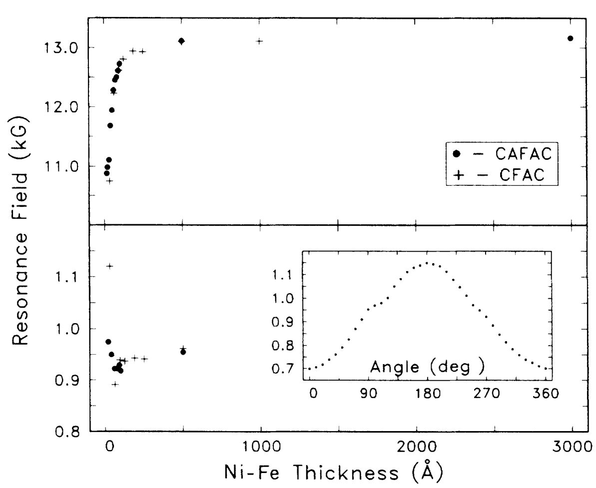

FIG. 2. Perpendicular (upper) and parallel (lower) resonance fields for CAFAC and CFAC structures as a function of the Permalloy layer thickness. The antiferromagnetic layer thickness is 150 Å. The inset shows the in-plane azimuthal variation of a CAFAC sample with $t_F = 60$ Å and $t_A = 150$ Å, illustrating the $\cos\phi$ dependence produced by exchange anisotropy. The parallel field plotted in the main figure is the mean value of the in-plane resonance.

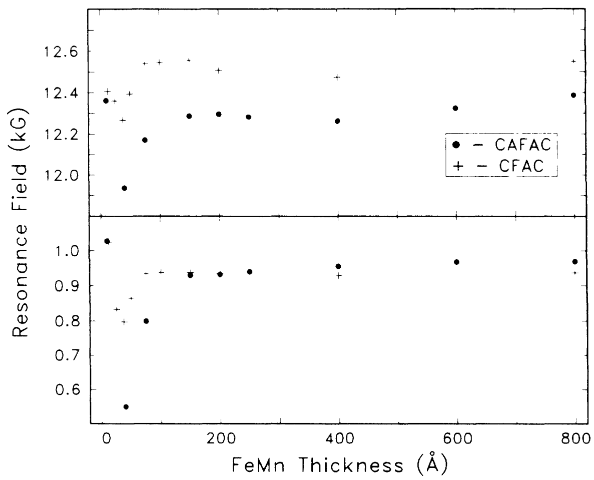

FIG. 3. Perpendicular (upper) and parallel (lower) resonance fields for the CAFAC and CFAC structures as a function of FeMn layer thickness. The Permalloy layer thickness is 60 Å.

shown in the inset. Data of this type were fit, for each film, to an equation of the form

$$H_{\parallel}=H_{\parallel}^{(0)}+H_{\parallel}^{(1)}\cos\phi+H_{\parallel}^{(2)}\cos2\phi \ . \tag{7}$$

The second term is of the form predicted by Eq. (4), and the last term corresponds to the usual uniaxially anisotropy of Permalloy. There may also be a contribution of the same form as the last term from misalignment of the sample (i.e., H moves in and out of the plane of the sample as the sample is rotated). Also, in the case that H_B is comparable in magnitude to $H_{\parallel}$, the magnetization is not aligned with the applied field, and a $\cos2\phi$ contribution appears. Both $H_{\parallel}^{(0)}$ and $H_{\perp}$ vary with the thickness of the Permalloy layer. This variation can arise, in principle, from variations in gyromagnetic ratio, magnetization, or from a surface anisotropy, and is analyzed in detail in Sec. IV.

