Dynamic Effects Of Magnetic Multilayer Interlayer Coupling

Michael J. Pechan and Jiansheng Xu
Department of Physics, Miami University, Oxford, OH 45056

David M. Kelly and Ivan K. Schuller
Department of Physics, University of California-San Diego, La Jolla, CA 92093

Abstract **----Coupling between magnetic layers in multilayer samples gives rise to dynamic effects which are manifest as anomalous modes in ferromagnetic resonance (FMR) spectra. According to the model presented, antiferromagnetic (ferromagnetic) coupling would produce such modes on the high (low) field side of the uniform FMR mode. Anomalous modes, observed in Fe/Cu and Fe/Cr multilayer samples, are analyzed to obtain coupling constants as a function of nonmagnetic layer thickness. The modes are shown to arise from 180° out-of-phase interlayer magnetization precession. The coupling is observed to be antiferromagnetic in all samples and to be an order of magnitude greater in the Cr system than in the Cu.**

I. INTRODUCTION

Interlayer magnetic coupling, has attracted much experimental and theoretical attention due to its impact on basic physics (long mean-free-path of polarized carriers) and its potential application, for example, in magnetoresistive devices. While the preponderance of research has focused upon static manifestations of the coupling, only a few studies have examined dynamic effects - and those have been limited to the less complex trilayer structures[1,2]. We have characterized dynamic interlayer coupling effects in *multilayer* structures. The interlayer coupling produces precessional phase differences between magnetic layers which are manifest as additional modes in FMR spectra. These modes have been investigated in Fe/Cu and Fe/Cr samples where the nonmagnetic layer thickness is varied for constant Fe layer thickness.

II. THEORY

Given that the Fe *intra*layer coupling is much greater than the *inter*layer coupling, the Fe layers respond dynamically like rigid, coupled rotators, each precessing about an internal field. The coupling energy is generally expressed as

$$E_{exch} = -J\,\vec{M}_1 \cdot \vec{M}_2 / M_1 M_2\,, \qquad (1)$$

where M is a layer's magnetization and J is the coupling constant in energy per unit area. If one considers each interface spin to be coupled to a spin directly across the nonmagnetic spacer layer, then one can define a spin-spin coupling constant and energy

$$J' = JA \qquad \text{and} \qquad U = -J'\,\hat{s}_1 \cdot \hat{s}_2 \qquad (2)$$

where A is the area on an interface occupied by a single spin (≈2Å x 2Å) and the unit vectors specify the layer moment direction. Assuming small amplitude excitations about the saturated (all layers aligned) condition, the continuum dispersion relation is given by [3]

$$\hbar\omega = \frac{2J'}{N_m S}(1-\cos ka), \qquad (3)$$

where N_m is thenumber of atoms in a chain (monolayers in a magnetic layer) and S is the spin # of each atom. In the "optic" mode ($ka = \pi$) a tightly coupled chain of spins in each layer is precessing 180° out-of-phase with its counterpart across the nonmagnetic layer with energy given by

$$\hbar\omega = \frac{4J'}{N_m S}. \qquad (4)$$

In a resonance experiment, such modes will be excited at fields separated from the uniform precession mode given by[4]

$$\hbar\omega = g\mu_B(H_u - H_a), \qquad (5)$$

where g is the spectroscopic splitting factor, H_u and H_A are the resonance fields for the uniform and anomalous modes respectively. Therefore, equating (4) and (5), the coupling constant can be obtained from FMR according to

$$J = J'/A = N_m S\, g\mu_B (H_u - H_a)/4A. \qquad (6)$$

This simple approach will be useful under conditions of saturation and for large (>10) numbers of bilayers in a sample. A more general analysis is developed in [5].

III. EXPERIMENTAL DETAILS

Thirteen Fe(50Å)/Cu(x)[6 ≤ x ≤ 100Å] and six Fe(30Å)/Cr(y)[5 ≤ y ≤ 50Å] samples were prepared by sputtering. The bilayer pattern was repeated 20 times in each Fe/Cu sample and, except for y = 18Å, 10 times in the Fe/Cr system. Two samples were prepared at y = 18, one with bilayer repeat of 50 and the other of 100. This was done to

Manuscript received February 15, 1993. This work was supported in part by the U.S. Department of Energy under Grant No. DE-FG02-86ER45281(MU) and the National Science Foundation under Grant No. NSF DMR 9201698(UCSD).

