AIP Journal of Applied Physics

Ferromagnetic resonance in Ag coupled Ni films

S. M. Rezende, J. A. S. Moura, F. M. de Aguiar, C. A. dos Santos, W. R. Schreiner, and S. R. Teixeira

Citation: Journal of Applied Physics **73**, 6341 (1993); doi: 10.1063/1.352642
View online: http://dx.doi.org/10.1063/1.352642
View Table of Contents: http://scitation.aip.org/content/aip/journal/jap/73/10?ver=pdfcov
Published by the AIP Publishing

Ferromagnetic resonance in Ag coupled Ni films

S. M. Rezende, J. A. S. Moura, and F. M. de Aguiar
Departamento de Física, Universidade Federal de Pernambuco, 50739 Recife-PE, Brazil

C. A. dos Santos
Departamento de Física, Universidade Federal do Rio Grande do Norte, 59072 Natal-RN, Brazil

W. R. Schreiner and S. R. Teixeira
Instituto de Física, Universidade Federal do Rio Grande do Sul, 91500 Porto Alegre-RS, Brazil

We present an X-band ferromagnetic resonance (FMR) study of polycrystalline single Ni films and of two Ni layers separated by an Ag layer at room temperature. Films were deposited by sputtering on glass using Ag over- and underlays. The single Ni films have a FMR mode with a dependence of the resonance field on the angle α between the magnetic field and the plane in good agreement with theory. In samples with two Ni films coupled through an intervenient Ag layer, only one FMR mode is observed if the two Ni have identical thicknesses. When the films have different thicknesses a second weak resonance appears. The field difference between the two modes is a measure of the coupling between the Ni films. Results were obtained for a series of samples with the Ag thickness varying in the range $10 < t < 30$ Å. Surprisingly, the two modes have opposite behavior with the variation of α, for all values of t. The results suggest that the coupling is antiferromagnetic when the field is parallel to the film plane and ferromagnetic when perpendicular, regardless of t.

I. INTRODUCTION

The magnetic interaction between ferromagnetic films separated by metallic nonmagnetic layers has been attracting increasing attention since it was discovered a few years ago.[1] Particular interest has arised about systems which show oscillatory behavior of the magnetic coupling with varying thickness of the nonmagnetic spacer layer, such as Fe/Cr, Co/Cr, and Co/Ru among others.[2-4] The interlayer coupling has been investigated by means of various techniques, such as magnetization[4] and torque measurements, magnetoresistance,[3] Brillouin scattering,[2] and ferromagnetic resonance (FMR).[5,6] Theoretical models have been proposed[7-9] to explain the oscillatory behavior of the coupling but controversies still exist. One system that has recently called attention is Ag/Ni.[10-12] The nonmiscibility of Ag and Ni elements allows the preparation of superlattices with sharp interfaces making this system very interesting from the point of view of materials engineering.

In this paper we present a FMR investigation of Ni single layers and Ni double layers separated by a Ag spacer layer. This is a convenient system for FMR studies because Ni has a relatively small saturation magnetization compared to other transition metals, so that it can be saturated perpendicularly to the film plane by fields used in X-band spectrometers. The initial objective of this study was to measure directly the coupling between Ni layers, since the FMR technique is most appropriate for this purpose.[5,6] However the results obtained with FMR at just one frequency do not allow a definitive interpretation of the resonance modes in Ni/Ag/Ni sandwiches and of the coupling between layers.

II. SAMPLES AND EXPERIMENTAL TECHNIQUE

The samples used in our experiments are polycrystalline single Ni layers and sandwiches Ni/Ag/Ni. The two Ni layers have thickness of 90 and 110 Å, made deliberately different so that the exchange, or out-of-phase, mode can be excited by the uniform microwave field. The Ag layer has variable thickness t in the range 10–30 Å. The sandwich has a 25 Å thick overlayer and a 50 Å thick underlayer of Ag, deposited on a glass substrate. We have also measured the resonance in single Ni layers and in sandwiches with identical Ni thicknesses. The samples were prepared by sputtering in a Balzers BAS 450 system pumped to a base vacuum of 1×10^{-6} mbar. Ag and Ni were sputtered in dc and rf modes respectively. A controlled Ar($5N$) partial pressure of 7×10^{-3} mbar was used during deposition and the target-substrate distance was 7 cm. The FMR spectrometer is homemade, employing a 400 mW klystron tube operating at a frequency of 9.4 GHz stabilized at the cavity resonance. The rectangular TE_{102} cavity with $Q \simeq 2500$ has field modulation coils operating at 100 kHz. The sample is located at the center of the cavity and mounted on a goniometer to allow measurement of the FMR spectra as a function of the angle between the static field H and the plane of the film. All data were taken at room temperature.

