Ferromagnetic resonance investigation of the residual coupling in spin-valve systems

R. L. Rodríguez-Suárez, S. M. Rezende, and A. Azevedo*
Departamento de Física, Universidade Federal de Pernambuco, Recife PE 50670-901, Brazil

(Received 20 October 2004; revised manuscript received 14 December 2004; published 2 June 2005)

The ferromagnetic resonance (FMR) technique has been used to investigate the properties of spin-valve systems. We derive the FMR dispersion relation taking into account the competition that appears between the direct exchange bias coupling and the indirect interlayer coupling. For uncoupled ferromagnetic (FM) layers, the system exhibits a dispersion relation corresponding to two independent systems: a single FM layer (free layer) and an exchange-coupled bilayer (reference/antiferromagnetic layers). In the interlayer coupled regime a unidirectional anisotropy is induced in the free layer and the FMR field is overall downshifted. Both features are observed experimentally and the results are compared with the model.

DOI: 10.1103/PhysRevB.71.224406 PACS number(s): 76.50.+g, 75.30.Ds, 75.70.−i, 75.75.+a

I. INTRODUCTION

Magnetic spin valves[1] have been widely investigated since the discovery of their magnetic properties and the realization of their potential applications as magnetoresistive sensor in magnetic read/write heads of storage devices[2] and in magnetoresistive random access memories (MRAMs). The basic scheme of a spin valve is shown in Fig. 1. It consists of two ferromagnetic (FM) metal layers separated by a thin nonmagnetic metal film, with one of the magnetic layers being in atomic contact with a thick antiferromagnetic (AF) layer. The first FM film, the reference layer, has the direction of its magnetization set in a fixed direction by the exchange bias coupling with the AF layer. The magnetization of the other FM layer is free to rotate in response to an in-plane external magnetic field. The operation point of a spin-valve sensor depends directly on the magnetic coupling between the two FM layers.[2] The interlayer magnetic coupling can be expressed as a superposition of different mechanisms. One of them, Neel's orange-peel coupling, is of magnetostatic nature, is highly dependent on the interface roughness, and favors a ferromagnetic alignment.[3] The other mechanism—the interlayer exchange coupling—is due to the indirect exchange interaction between the magnetizations of the two ferromagnetic films across a nonmagnetic metal layer.[4] This coupling can favor parallel (ferromagnetic), antiparallel (antiferromagnetic), or 90° (biquadratic) alignment, depending on the thickness and chemical nature of the spacer layer. The magnetization direction of the reference layer is fixed by the exchange anisotropy, which arises from the direct coupling with the antiferromagnetic surface,[5] is relatively insensitive to moderate magnetic fields. In order to avoid the detrimental coupling between both FM layers, the spacer layer must be sufficiently thick. Since the total thickness of a spin valve sensor for 100 Gbit/in.[2] application is on the order of 600 Å, there is a limitation in the spacer layer thickness. Thus, there is a significant issue concerning the magnitude of the effective magnetic coupling between the reference and the free layers. Ferromagnetic resonance (FMR) has been shown to be the most successful technique to determine the values of the effective fields associated with the couplings between the various layers in magnetic multilayer systems.[6,7]

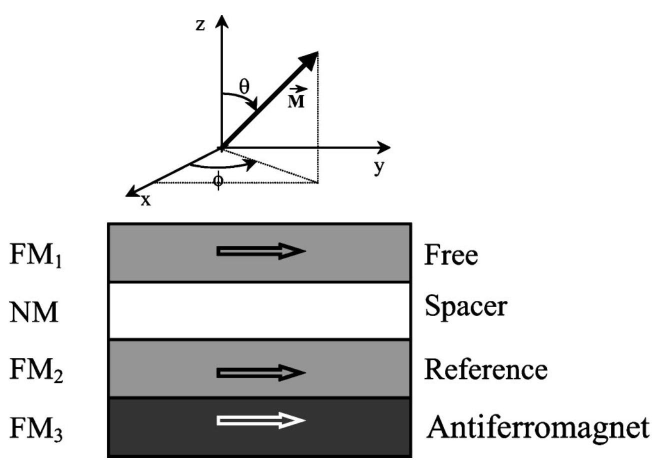

FIG. 1. Schematic view of the spin valve system and the coordinate system used in the ferromagnetic resonance analysis. In order not to overwhelm the figure, the vectors for the magnetizations and the magnetic field are not shown. The white arrow in the antiferromagnetic layer corresponds to the magnetization for one of the AF sublattices.