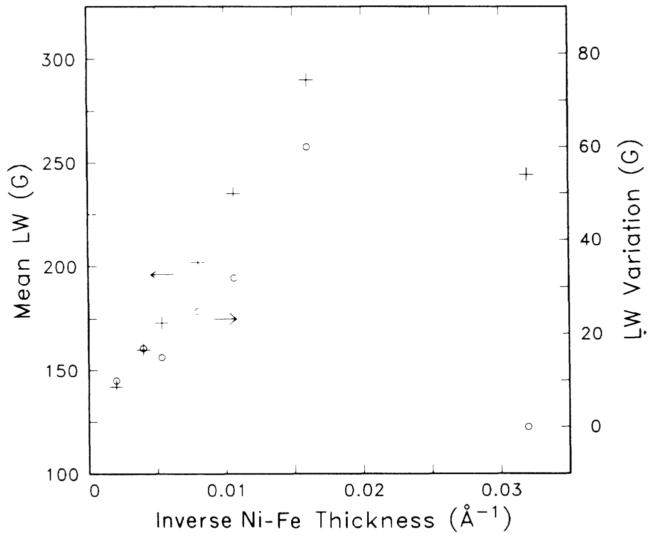

FIG. 5. Mean peak-to-peak FMR linewidth and its in-plane azimuthal variation as a function of t_F^{-1}. Data are shown for the CFAC sequence of samples, measured at Q band.

Figure 3 shows the behavior of the parallel and perpendicular resonance fields as a function of the thickness of the A layer. Note, in particular, the difference in the perpendicular resonance field between the CFAC and CAFAC samples. As we will show in more detail below, this difference is due to a surface-anisotropy-induced exchange shift [in addition to that described by Eq. (4)] which correlates with the bias field.

Linewidth data are shown in Figs. 4 and 5. The behav-

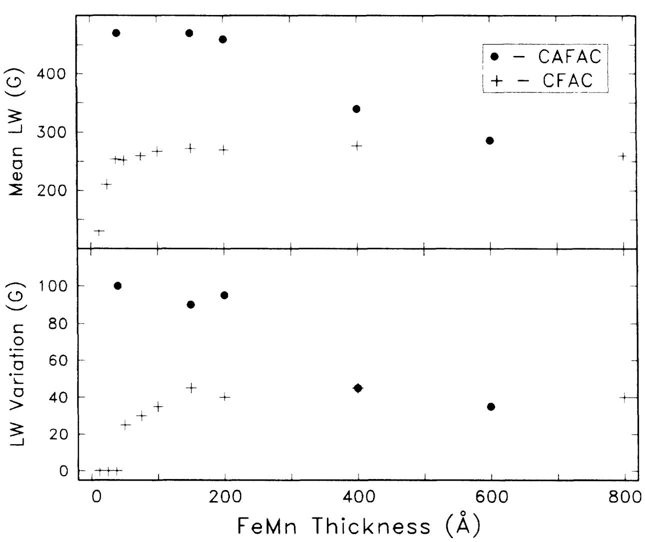

FIG. 4. FMR linewidth (LW) for the in-plane resonance measured at Q band. The upper plot shows the mean value and the lower plot the azimuthal variation of the peak-to-peak linewidth, as a function of FeMn layer thickness.

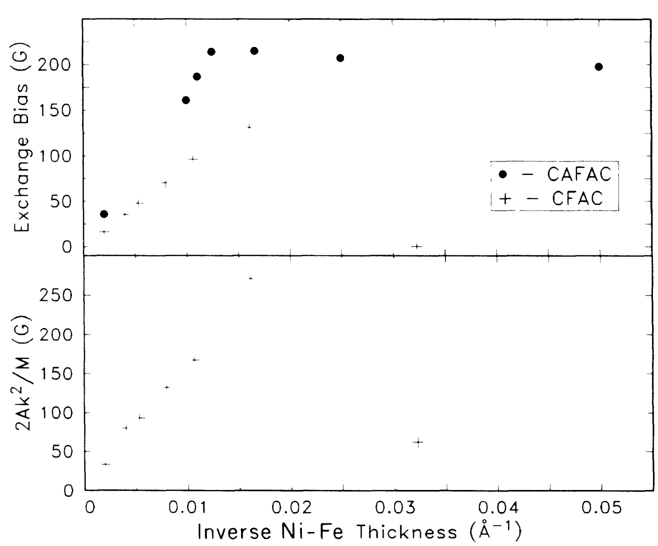

FIG. 6. The exchange-bias field, as determined by the coefficient of the $\cos\phi$ term in the azimuthal dependence of the resonance field, and the additional exchange shift as a function of t_F^{-1}.