III. RESULTS AND DISCUSSION

Typical field derivative FMR spectra for all samples are similar to those shown in Fig. 1 for the $t = 15$ Å sandwich. There is a strong, or main resonance, which shifts upwards in field as the angle α between the field **H** and the plane varies from 0 to 90°. The field-angle behavior of this mode is nearly identical in all samples and is also the same as in a single 200 Å thick layer of Ni or in sandwiches with identical Ni layers. Thus, the main resonance is assigned to the in-phase or acoustic mode in a saturated sample, as will be shown shortly. The weak, or secondary resonance has opposite behavior, it shifts downwards in field with increas-

0021-8979/93/106341-03$06.00

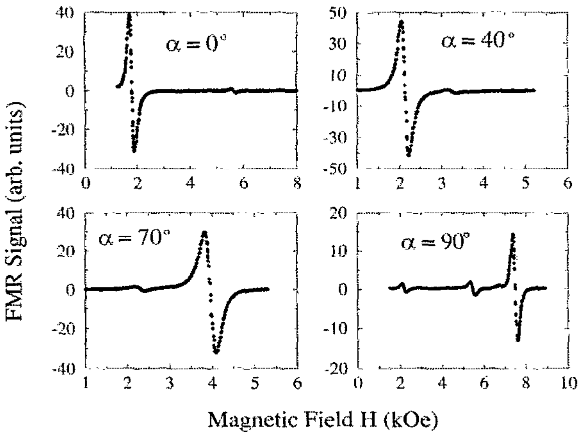

FIG. 1. FMR spectra of Ni (110 Å)/Ag/(15 Å)/Ni(90 Å) sandwich for several angles α between the external field and the plane of the sample at 9.4 GHz.

ing angle α. The relative amplitudes of both modes do not change much as they shift with varying α, even when they cross each other at $\alpha \approx 50°$. Since the secondary mode appears only in sandwiches, it is attributed to the coupling between the magnetizations in the two Ni layers. However, its field dependence is quite surprising, so its precise nature is not entirely clear at the moment.

The angular dependences of the fields for the main (□) and secondary (●) resonances are shown in Fig. 2 for the $t = 15$ Å sandwich. Also shown in the figure is a third weak mode (▲), which appears only in some samples and in the vicinity of $\alpha = 90°$ or $\alpha = 0°$. The field dependence of the main resonance has been calculated assuming that it corresponds to the acoustic mode and that the magnetization is saturated over the entire range. Using the equations given by Layadi and Artman[6] for the angular dependence of the resonance field we obtain with $4\pi M_{\text{eff}} = 4.2$ kG the solid curve in Fig. 2. This effective magnetization includes a small uniaxial anisotropy, estimated from the value of the linewidth to be of the order of 0.3 kOe. This value for the magnetization is similar to that obtained by other authors[6,13] for 100 Å thick Ni layers. The good agreement between theory and data indicates that the main resonance is indeed the acoustic or in-phase mode. The nature of the secondary resonance, however, is not completely understood since its resonance field has the opposite behavior with varying angle. Assuming a coupling between the two Ni layers with energy per unit area in the form

$$E_{12} = -K\mathbf{M}_1 \cdot \mathbf{M}_2\,, \tag{1}$$

the resonance frequency for the out-of-phase precession or optic mode, for parallel moments and the field perpendicular to the film ($\alpha = 90°$) is, in the saturated region[5,14]

$$\omega^- = \gamma(H + 2H_{\text{ex}} - 4\pi M_{\text{eff}}), \tag{2}$$

where $H_{\text{ex}} = KM/t$ is the exchange coupling field between the two layers. Since the resonance frequency for the acoustic mode at $\alpha = 90°$ is