In this paper we investigate the competition between the exchange-bias coupling and the interlayer exchange coupling, in spin-valve systems, from both the theoretical and experimental point of views. We present a calculation of the spin wave dispersion relation in these systems that can be used to interpret the in-plane ferromagnetic resonance field dependence. The calculation takes into account an in-plane static magnetic field, the demagnetization fields and the uniaxial anisotropies of both FM layers, the bilinear interlayer exchange interaction between the FM films, the exchange-bias coupling between the reference and the AF layers, and the domain wall energy of the AF as described in the model proposed by Maury *et al.*[8]

In the following sections we describe the theoretical model used to calculate the FMR spin wave dispersion relation in spin valves and also show the experimental measurements. In Sec. IV we interpret the results emphasizing the influence of the exchange anisotropy together with the interlayer exchange coupling in the FMR spectra.

II. MODEL

We consider three coupled magnetic layers denoted by FM_1 (free layer), FM_2 (reference or pinned layer), and AF_3 (antiferromagnetic), which are schematically shown in Fig. 1. The magnetization vectors for the three layers are given by $\vec{M}_1$, $\vec{M}_2$, $\vec{M}_3$ ($\vec{M}_3$ is the magnetization for one of the AF sublattices in atomic contact with FM_2) and the thicknesses are t_1, t_2, and t_3, respectively. The magnetization direction of the reference layer is defined by means of the direct exchange coupling with the antiferromagnetic layer. The free layer is separated from the reference layer by a nonmagnetic metallic spacer of thickness d. The magnetic free energy per unit area of the entire structure can be written as

$$E = E_{FM} + E_{EA} + E_{EX}, \tag{1}$$

where the first term represents the free energy of the ferromagnetic films, the second term represents the contribution of the direct exchange coupling at the FM_2/AF_3 interface including the AF domain wall energy, and the last term represents the interlayer exchange coupling between the free and the pinned layers. Assuming the coordinate system shown in Fig. 1, the equilibrium positions of $\vec{M}_1$, $\vec{M}_2$, and $\vec{M}_3$, given by the polar (θ_1, θ_2, and θ_3) and azimuthal (ϕ_1, ϕ_2, and ϕ_3) angles, can be calculated by minimizing the free energy described in Eq. (1). Following the Smit and Beljers scheme,[9,10] the dispersion relation of the spin valve system described above, can be calculated as the roots of the determinant of the following 6×6 matrix:

$$\begin{bmatrix} E_{\phi_2\phi_2} & E_{\phi_2\theta_2}-iz_2 & E_{\phi_2\phi_3} & E_{\phi_2\theta_3} & E_{\phi_2\phi_1} & E_{\phi_2\theta_1} \\ E_{\phi_2\theta_2}+iz_2 & E_{\theta_2\theta_2} & E_{\theta_2\phi_3} & E_{\theta_2\theta_3} & E_{\theta_2\phi_1} & E_{\theta_2\theta_1} \\ E_{\phi_2\phi_3} & E_{\theta_2\phi_3} & E_{\phi_3\phi_3} & E_{\phi_3\theta_3}-iz_3 & E_{\phi_3\phi_1} & E_{\phi_3\theta_1} \\ E_{\phi_2\theta_3} & E_{\theta_2\theta_3} & E_{\phi_3\theta_3}+iz_3 & E_{\theta_3\theta_3} & E_{\theta_3\phi_1} & E_{\theta_3\theta_1} \\ E_{\phi_2\phi_1} & E_{\theta_2\phi_1} & E_{\phi_3\phi_1} & E_{\theta_3\phi_1} & E_{\phi_1\phi_1} & E_{\phi_1\theta_1}-iz_1 \\ E_{\phi_2\theta_1} & E_{\theta_2\theta_1} & E_{\phi_3\theta_1} & E_{\theta_3\theta_1} & E_{\phi_1\theta_1}+iz_1 & E_{\theta_1\theta_1} \end{bmatrix}, \tag{2}$$

where each element E_{ij} denotes the second derivative of the free energy with respect to the equilibrium angles θ_i and ϕ_i, $z_i=(\omega/\gamma_i)t_iM_i\sin(\theta_i)$ and γ_i ($i=1,2,3$) are the gyromagnetic ratios for the magnetization of each layer.