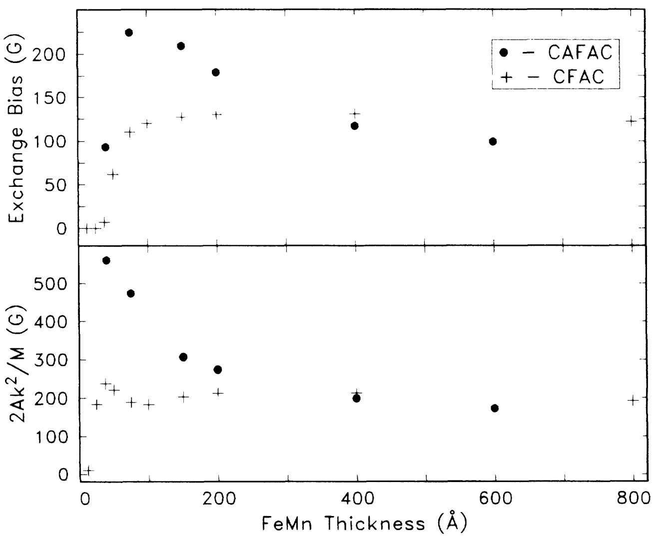

FIG. 7. The exchange-bias field, as determined by the coefficient of the cosϕ term in the azimuthal dependence of the resonance field, and the additional exchange shift as a function of FeMn layer thickness.

ior with both A and F layer thickness is very similar to that shown by the bias field (see Figs. 6 and 7). In addition to the t_F^{-1} dependence of the mean linewidth shown by Speriosu *et al.*[10] we find a similar dependence of the amplitude of the linewidth variation. Both the linewidth and its azimuthal variation mirror the bias field dependence on A and F thickness, implying that exchange anisotropy is a line-broadening mechanism.

IV. ANALYSIS AND DISCUSSION

The condition for perpendicular FMR in thin films is given by

$$\omega/\gamma = H - 4\pi M + (2A/M)k^2 , \tag{8}$$

where M is the saturation magnetization, γ is the gyromagnetic ratio, and A is the spin-wave stiffness. When the field is in the plane of the film, the resonance condition is

$$\omega/\gamma = \{[H + (2A/M)k^2][H - 4\pi M + (2A/M)k^2]\}^{1/2} . \tag{9}$$

Note that these equations depend on the assumption that M, γ, and A are uniform throughout the film.

Using the expression given by Speriosu *et al.*[10] for the pinning due to a unidirectional surface anisotropy [see Eq. (3) above], we obtain an expression for the azimuthal dependence of the in-plane resonance,

$$H_\parallel = [(\omega/\gamma)^2 + (2\pi M)^2]^{1/2} - 2\pi M - (K_{AF}/Mt_F)\cos\phi - (2A/M)k^2 , \tag{10}$$

where now the last term accounts for any surface pinning mechanisms other than the exchange anisotropy energy.

The azimuthal dependence of the in-plane resonance gives immediately the bias field via Eq. (2). This quantity is plotted in Fig. 6, as a function of the inverse ferromagnetic film thickness, and in Fig. 7, versus the antiferromagnetic film thickness. Figure 6 shows clearly that Eq. (2) holds for $t_F \gtrsim 60$ Å. Moreover, the effect of two interfaces in the trilayer CAFAC series is seen to increase the exchange bias field from that of a single interface. This is a somewhat surprising result, since, for the lower A layer, which grows in the absence of the saturated ferromagnet, one might not expect any net exchange across the A-F interface within the simple model outlined above for the establishment of the exchange field. It is, however, consistent with previous work on Permalloy–iron-manganese film systems by Tsang *et al.*[5] who observed substantial exchange in an A-F bilayer film couple.

Figure 7 shows that the bias film produced by the lower A layer depends sensitively on its thickness, in contrast to the upper A layer. The bilayer series, CFAC, which only has an A layer deposited on top, shows a bias field essentially independent of t_A for thicknesses greater than about 100 Å. The trilayer films, on the other hand, show a pronounced maximum near 100 Å. Indeed, if one assumes that the contributions of the two interfaces are additive, then the lower A film produces no additional bias field for thicknesses greater than about 500 Å, and its effect at 75 Å is equal to that of the upper film.

