Upper bound for the magnetic proximity effect extracted from Brillouin light scattering

Johan J. Åkerman,[1,*] I. Guedes,[2] C. Leighton,[1,†] M. Grimsditch,[2] and Ivan K. Schuller[1]
[1]*Physics Department 0319, University of California–San Diego, La Jolla, California 92032-0319*
[2]*Materials Science and Technology Division, Argonne National Laboratory, Argonne, Illinois 60439*
(Received 16 May 2001; published 1 March 2002)

The effective magnetic thickness of Fe films and of Fe/Al and Fe/Pd bilayers is determined using Brillouin light scattering. The magnetic thickness is extracted by fitting the field dependence of the frequencies of two magnon modes. Within experimental errors of about 1 Å, no change in the effective magnetic thickness of the Fe layers was detected. If a net magnetization does exist in Pd when in contact with Fe, it is sufficiently different in nature so as to not modify the Fe spin waves.

DOI: 10.1103/PhysRevB.65.104432 PACS number(s): 75.70.−i, 76.50.+g, 78.35.+c

I. INTRODUCTION

Electron-electron interactions are responsible for a wide range of properties in condensed-matter systems, e.g., superconductivity and ferromagnetism. When two different materials are brought into close contact, electrons in one material can sometimes transfer these properties to the adjoining material resulting in what is known as a proximity effect. In the case of a superconductor–normal-metal interface, the effect is large because of the relatively long superconducting coherence length. The magnetic analog, on the other hand, is expected to be much less pronounced,[1–5] since the magnetic coherence length is only a few atomic spacings in metals and even shorter in insulators. Experimentally its detection is also more challenging since magnetostatic and dynamic interactions can confuse the interpretation of the data.

A number of experimental studies focused on the detrimental effect a nonmagnetic metal has on thin ferromagnetic films. So-called ''dead layers'' up to a few Å thick have been observed.[6–8] The opposite effect, i.e., a signature of a magnetic moment in nonmagnetic materials, was observed in thin films and multilayers where Fe interfaces with, e.g., Pd,[9–14] La,[15,16] and Ce.[15,16] An Fe impurity in a Pd host is also known to induce a polarized cloud[17,18] that extends out to about 10 Å,[19] and has a total moment of up to $\mu_{\mathrm{Fe+Pd}} = 12.9\mu_B$. The easy polarizability of Pd is the result of a large density of states at the Fermi level, which strongly exchange enhances its magnetic susceptibility and puts Pd on the brink of ferromagnetism.[20,21] Pd was recently also claimed to acquire a magnetic moment when in contact with an *antiferromagnet* such as NiO.[22] However, neutron-diffraction measurements, with enhanced relative sensitivity to Pd magnetism, did not observe any Pd moment in NiO/Pd bilayers and multilayers.[23]

In spin-dependent tunneling experiments a finite spin polarization persists up to a few tens of Å for Au films on Fe.[24] More recently, the magnetoresistance of magnetic tunnel junctions was used to probe the induced spin polarization in nonmagnetic metals. However the interpretation of such experiments is not straightforward, as a distribution of pinholes can mimic the effect of a decay with increasing thickness.[25,26]

A magnetic proximity effect was also suggested to give rise to a superparamagnetic to ferromagnetic transition in films of isolated Ni grains, when covered by nonmagnetic overlayers.[27] The overlayer seems to magnetically connect the Ni grains, and the strength of this coupling correlates with the magnetic susceptibility of the overlayer material.

Brillouin light scattering (BLS) is the inelastic scattering of light due to low-lying excitations in a material. It is a convenient tool for investigating both acoustic phonons and spin-wave excitations. Since the frequencies of spin waves in thin ferromagnetic films depend on the film thickness, the technique will be used here to probe the changes in magnetic thickness introduced by various interfaces.

II. EXPERIMENT

Fe/X/ZnF_2 and X/Fe/ZnF_2 (X=Al,Pd), thin films were grown on Si(100) substrates by sequential electron-beam evaporation. All depositions were carried out at room temperature with a base pressure of about 5×10^{-7} Torr and a pressure during deposition of about 5×10^{-6} Torr for Fe, Pd, and ZnF_2, and 1.5×10^{-5} Torr for Al. The deposition rate was 1 Å s^{-1} for all materials. While both Fe and ZnF_2 were deposited over the entire sample, the nonmagnetic metals were deposited as strips (1×15 mm^2) through a stepper-motor controlled shadow mask. In this way the same Fe film can be used to study a range of interfaces. The time between the deposition of a strip and the subsequent deposition of the Fe film ranged from 10 to 30 min. We did not observe any dependence on this waiting time. ZnF_2 serves as a transparent, insulating, and nonmagnetic capping layer that prevents oxidation of the Fe film while not interfering with the BLS measurement. Initial experiments with uncapped films showed a noticeable decrease in the magnetic thickness as a function of time, which we ascribe to oxidation. Films capped with 120-Å ZnF_2 showed no time dependence of the magnetic thickness.