The first term in Eq. (1) can be written as follows:

$$E_{FM} = -\vec{H}_0\cdot(\vec{M}_1+\vec{M}_2) + \left[2\pi(\vec{M}_1\cdot\hat{n})^2 - K_{u1}\left(\frac{\vec{M}_1\cdot\hat{u}}{M_1}\right)^2\right]t_1 + \left[2\pi(\vec{M}_2\cdot\hat{n})^2 - K_{u2}\left(\frac{\vec{M}_2\cdot\hat{u}}{M_2}\right)^2\right]t_2. \tag{3}$$

where the first term represents the interaction of the magnetizations of the two FM layers with the external dc field $\vec{H}_0$, and the terms in the square brackets represent the demagnetization and the uniaxial anisotropy energies for the free and the reference layers, respectively. The corresponding uniaxial anisotropy fields are $H_{u1}=2K_{u1}/M_1$ and $H_{u2}=2K_{u2}/M_2$, where K_{u1} and K_{u2} are the uniaxial anisotropy constants for the both FM layers. We assume that the uniaxial anisotropy fields of the FM layer points parallel to $\hat{u}$ and the film normal points along $\hat{n}$, and t_1 and t_2 are the thicknesses of the FM layers. We also assume that the cubic magnetocrystalline anisotropy of the Permalloy films is negligible and the surface anisotropy contribution is incorporated into the demagnetization energy term.

The second term in Eq. (1) corresponds to the contribution for the free energy of the interface between the FM_2 and the AF_3 layers. It can be written as follows:

$$E_{EA} = -\frac{J_E\vec{M}_2\cdot\vec{M}_3}{(M_2M_3)} - \frac{\sigma_W\vec{M}_3\cdot\hat{u}}{M_3}, \tag{4}$$

where the first term is the exchange-bias energy with the macroscopic coupling constant J_E, and the effective field associated to the exchange coupling is defined as $H_E=J_E/(t_2M_2)$. Here we assume that AF layer has the same anisotropy axes as defined by the unit vector $\hat{u}$, so that exchange energy is proportional to the difference of the in-plane magnetization angles, ϕ_1 and ϕ_3. The second term stands for the energy due to the planar domain wall at the AF layer, where $\sigma_W=2\sqrt{A_{AF}K_{AF}}$ is the energy per unit surface of a 90° domain wall in the AF layer and is associated with the effective domain wall field $H_W=\sigma_W/M_2t_2$.

The last term in Eq. (1), corresponding to the interlayer exchange coupling between the free and the reference layers, can be phenomenologically written as follows:

$$E_{EX} = -\frac{J_{bl}\vec{M}_1\cdot\vec{M}_2}{(M_1M_2)} - J_{bq}\left[\frac{\vec{M}_1\cdot\vec{M}_2}{(M_1M_2)}\right]^2, \tag{5}$$

where the parameters J_{bl} (bilinear) and J_{bq} (biquadratic) describe the nature and the strength of the coupling. If the term with J_{bl} dominates, then the coupling is ferro (antiferro)-

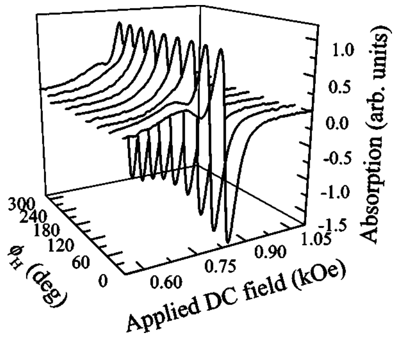

FIG. 2. Ferromagnetic resonance absorption spectra for an IrMn/Py/Cu/Py spin valve system as a function of the in-plane angle. The absorption modes corresponding to the free (intense peak) and reference (weak peak) layers are shown. The linewidths and ferromagnetic resonance field values were extracted from the spectra using a double-Lorentzian curve-fitting procedure.

magnetic for positive (negative) J_{bl}. If the term with J_{bq} dominates and is negative, the 90° coupling will prevail. In this paper we will neglect the biquadratic contribution. The effective interlayer exchange field acting on each individual layer is defined as $H_{bl}=J_{bl}/(t_{FM}M_{FM})$, where t_{FM} and M_{FM} are the FM layer thickness and the FM spontaneous magnetization, respectively.