Figure 7 also shows a rapid drop-off in bias field when the A layer thickness is reduced below about 80 Å. This effect was previously reported by Parkin *et al.*[9] and Mauri *et al.*[11] Mauri *et al.* suggested this drop-off arose when the anisotropy energy per unit area of the A layer fell below the interfacial exchange energy per unit area as the A thickness was decreased. More recent detailed measurements of the azimuthal dependence of the torque on A thickness are not consistent with this interpretation.[15] An alternative model to account for this behavior has recently been proposed.[16]

With the azimuthal dependence of the in-plane field evaluated, Eqs. (8) and (10) now contain the three unknowns: M, γ, and Ak^2. The determination of each of these thus requires an additional measurement. We initially tried to measure the magnetization directly using a SQUID magnetometer, but found that, although the sensitivity of the instrument is sufficiently high, the errors in correcting for substrates and sample holders were too large. Therefore, we performed Q-band (34 GHz) FMR measurements in parallel orientation, as a third measurement for selected samples. The perpendicular resonance, which would have given a consistency check on the data, was not observable at the maximum magnetic field available.

The results of the analysis for M, γ, and Ak^2 are presented in Figs. 6 through 9. Figures 8 and 9 depict the variation of the magnetization and gyromagnetic ratio with the thickness of the ferromagnetic and antiferromagnetic layers, respectively. M varies by less than 10% and γ by less than 0.5% for ferromagnetic film thicknesses greater than 50 Å. With the F layer thickness fixed at 60 Å the variation with t_A is similarly weak. These results can be used to estimate the thickness of the interfacial region. First, from Fig. 8, we determine that the bulk magnetization of the Permalloy used in our ex-

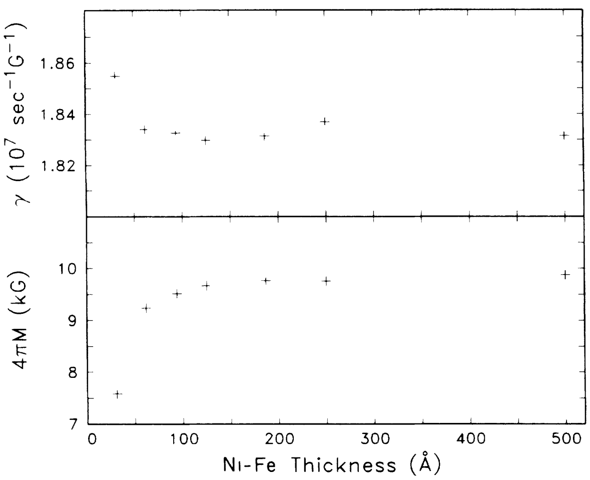

FIG. 8. The gyromagnetic ratio and saturation magnetization of the Permalloy layer as a function of its thickness for the CFAC series of samples with FeMn layer thickness of 150 Å.

periments is $4\pi M = 9.8$ kG. Next, in Fig. 9 we see that the effect of an A interface is to depress the average magnetization, and that two interfaces are roughly twice as effective as one (9.2 and 9.5 kG, respectively). Hence we conclude that the magnetization in the Permalloy layer is reduced near the antiferromagnetic interface. Assuming, for simplicity, a magnetization profile which varies linearly from zero at the nominal interface to the bulk value over a distance l, then the measured average magnetization will be $4\pi M(1-l/2t_F)$ for a single A interface. Thus the measured 10% drop in M at 50 Å thickness implies that $l = 10$ Å, or 3–4 atomic layers. We emphasize that this analysis is model dependent, and we present it only as an illustration of the sharpness of the interface. The result is in agreement with the conclusion of a previous study.[10]

The third parameter which is necessary to reconcile, and can be extracted from, the X- and Q-band data is an "exchange shift" $2Ak^2/M$ (not to be confused with the bias field) which is found (see Fig. 6) to be inversely proportional to t_F. Hence, like the exchange anisotropy, it is an interfacial effect and indeed, as comparison of the upper and lower parts of Figs. 6 and 7 shows, correlates closely with the bias field—even to the extent that it is markedly reduced in the thinnest F sample where the bias field vanishes.