The BLS experiments were performed with the external field applied in the film plane and after magnetically saturating the sample to ensure a single domain state of the Fe film. 150-mW of 514.5-nm radiation from an Ar-ion laser was focused onto the sample. The light inelastically scattered from the thermally excited Damon-Eshbach (DE) mode and the first bulk standing spin-wave[28] (SW) mode was frequency analyzed using a five-pass Fabry-Perot interferometer.

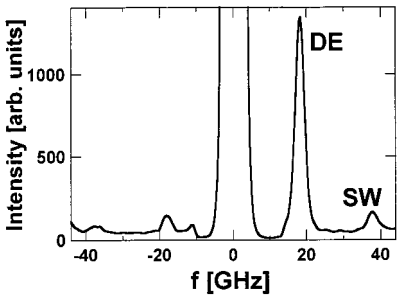

FIG. 1. Brillouin spectrum of one of the Fe films. The Damon-Eshbach (DE) and standing-wave (SW) modes are clearly seen.

III. RESULTS AND DISCUSSION

Figure 1 shows a typical BLS spectrum from one of our films. The DE and SW modes are clearly seen, and their frequency positions were determined to within 1%. The weaker intensity of the peaks on the Stokes side (i.e., the negative frequency shift) is related to time-reversal effects; however, their frequency shift is the same as those on the anti-Stokes side. In a film with no anisotropy the frequency of these modes are given by[28]

$$\omega_{\mathrm{DE}}=\gamma\{H(H+4\pi M)+(2\pi M)^2[1-\exp(-2qL)]\}^{1/2}, \tag{1}$$

$$\omega_{\mathrm{SW}}=\gamma\{[H+D(\pi/L)^2][H+D(\pi/L)^2+4\pi M]\}^{1/2}, \tag{2}$$

where M is the magnetization, γ is the gyromagnetic ratio ($=2.91$ GHz/kG), D is the spin-wave stiffness ($=2.18\times10^4$ kOe Å^2), H is the applied field, q is the wave-vector component parallel to the film surface, and L is the film thickness. Using Eqs. (1) and (2), the magnetic-field dependence of the frequencies, shown in Fig. 2, was analyzed by fitting simultaneously ω_{DE} and ω_{SW} using a least-square fit, with $4\pi M$ and L as the fit parameters. This method was used many times to successfully determine spin-wave modes in thin magnetic films.[28,29]

Figure 3 presents the film thicknesses extracted from such fits in a Fe200 Å/X70 Å/$ZnF_2$120 Å sample as a function of strip material. The error bars for L ($\sim$1 Å) are obtained from the fitting routine. As such, this error represents a statistical error due to the accuracy of the frequency measurements. It does not include any systematic error, which could arise due to our neglect of anisotropies in the equations; however, any

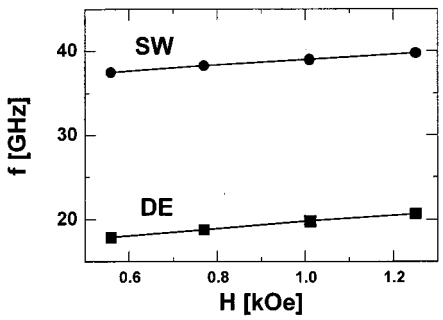

FIG. 2. Field dependence of the DE and SW modes. The solid lines are fits as described in the text.

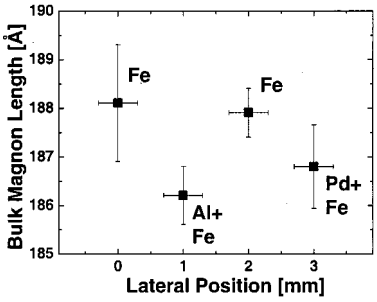

FIG. 3. Effective length of the bulk standing spin wave for different bilayer combinations. Al and Pd are deposited on top of Fe.

such systematic error is not expected to vary from spot to spot on a given sample. The lateral error bars correspond to the accuracy with which the laser spot can be positioned. The values of $4\pi M$ for the four portions were 18.5, 18.6, 18.2, and 18.3 kG, respectively, and all have estimated errors of 0.2 kG. Within this error there is no change in the value of the magnetization.

L is found to be 188 Å, where the Fe film interfaces directly with ZnF_2, and 186 and 186.5 Å for interfaces with Al and Pd, respectively. Hence no constructive proximity effect is observed. Conversely, both Al and Pd seem to *decrease* the standing wave spin-wave length slightly.