III. EXPERIMENTS

We have investigated two samples of $Ir_{20}Mn_{80}(125\ Å)/Ni_{81}Fe_{19}(100\ Å)/Cu(d)/Ni_{81}Fe_{19}(100\ Å)$, with $d=60$ and 168 Å. The films of Permalloy (Py) and Cu were dc sputtered at room temperature in a pure argon atmosphere of 3.0×10^{-3} Torr. The base pressure before depositing was typically 1.5×10^{-7} Torr and the substrate were commercial electronic grade Si(001) wafers. To get reasonable exchange-bias field, the IrMn layers were deposited in an argon sputtering pressure of around 8.0×10^{-3} Torr.[11] The ferromagnetic resonance data were obtained with a home-built X-band spectrometer operating at 8.61 GHz, with the sample mounted on the tip of an external goniometer to allow measurement of the in-plane resonance field H_R as a function of the azimuthal angle. The dc magnetic field was provided by a 9 in. electromagnet and was modulated with a 1.2 kHz ac component of a few oersteds using a pair of Helmholtz coils. To improve the measurement of the FMR field and the linewidth values, the experimental absorption lines were numerically adjusted to double Lorentzian functions.

Figure 2 shows the FMR spectra of the spin-valve $IrMn/Ni_{81}Fe_{19}/Cu(168\ Å)/Ni_{81}Fe_{19}$ as a function of the in-plane angle. In this sample the thickness of the Cu layer was chosen large enough to assure that the magnetization of the Py layers is not coupled. The spectra exhibit one intense absorption peak located around $H_0=0.86$ kOe, with a value that changes slightly with the azimuthal angle ϕ_H. This intense peak corresponds to the uniform mode of resonance of the free layer magnetization and indicates a very small uniaxial anisotropy field. Additionally, there is a small absorption peak corresponding to the uniform mode of precession of the reference layer magnetization. This absorption mode exhibits resonance field values that change as a function of the azimuthal angle, revealing a unidirectional anisotropy symmetry. An interlayer coupling between the two FM films is detected for the sample of thinner spacer layer and the angular dependences of the resonance fields change considerably. Before showing the data for the other sample the dependence of the two peak positions on the in-plane angle will be interpreted in Sec. IV

IV. RESULTS AND DISCUSSION

In this section, we present the derivation of the spin-wave dispersion relation of the spin-valve structure, which is used to interpret the FMR data. We consider that the dc magnetic field is applied in the plane of the films, with the direction characterized by an azimuthal angle ϕ_H with the easy axis direction. We also consider that $\gamma_1=\gamma_2=\gamma$ and all the magnetizations are parallel to the plane of the sample, i.e., $\theta_H=\theta_1=\theta_2=\theta_3=\pi/2$. The FMR dispersion relation, derived from the determinant of Eq. (2), can be written as a function of the second derivatives of the energy as

$$\left(\frac{\omega^4}{\gamma^4}\right) - \left(\frac{\omega^2}{\gamma^2}\right)\left[\left(E_{\phi2\phi2} - \frac{E^2_{\phi2\phi3}}{E_{\phi3\phi3}}\right)\left(E_{\theta2\theta2} - \frac{E^2_{\theta2\theta3}}{E_{\theta3\theta3}}\right)\right]\frac{1}{(t_2M_2)^2} - \left(\frac{\omega^2}{\gamma^2}\right)\left(2E_{\phi2\phi1}E_{\theta2\theta1}\frac{1}{t_2M_2t_1M_1} + E_{\phi1\phi1}E_{\theta1\theta1}\frac{1}{(t_1M_1)^2}\right) + \left[E^2_{\theta2\theta1} - E_{\theta1\theta1}\left(E_{\theta2\theta2} - \frac{E^2_{\theta2\theta3}}{E_{\theta3\theta3}}\right)\right]\left[E^2_{\phi2\phi1} - E_{\phi1\phi1} \times\left(E_{\phi2\phi2} - \frac{E^2_{\phi2\phi3}}{E_{\phi3\phi3}}\right)\right]\frac{1}{(t_2M_2t_1M_1)^2} = 0. \quad (6)$$

In order to check the validity of Eq. (6), it is easy to analyze the situation in which the FM layers exhibit no coupling (i.e., $H_{bl}=0$) and $E_{\phi2\phi1}=E_{\theta2\theta1}=0$. It means that one of the real roots of Eq. (6) will describe the spin wave dispersion relation of a FM/AF exchange coupled system[10]

$$\left(\frac{\omega^2}{\gamma^2}\right) = \left[\left(E_{\phi2\phi2} - \frac{E^2_{\phi2\phi3}}{E_{\phi3\phi3}}\right)\left(E_{\theta2\theta2} - \frac{E^2_{\theta2\theta3}}{E_{\theta3\theta3}}\right)\right]\frac{1}{(t_2M_2)^2}. \quad (7)$$

The other root will correspond to the dispersion relation of a single ferromagnetic film[9]

$$\left(\frac{\omega^2}{\gamma^2}\right) = E_{\phi1\phi1}E_{\theta1\theta1}\frac{1}{(t_1M_1)^2}. \quad (8)$$

Remember that in this case $E_{\theta1\phi1}=0$ because $\theta_1=\theta_H=\pi/2$.