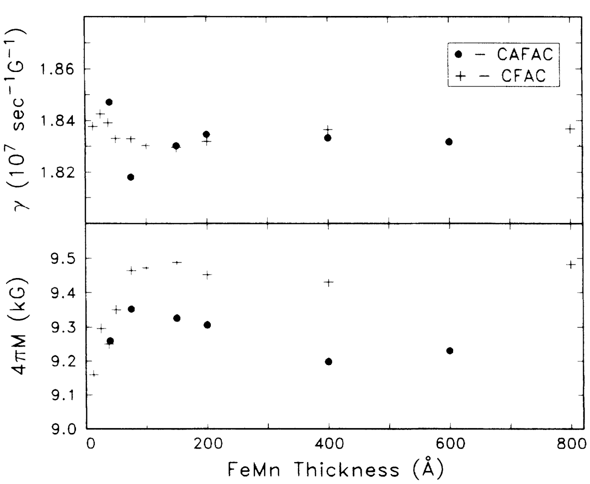

FIG. 9. The gyromagnetic ratio and saturation magnetization of the Permalloy layer ($t_F = 60$ Å) as a function of the thickness of the FeMn layer(s).

The traditional explanation of this type of spin-wave exchange shift of the FMR mode is that it arises from surface anisotropy, which results in "partial pinning" of the rf magnetization at the interfaces.[17] In this case we believe that the origin of the perpendicular anisotropy is the exchange interaction between the ferromagnets and antiferromagnets. The easy directions of FeMn are the [111] cube diagonals, hence in the preferred [111] growth texture of our samples the A easy axes are not in the plane of the interface. Thus the same exchange interaction which gives rise to the bias field will tend to tilt the interfacial ferromagnetic moments.

The same mechanism also accounts for the reduction of magnetization near the interface, described above. The interfacial F moments are tilted away from the direction of mean magnetization, in a random fashion depending on the local A domain orientation, thereby reducing the average magnetization.

The exchange bias produced by an A layer deposited before the F layer can be understood in terms of a model in which the antiferromagnetic domain pattern is not locked rigidly to the lattice as conventionally assumed. (We can quickly discount the trivial explanation that during deposition the A layer was heated above its Néel temperature—for films of the thickness discussed here, surface heating is of order 1 K or less.) When the F layer is deposited and magnetized, the A layer can reduce the interfacial exchange energy by rearranging its domain wall structure into a new (meta) stable minimum. Reversal of the F magnetization will not necessarily be accompanied by reversal of the same set of A domains, leading to a different local minimum in the total energy and hence to a bias field. Such a mechanism also explains the field-"training" effect seen in cyclic hysteresis studies:[2,7] As the F magnetization is successively reversed, the A domain pattern finds new metastable minima, until kinetic effects (for example, the absence of any more mobile domain walls) prevent it from finding any lower energy state. Malozemoff[13] has discussed the importance of the antiferromagnetic domain pattern in determining the overall magnitude and temperature dependence of the exchange bias.

The existence of a (nearly) random A domain pattern explains the FMR linewidth, its anisotropy, and their correlation with the bias field. Each A domain exerts a field on the ferromagnet differing in orientation, but since the ferromagnetic coherence length is larger than that of the antiferromagnet, these tend to average out (to the bias field), and their effect remains only as a line-broadening mechanism. As the F magnetization rotates in the plane of the film, the distribution of local fields changes and the angular variation of the root-mean-square fluctuation exhibits a $\cos\phi$ dependence.

Specifically, consider the following simple model of the domain pattern: two possible orientations of the A sublattice magnetization, with atomically abrupt domain walls, and a characteristic size $\xi_A = \pi a\sqrt{J_A/K_A}$. This is clearly an oversimplification of the actual domain structure inherent to the NiFe/FeMn system with its [111] texture, but contains all of the essential physics and serves to illustrate how bias and linewidth anisotropy arise. Let the areal fraction of domains aligned parallel to the bias direction be $(1+\eta)/2$, those antiparallel be $(1-\eta)/2$. If the local exchange field acting on F along the A sublattice direction is H_E, then this distribution leads to an average field $H_{av} = \eta H_E \cos\phi$, i.e., the bias field is $H_B = \eta H_E$. The coherence length in the ferromagnet is $\xi_F \simeq \pi a\sqrt{J_F/K_F}$. Then there are $N = (\xi_F/\xi_A)^2$ A domains within each region where the F magnetization is reasonably uniform. The root-mean-square fluctuation of the field within this region, i.e., the FMR linewidth, is thus

$$\Delta H = \frac{1}{\sqrt{N}} H_E \cos\phi(1-2\eta^2) \simeq \frac{\xi_F}{\xi_A}\frac{H_B}{\eta}\cos\phi \ . \qquad (11)$$