Similar results were obtained for samples where the deposition order is reversed. In Fig. 4(a) we show L vs interface material for a X100 Å/Fe200 Å/$ZnF_2$120 Å sample. As a test of the Me/Fe interface quality, this sample also had an Fe strip such that a measurement of L in a Fe100 Å/Fe200 Å/$ZnF_2$120 Å structure could be carried out. It is evident from Fig. 4(a) that the Fe/Fe interface is of

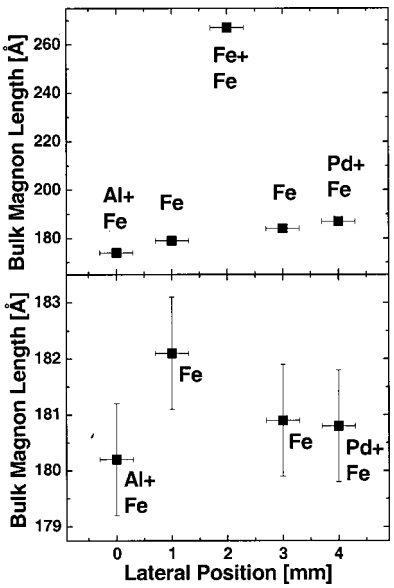

FIG. 4. (a) Effective length of the bulk standing spin wave when the deposition order was reversed. Fe film is deposited on top of Al, Pd, and Fe. (b) Blow-up of the data in (a) after the Fe thickness gradient was removed

high enough quality to allow for the unhindered formation of the SW mode with $L = 267$ Å. A small, unintentional, gradient of the Fe film thickness (3.1 Å mm^{-1}) can be observed in the figure. After subtraction of this thickness gradient, an expanded plot of the same data for the Al and Pd strips [Fig. 4(b)] again shows, within the accuracy of the measurement, that neither Al nor Pd has any constructive effect on L.

Within the experimental error the present results show no change in the effective magnetic thickness of Fe layers in contact with Al or Pd. If such a length change occurs, it is less than ~1 Å at Fe/Pd and Fe/Al interfaces. However, this does not necessarily rule out the existence of a magnetic proximity effect per se. Since the BLS analysis assumes that the measured spin waves reside in a layer with uniform magnetization, our results suggest that if a net magnetization is induced, as is known to happen at Fe/Pd interfaces,[9–14] it is sufficiently different from that in the Fe layer so as not to allow for the spin wave node to extend significantly into the Pd. At present, we do not know of any available theory that would allow us to extract a spatially varying magnetization from BLS data.

It should also be noted that our analysis assumed no magnetic anisotropy in the films. Although this approximation in itself is likely to be appropriate since all data are treated equally, it is possible that the Al and Pd could induce a surface anisotropy different to that produced by ZnF_2. This in turn could affect the spin-wave frequencies and mask an existing proximity effect.

IV. CONCLUSIONS

We have determined the effective length of the standing spin-wave mode in Fe films and Fe/Al and Fe/Pd bilayers using Brillouin light scattering. We find that, to within 1 Å, there is no change in the effective thickness over which the magnetization is comparable to that in pure Fe. Within the experimental errors of about 1 Å no change in the effective magnetic thickness of the Fe layers, when in contact with Al or Pd, was detected. As a net magnetization is known to be induced in Pd when in contact with Fe, we conclude that the nature of this induced magnetization is sufficiently different so as to not change the length of the Fe spin waves.

Note added in proof. Recently, we became aware of two theoretical treatments of the problem[30,31] which are essentially in agreement with our experimental results presented here.

ACKNOWLEDGMENTS

Work at ANL was supported by the U.S. Department of Energy, BES, Materials Science under Grant No. W-31-109-ENG-38. I. G. wishes to acknowledge DF/UFC and CNPq for support during his stay at ANL. This work was supported by the U.S. DOE.

*Present address: Motorola Labs, 7700 S. River Parkway ML34, Tempe, AZ 85284.

†Present address: Dept. of Chemical Engineering and Material Science, University of Minnesota, 421 Washington Ave SE, Minneapolis, MN 55455.

[1] M. Kiwi and M. J. Zuckermann, in *Magnetism and Magnetic Materials—1973*, edited by R. E. Taylor and J. J. Rhyne, AIP Conf. Proc. No. 18 (AIP, New York, 1997), p. 347.

[2] M. J. Zuckermann, Solid State Commun. **12**, 745 (1973).

[3] B. N. Cox, R. A. Tahir-Kheli, and R. J. Elliott, Phys. Rev. B **20**, 2864 (1979).

[4] J. Tersoff and L. M. Falicov, Phys. Rev. B **26**, 6186 (1982).