Considering $t_1=t_2=t$, the spin wave dispersion relation given by Eq. (6) can be explicitly written as a function of the applied field as

$$\left(\frac{\omega^4}{\gamma^4}\right) - \left(\frac{\omega^2}{\gamma^2}\right)A(H) + B(H) = 0, \quad (9)$$

where

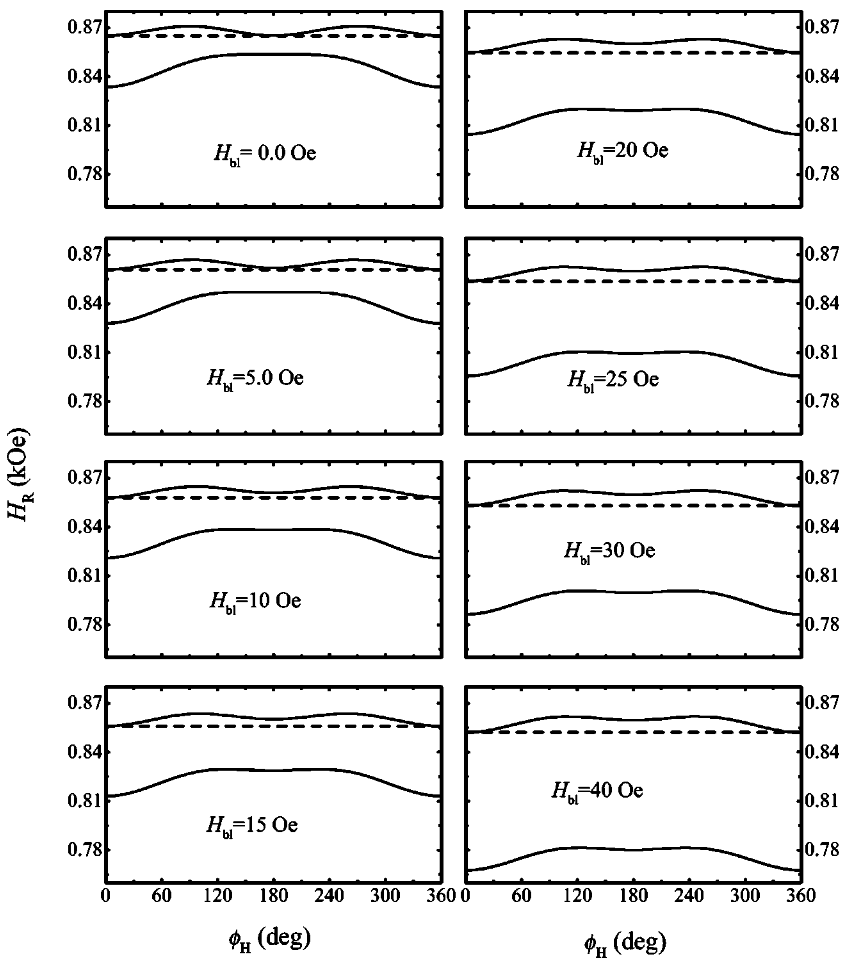

FIG. 3. Calculated angular dependence of the FMR field for the spin valve system for several values of the bilinear interlayer coupling. As the H_{bl} value increases a unidirectional anisotropy sets up at the free layer and an overall downshift field occurs in agreement with the experimental data. The phenomenological parameters used in the numerical analysis were: $H_{u1}=H_{u2}=3.0$ Oe, $4\pi M_1=10$ kOe, $4\pi M_2=10.3$ kOe, and $H_{E(2,3)}=0.010$ kOe.