0018-9464/93$03.00 © 1993 IEEE

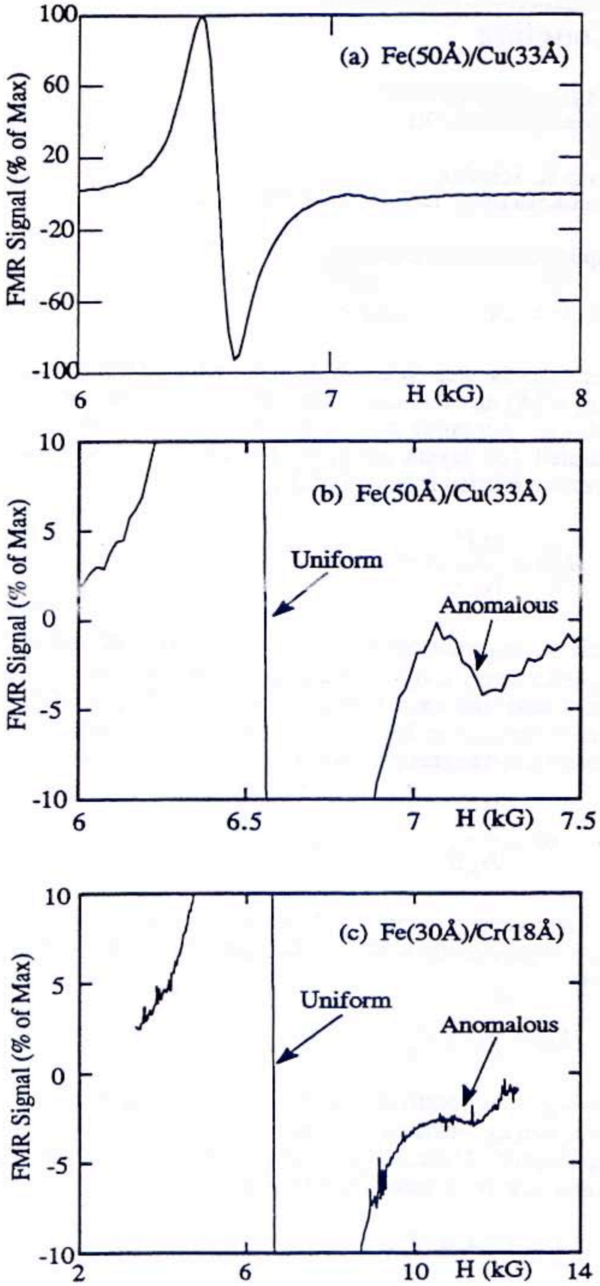

Fig. 1 Representative raw FMR spectra. (a) Fe/Cu; (b) same as (a) expanded; (c) Fe/Cr expanded.

determine the nature of the mode excited within the superlattice structure. X-ray analysis shows interface roughness / interdiffusion limited to the first one-to-two monolayers at an interface[6]. Magnetization in the Fe layer is within 90% of bulk[7]. FMR measurments have been made at 35 GHz with the sample forming the bottom wall of a TE 102 mode cavity. Field orientation is in the plane of the film and its value is determined with accuracy of ±5 Oe. Utilizing 35 GHz radiation ensures that the dc resonance field is greater than the maximum saturation field required to align the antiferromagnetically coupled layers in both the Fe/Cr and Fe/Cu systems[6,8].

IV. RESULTS

Representative ferromagnetic resonance (FMR) spectra from Fe(50Å)/Cu(x) and Fe(30Å)/Cr(y) multilayer samples are shown in Fig. 1. Particularly noteworthy are the "anomalous" modes which appears in addition to the large uniform modes. (The uniform mode is produced by the in-phase precession of all magnetic layers in the internal magnetic field.). Note that the separation between the uniform mode and the anomalous mode is almost an order of magnitude larger in the Fe/Cr than in the Fe/Cu, indicating a much larger coupling strength. Also the relative anomalous mode amplitude is considerably smaller in the Cr system, again, consistent with stronger coupling and the associated smaller cone angle for the out-of-phase precession.

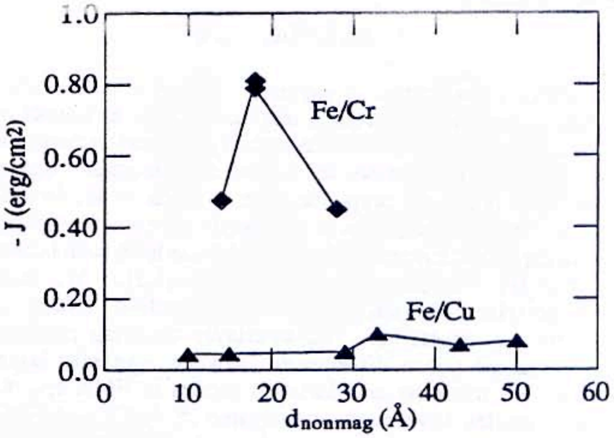

Fig. 2. Coupling constants as a function of nonmagnetic layer thickness. Triangles: Fe/Cr. Diamonds: Fe/Cu.