[5] R. M. White and D. J. Friedman, J. Magn. Magn. Mater. **49**, 117 (1985).

[6] G. Bergmann, Phys. Rev. Lett. **41**, 264 (1978).

[7] E. M. Gyorgy, J. F. Dillon, Jr., D. B. McWhan, L. W. Rupp, Jr., L. R. Testardi, and P. J. Flanders, Phys. Rev. Lett. **45**, 57 (1980).

[8] J. S. Moodera and R. Meservey, Phys. Rev. B **29**, 2943 (1984).

[9] Z. Celinski, B. Heinrich, J. F. Cochran, W. B. Muir, A. S. Arrott, and J. Kirschner, Phys. Rev. Lett. **65**, 1156 (1990).

[10] S. Blügel, B. Drittler, R. Zeller, and P. H. Dederichs, Appl. Phys. A: Solids Surf. **49**, 547 (1989).

[11] O. Rader, C. Carbone, W. Clemens, E. Vescovo, S. Blügel, W. Eberhardt, and W. Gudat, Phys. Rev. B **45**, 13 823 (1992).

[12] O. Rader, E. Vescovo, J. Redinger, S. Blügel, C. Carbone, W. Eberhardt, and W. Gudat, Phys. Rev. Lett. **72**, 2247 (1994).

[13] E. E. Fullerton, D. Stoeffler, K. Ounadjela, B. Heinrich, Z. Celinski, and J. A. C. Bland, Phys. Rev. B **51**, 6364 (1995).

[14] J. Vogel, A. Fontaine, V. Cros, F. Petroff, J.-P. Kappler, G. Krill, A. Rogalev, and J. Goulon, Phys. Rev. B **55**, 3663 (1997).

[15] F. Klose, O. Schulte, F. Rose, W. Felsch, S. Pizzini, C. Giorgetti, F. Baudelet, E. Dartyge, G. Krill, and A. Fontaine, Phys. Rev. B **50**, 6174 (1994).

[16] L. Sève, N. Jaouen, J. M. Tonnerre, D. Raoux, F. Bartolomé, M. Arend, W. Felsch, A. Rogalev, J. Goulon, C. Gautier, and J. F. Bérar, Phys. Rev. B **60**, 9662 (1999).

[17] J. Crangle and W. R. Scott, J. Appl. Phys. **36**, 921 (1965).

[18] G. J. Nieuwenhuys, Adv. Phys. **24**, 515 (1975).

[19] G. G. Low and T. M. Holden, Proc. Phys. Soc. London **89**, 119 (1966).

[20] S. Foner, R. Dolco, Jr., and E. J. McNiff, J. Appl. Phys. **39**, 551 (1968).

[21] T. Jarlborg and A. J. Freeman, Phys. Rev. B **23**, 3577 (1981).

[22] T. Manago, T. Ono, H. Miyajima, K. Kawaguchi, and M. Sohma, J. Phys. Soc. Jpn. **68**, 334 (1999).

[23] A. Hoffmann, M. R. Fitzsimmons, J. A. Dura, and C. F. Majkrzak, Phys. Rev. B **65**, 024428 (2002).

[24] J. S. Moodera, M. E. Taylor, and R. Meservey, Phys. Rev. B **40**, 11 980 (1989).

[25] B. J. Jönsson-Åkerman, R. Escudero, C. Leighton, S. Kim, I. K. Schuller, and D. A. Rabson, Appl. Phys. Lett. **77**, 1870 (2000); D. A. Rabson, B. J. Jönsson-Åkerman, R. Escudero, C. Leighton, S. Kim, and I. K. Schuller, J. Appl. Phys. **89**, 2786 (2001); J. J. Åkerman, R. W. Dave, J. M. Slaughter, and I. K. Schuller, Appl. Phys. Lett. **79**, 3104 (2001).

[26] P. LeClair, H. J. M. Swagten, J. T. Kohlhepp, R. J. M. van de Veerdonk, and W. J. M. de Jonge, Phys. Rev. Lett. **84**, 2933 (2000).

[27] A. Frydman and R. C. Dynes, Solid State Commun. **110**, 485 (1999).
[28] P. Grünberg, C. M. Mayr, W. Vach, and M. Grimsditch, J. Magn. Magn. Mater. **28**, 319 (1982).
[29] A. P. Malozemoff, M. Grimsditch, J. Aboaf, and A. Brunsch, J. Appl. Phys. **50**, 5885 (1979).
[30] G. J. Mata, E. Pestana, and M. Kiwi, Phys. Rev. B **26**, 3841 (1982).
[31] D. Altbir, M. Kiwi, G. Martinez, and M. J. Zuckermann, Phys. Rev. B **40**, 6963 (1989).