$$A(H)=[H\cos(\phi_2-\phi_H)+a_1][H\cos(\phi_2-\phi_H)+a_2]+[H\cos(\phi_1-\phi_H)+a_3][H\cos(\phi_1-\phi_H)+a_4]+2\frac{M_1}{M_2}H_{\mathrm{bl}}^2\cos(\phi_1-\phi_H) \quad (10)$$

$$B(H)=\left\{\frac{M_1}{M_2}H_{\mathrm{bl}}^2-[H\cos(\phi_1-\phi_H)+a_4]\times[H\cos(\phi_2-\phi_H)+a_1]\right\}\times\left\{\frac{M_1}{M_2}H_{\mathrm{bl}}^2\cos^2(\phi_1-\phi_2)-[H\cos(\phi_1-\phi_H)+a_3]\times[H\cos(\phi_2-\phi_H)+a_2]\right\} \quad (11)$$

and

$$a_1=4\pi M_2+H_{U2}\cos^2\phi_2+H_1^{eff} \quad (12)$$

$$a_2=H_{U2}\cos 2\phi_2+H_2^{eff} \quad (13)$$

$$a_3=H_{U1}\cos 2\phi_1+H_{\mathrm{bl}}\cos(\phi_1-\phi_2) \quad (14)$$

$$a_4=4\pi M_1+H_{U1}\cos^2\phi_1+H_{\mathrm{bl}}\cos(\phi_1-\phi_2). \quad (15)$$

Here H_1^{eff} and H_2^{eff} are given by

$$H_1^{eff}=\frac{M_1}{M_2}H_{\mathrm{bl}}\cos(\phi_1-\phi_2)+\frac{H_W\cos\phi_3\cos(\phi_2-\phi_3)-H_E\mathrm{sen}^2(\phi_2-\phi_3)}{\frac{H_W}{H_E}\cos\phi_3+\cos(\phi_2-\phi_3)} \quad (16)$$

$$H_2^{eff}=\frac{M_1}{M_2}H_{\mathrm{bl}}\cos(\phi_1-\phi_2)+\frac{H_W\cos\phi_3\cos(\phi_2-\phi_3)}{\frac{H_W}{H_E}\cos\phi_3+\cos(\phi_2-\phi_3)}. \quad (17)$$

Notice that by making $H_{\mathrm{bl}}=0$, Eqs. (16) and (17) will be equivalent to the expressions obtained by Geshev *et al.*[10] for an exchange-coupled bilayer system. It is also easily shown that the dispersion relation obtained above [Eq. (6)] will reduce to Eq. (3) of Ref. 10, in the limit of H_{bl} null.

Figure 3 shows numerical simulation of the FMR field as a function of the azimuthal angle, given by Eq. (9), for various values of the interlayer bilinear-coupling field. The phenomenological parameters used in the numerical analysis

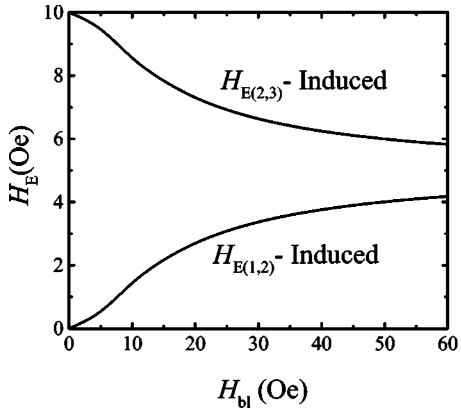

FIG. 4. Calculated values of the induced exchange bias field in both the free and the reference layers as a function of the H_{bl} value. The value of H_E is given by $H_E = \delta H_R/2 = 1/2(H_\pi - H_0)$, as discussed in the text. The same set of phenomenological parameters described in Fig. 1 was used in the numerical calculations.