The coupling energy density is shown as a function of nonmagnetic layer thickness in Fig. 2. Although all coupling observed is antiferromagnetic, the dynamic coupling of Fe across Cu is considerably weaker than across Cr. These coupling strengths are consistent with those obtained via static techniques in sputtered multilayer systems [6,7]. For example, a typical field (H_{sat}) required to saturate the Fe/Cr magnetoresistance is approximately 5 kG. Using the effective field model [9], the resulting coupling constant, given by

$$J_{static} = H_{sat} M t_{Fe}/4 \qquad (7)$$

is 0.6 erg/cm^2, for t_{Fe} = 30Å.

Notice that utilizing our "optic" mode model, the two Fe(30Å)/Cr(18Å) samples, which differ by a factor of two in total number of bilayers, yield the same coupling constant. If the modes observed arise from the longest wavelength limit [nodes at the top and bottom layers and a single antinode in the interior of the multilayer stack], the excitation energy, represented by the FMR field separation, should depend upon total number of bilayers (N) making up the multilayer. The Fe(30Å)/Cr(18Å) samples exhibit no N dependence in the excitation energy, supporting the optic mode picture. In addition, *if* the anomalous FMR modes observed in Fe(30Å)/Cr(18Å) were due to the lowest energy excitation, interlayer coupling energies of several hundred ergs/cm^2 would be required. These lower energy modes are most likely not resolved from the uniform mode.

Anomalous modes were absent from several spectra in both the Fe/Cr and Fe/Cu systems. This, along with the wide variation of the coupling constants within each system, may be evidence for oscillations in the coupling strength, however smaller nonmagnetic layer thickness step size is required to establish this. These samples are in preparation. For this reason, only samples exhibiting anomalous modes are shown in Fig. 2.

V. SUMMARY

"Optic" out-of-phase magnetic interlayer precession modes have been observed in Fe/Cu and Fe/Cr multilayers as anomalous modes in FMR spectra. In analogy with spin wave treatments, a model has been developed to evaluate the interlayer coupling constant. The extracted constants are consistent with those obtained from static techniques.

ACKNOWLEDGMENT

We would like to acknowledge helpful discussions with Brett Heinrich and Jianhong Huang.

REFERENCES

[1] J.J. Krebs, P. Lubitz, A. Chaiken and G.A. Prinz, "Magnetic resonance determination of the antiferromagnetic coupling of Fe layers through Cr," *Phys. Rev. Lett.*, vol. 63, pp. 1645-1648, October 1989.

[2] B. Heinrich, Z. Celinski, J.F. Cochran, W.B. Muir, J. Rudd, Q.M. Zhong, A.S. Arrott, K. Myrtle and J. Kirschner, *Phys. Rev. Lett.* , vol. 64, pp. 673-676, February 1990.

[3] As developed in, for example, Charles Kittel, "Introduction to Solid State Physics," 3rd ed., Wiley, 1986, pp. 430-433.

[4] Ibid. [3], p. 482.

[5] Philip E. Wigen and Zhenyong Zhang, "Ferromagnetic resonance in coupled magnetic multilayer sytems," *Brazilian Journal of Physics,* vol. 22, December 1992.

[6] Eric E. Fullerton, Ivan K. Schuller, H. Vanderstraeten and Y. Bruynseraede, "Structural refinement of superlattices from x-ray diffraction," *Phys. Rev. B.*, vol. 45, pp. 9292-9310, April 1992.

[7] Eric E. Fullerton, David M. Kelly, J. Guimpel, Ivan K. Schuller and Y. Bruynseraede, "Roughness and giant magnetoresistance in Fe/Cr superlattices," *Phys. Rev. Lett..*, vol. 68, pp. 859-862, February 1992.

[8] W.R. Bennett, W. Schwarzacher and W.F. Egelhoff, Jr., "Concurrent enhancement of Kerr rotation and antiferromagnetic coupling in epitaxial Fe/Cu/Fe structures," *Phys. Rev. Lett*, vol. 65 pp. 3169-3172, December 1990.

[9] A. Fert, A. Barthelemy, P. Lequien, R. Loloee, D.K. Lottis, D.H. Mosca, F. Petroff, W.P. Pratt and P.A. Schroeder, "Magnetic multilayers: oscillatory interlayer exchange and giant magnetoresistance," *J. Magn. Magn. Mater.* vols. 104-7, pp1712-1716, 1992.