Qualitatively this description has all the features observed in the data: namely, a bias field reduced relative to that expected from the strength of the interfacial exchange interaction, and a linewidth which scales with the bias and is anisotropic. The linewidth anisotropy is, however, overestimated and will be reduced by any angular spread in the domain pattern to the form of $(H_E/\sqrt{N})(1+b\cos\phi)$, where $b<1$ and depends on the details of the domain structure.

In order to fit the data quantitatively, and taking $J_{AF} \simeq 30$ meV as in Sec. I, we must have $\eta \sim 10^{-2}$. Unfortunately, we know of no independent measurement which might give a check on η and so help validate this model. The coherence lengths are $\xi_A \simeq 300$ Å and $\xi_F \simeq 2000$ Å, yielding linewidth estimates of order a kilogauss for the thinnest films measured. This is somewhat larger than observed because of the unrealistic domain pattern used in the calculation.

Thus, the picture of antiferromagnetic domains, which can relax by slight motion of the domain walls to find a local energy minimum slightly biased in directional distribution, yields semiquantitative agreement with experiment. Detailed comparison will require a more exact mathematical treatment of the model than the crude simplification presented here.

V. SUMMARY

The present study extends previous work on the Permalloy–iron-manganese film system and confirms the complex but intriguing properties associated with the interfacial exchange coupling. An important conclusion from our results is that the interface is relatively sharp, on the scale of a few atomic layers. Such a conclusion is supported by the weak dependence of the saturation magnetization and gyromagnetic ratio on ferromagnetic film thickness and by the proportionality of exchange bias field on inverse t_F for F thicknesses at least as small as 60 Å.

It has been shown that the magnetization is reduced in the ferromagnet near the interface, perhaps due to the fact that the antiferromagnetic easy axes do not lie in the plane of the interface. A semiquantitative estimate of the distance over which this suppression occurs yields about 10 Å or 2–4 atomic layers. Studies on multilayered F-A films indeed show that the exchange bias field satisfies the $H_B \propto 1/t_F$ relationship for t_F values as low as 25 Å below which the exchange bias field gradually falls to zero for t_F of order 10 Å.[18]

Our data show the azimuthal variation of in-plane resonance seen previously and discussed by Speriosu *et al.*[10] This is a direct consequence of interfacial exchange anisotropy giving rise to surface pinning, and can be used to determine the exchange bias field. Further analysis shows that there is an additional pinning of the FMR mode, leading to an exchange shift which scales with inverse F layer thickness. We suggest that this shift is due to a surface anisotropy induced by exchange with the A moments which have a component perpendicular to the interface. Since this is an interfacial effect, it leads to a t_F^{-1} dependence, and, in addition, since, like the exchange bias, it requires that the antiferromagnetization be at least partially locked, it correlates closely with the bias field.

Lastly, we have discussed our data in terms of phenomenological model for the exchange bias behavior in which there is a metastable antiferromagnetic domain pattern, with at least some of the A domain walls free to move in response to changes in the F magnetization. Such a picture is required in order to account for the observation that a bias field results from antiferromagnetic layers deposited *before* the ferromagnet. The effect has a threshold at $t_A \simeq 40$ Å, below which the entire A layer reorients in response to each reversal of F magnetization, and decreases to zero at a thickness $t_A \lesssim 400$ Å, where the A magnetization is virtually completely locked. A partially mobile A domain pattern also explains the "training" effect observed in cyclic hysteresis measurements. The hysteresis loop changes on each successive cycle because the domain structure passes through a succession of metastable states, until eventually kinetic barriers prevent any further rearrangement.

The FMR linewidth data can also be understood in terms of a mosaic of antiferromagnetic domains. Each domain exerts a local field on the ferromagnet, but since the F coherence length is much larger than the A coherence length, these fluctuations are effectively averaged out to leave a moderate linewidth and anisotropy, both of which scale with the bias field.

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