were: $H_{u1}=H_{u2}=3.0$ Oe, $4\pi M_1=10$ kG, $4\pi M_2=10.3$ kG, and $H_E=10$ Oe. We have considered that the AF domain wall field is much stronger than the exchange-coupling field, i.e., $H_E \ll H_W$, and also considered that $J_E, J_{bl} > 0$. For $H_{bl}=0$, the free layer and the bilayer composed by the reference and the AF layers are decoupled. In this case the FMR behavior is described by two independent dispersion relations given by Eqs. (7) and (8). The in-plane dependence of the FMR resonance field for the free layer exhibits twofold symmetry characteristics of uniaxial anisotropy. On the other hand, the in-plane dependence of the resonance field for the reference layer exhibits unidirectional anisotropy superimposed with a very small uniaxial field. Significant changes in the shape of the FMR versus ϕ_H curves occur for $H_{bl}>0$. As the value of H_{bl} increases, the twofold symmetry of the uniaxial anisotropy of the free layer is broken, and a unidirectional anisotropy symmetry is established. This unidirectional anisotropy that appears in the free layer magnetization is induced by the interlayer coupling with the reference layer, which is exchange coupled to the AF layer. Considering both H_W and H_E much smaller than $4\pi M_A$, it can be shown that for $H_E < H_W$, the difference between the resonance fields at $\phi_H=\pi$ and $\phi_H=0$ is $\delta H_R = H_\pi - H_0 = 2H_E H_W^2/(H_W^2 - H_E^2)$.[12] This means that for $H_E \ll H_W$ the exchange bias field $H_E = \delta H_R/2$. So, from the H_R versus ϕ_H curves we can extract the value of H_E as a function of bilinear field value. Figure 4 shows the values of the induced exchange bias field (H_E—induced), as a function of H_{bl} for the free and the reference layers. Here we are assuming that $H_E=\delta H_R/2=(H_\pi - H_0)/2$. The increase in the value of the bilinear field induces an increasing exchange bias field in the free layer ($H_{E(1,2)}$ induced) and a decreasing exchange bias field in the existing exchange bias field in the reference layer ($H_{E(2,3)}$ induced). Another interesting feature that can be seen in Fig. 3 is the overall negative shift in the ferromagnetic resonance field of the reference layer. Figure 5 shows the value of the resonance field averaged on each azimuthal angle, as a function of H_{bl}, for the free and the reference layers. Notice that the downshift in the average FMR absorption field is much more relevant for the reference layer than for the free layer.

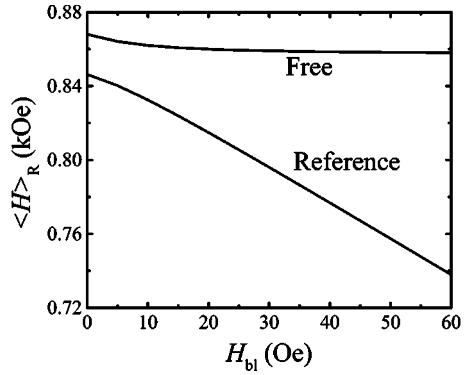

FIG. 5. Interlayer-coupling dependence of the average ferromagnetic resonance field obtained from the numerical calculations for the free and the reference layers. The downshift field value is more pronounced in the reference layer. The same set of phenomenological parameters described in Fig. 1 was used in the numerical calculations.

Figure 6 shows the experimental FMR data for the two spin valve systems: No. 1 Si(001)/IrMn(125 Å)/$Ni_{81}Fe_{19}$(100 Å)/Cu(168 Å)/$Ni_{81}Fe_{19}$(100 Å) (open circles) and No. 2 Si(001)/IrMn(125 Å)/$Ni_{81}Fe_{19}$(0 Å)/Cu(60 Å)/$Ni_{81}Fe_{19}$(100 Å) (open squares). The solid lines are numerical fits obtained by Eqs. (9)–(15) with the following parameters: for the sample No. 1: $4\pi M_1=10.125$ kG, $4\pi M_2=10.829$ kG, $H_{U1}=2.04$ Oe, $H_{U2}=3.9$ Oe, $H_E=19.7$ Oe, $H_W=800$ Oe, and $H_{bl}=0$ Oe; for sample No. 2: $4\pi M_1=10.206$ kG, $4\pi M_2=10.945$ kG, $H_{U1}=3.3$ Oe, $H_{U2}=5$ Oe, $H_E=19.7$ Oe, $H_W=800$ Oe, and $H_{bl}=15$ Oe. Sample No. 1 is a spin valve that exhibits no coupling between the FM layers since the Cu layer is thick enough to avoid the interlayer coupling. The in-plane dependence of the FMR field for the free layer exhibits a small uniaxial anisotropy. On the other hand the in-plane dependence of the FMR field of the reference layer exhibits a unidirectional anisotropy field value of around 20 Oe superimposed on a very small uniaxial anisotropy. Sample No. 2 is similar to sample No. 1 except by the Cu layer thickness that is about three times smaller. The smaller Cu layer thickness induces an interlayer

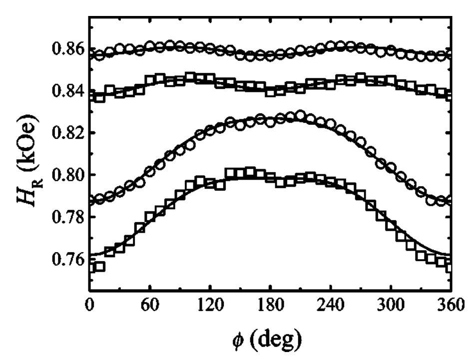

FIG. 6. In-plane FMR fields for sample No. 1: IrMn/Py/Cu(168 Å)/Py (open circles) and sample No. 2: IrMn/Py/Cu(60 Å)/Py (open squares). The solid lines are fits to the data obtained with Eqs. (9)–(15) as described in the text. A downshift resonance field occurs for the thinner interlayer sample, in agreement with the model.

coupling between the two layers of Permalloy characterized by an effective field $H_{\mathrm{bl}}=15$ Oe. These coupled layers exhibit an overall downshift of the FMR field always found in exchange-biased structures and is in agreement with the numerical result obtained by the model as shown in Fig. 5. The good agreement between the experimental results and the numerical predictions, given by the free energy model, suggests a reasonable confidence in the set of parameters extracted from the fits. The validity of the phenomenological parameters extracted from angular measurements of the FMR field has been previously investigated in exchange-coupled bilayers.[13]

V. SUMMARY

In this paper, we have investigated the FMR properties of spin-valve systems considering the effect of the residual coupling existent between the free and reference layers. An analytical expression for the FMR dispersion relation was obtained taking into account all the relevant interactions, namely: interlayer exchange coupling between the two FM layers, exchange-bias coupling between the reference and the AF layers, the domain wall that builds up at the AF material, as well as the uniaxial anisotropies and Zeeman interactions. The dispersion relation was written as a function of the second derivatives of the free energy, given in Eq. (6), and their validity was checked taking the limit of uncoupled FM layers. Our model anticipates the FMR properties in systems that exhibit a residual interlayer coupling and accounts for two main features: the appearance of a unidirectional anisotropy in the free layer and an isotropic downshift of the FMR field of both FM layers. All the FMR properties were experimentally achieved in an IrMn/Py/Cu/Py system, and were numerically interpreted by the theoretical model.

ACKNOWLEDGMENTS

This work has been supported by CNPq, under Grant No. 476746/03-5, and by FINEP, FACEPE, and CAPES (Brazilian agencies).

*Corresponding author. E-mail address: aac@df.ufpe.br

[1] B. Dieny, V. S. Speriosu, S. S. P. Parkin, B. A. Gurney, D. R. Wilhoit, and D. Mauri, Phys. Rev. B **43**, 1297 (1991).

[2] C. Tsang, R. E. Fontana, T. Lin, D. E. Hein, V. S. Speriosu, B. A. Gurney, and M. L. Williams, IEEE Trans. Magn. **30**, 3801 (1994).

[3] J. C. S. Kools and W. Kula, J. Appl. Phys. **85**, 4466 (1999).

[4] P. Grünberg, R. Schreiber, Y. Pang, M. B. Brodsky, and H. Sowers, Phys. Rev. Lett. **57**, 2442 (1986).

[5] J. Nogués and Iva K. Schuller, J. Magn. Magn. Mater. **192**, 203 (1999); A. E. Berkowitz and K. Takano, *ibid.* **200**, 552 (1999).

[6] R. L. Rodríguez-Suárez, L. H. Vilela Leão, F. M. de Aguiar, S. M. Rezende, and A. Azevedo, J. Appl. Phys. **94**, 4544 (2003); S. M. Rezende, C. Chesman, M. A. Lucena, A. Azevedo, F. M. de Aguiar, and S. S. P. Parkin, *ibid.* **84**, 958 (1998).

[7] A. Layadi, Phys. Rev. B **63**, 174410 (2001); **66**, 184423 (2002).

[8] D. Mauri, H. C. Siegmann, P. S. Bagus, and E. Kay, J. Appl. Phys. **62**, 3047 (1987).

[9] J. Smit and H. G. Beljers, Philips Res. Rep. **10**, 113 (1955).

[10] J. Geshev, L. G. Pereira, and J. E. Schmidt, Phys. Rev. B **64**, 184411 (2001).

[11] A. J. Devasahayan, P. J. Sides, and M. H. Kryder, J. Appl. Phys. **83**, 7216 (1998).

[12] J. R. Fermin, M. A. Lucena, A. Azevedo, F. M. de Aguiar, and S. M. Rezende, J. Appl. Phys. **87**, 6421 (2000).

[13] S. M. Rezende, M. A. Lucena, A. Azevedo, A. B. Oliveira, F. M. de Aguiar, and W. F. Egelhoff, Jr., J. Magn. Magn. Mater. **226**, 1683 (2001); J. R. Fermin, M. A. Lucena, A. Azevedo, F. M. de Aguiar, and S. M. Rezende, J. Appl. Phys. **87**, 6421 (2000).