$$\omega^+ = \gamma(H - 4\pi M_{\text{eff}}), \tag{3}$$

the difference between the fields for resonance at fixed ω for the acoustic and optic modes, $H^+ - H^- = 2H_{\text{ex}}$, is a direct measure of the coupling between layers. With the field parallel to the film plane ($\alpha = 0°$) and parallel moments, the field difference between the acoustic and optic mode is also given by $2H_{\text{ex}}$. Since the relative positions of the two modes are reversed when the field changes from perpendicular to parallel, we speculate that the coupling between the films changes from ferromagnetic to antiferromagnetic as α varies from 90° to 0°. Antiferromagnetic coupling has been previously observed in Ag/Ni superlattices with in-plane field.[10,11] The surprising result here is that the behavior described is observed for all thicknesses in the range $10 < t < 30$ Å.

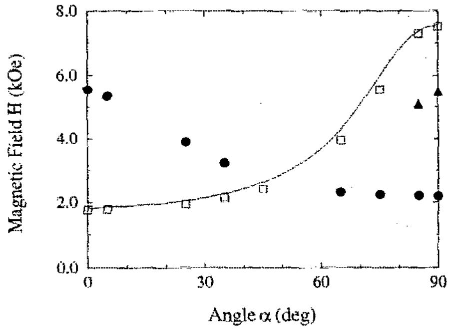

FIG. 2. Angular dependence of the fields for resonance of the same sample of Fig. 1, as described in the text.

If we stick to the interpretation that the coupling is antiferromagnetic when the field is in the plane, we have to consider the behavior of the magnetic moments. For small fields the moments in the two layers are antiparallel and nearly perpendicular to the field. With increasing field they rotate towards each other until they align with the field at $H = 2H_{\text{ex}}$. At this field the expressions for the resonance frequencies change so that the difference $H^+ - H^-$ does not give H_{ex} directly. We have analyzed the field dependence using the expressions of Ref. 14 for the resonance frequencies. Fig. 3(a) shows the comparison between theory and the data of Figs. 1 and 2 for the 15 Å sandwich with the field in the plane, assuming antiferromagnetic coupling with $H_{\text{ex}} = -2.0$ kOe and $4\pi M_{\text{eff}} = 4.5$ kG. The agreement is satisfactory. For the field perpendicular to the film we consider ferromagnetic coupling with $H_{\text{ex}} = 1.0$ kOe and $4\pi M_{\text{eff}} = 4.2$ kG to obtain the solid lines in Fig. 3(b). In this case the agreement between theory and data is very good and the origin of the third mode is explained.

The change in the coupling sign when the field varies from parallel to perpendicular to the film, suggests magnetostatic effects arising from interface roughness as the source of coupling. While aligned in the plane, magnetic roughness poles generate fields which oppose the magnetization of adjacent layers. However, with the magnetization perpendicular to the film, these same poles would produce fields along the magnetization of the adjacent layer. This mechanism would also be consistent with the change in magnitude of the coupling field. The value $H_{\text{ex}} = 1.0$ kOe

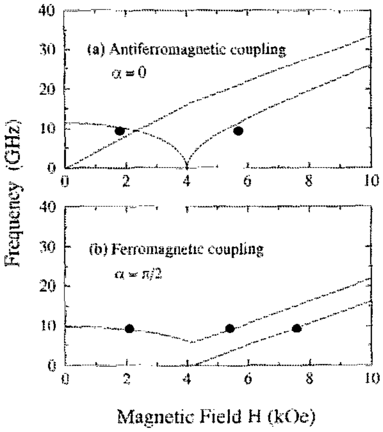

FIG. 3. (a) Comparison between data (circles) and the model (solid lines) of Ref. 14 for field parallel to the film plane ($\alpha = 0$) considering antiferromagnetic coupling, $H_{ex} = -2.0$ kOe, $4\pi M = 4.5$ kG. (b) Data and model for field perpendicular to film ($\alpha = \pi/2$), ferromagnetic coupling, $H_{ex} = 1.0$ kOe, $4\pi M = 4.2$ kG.

used to fit the ferromagnetic coupling case of Fig. 3(b) is about the same reported in Ref. 10 for Ag/Ni multilayers and of the same order of that reported in Ref. 6 for Ni/Ag/NiFe sandwiches. However, the value $H_{ex} = -2.0$ kOe obtained in the antiferromagnetic case might be a little too large. Since the fit in Fig. 3(a) is not entirely satisfactory and we have not measured the FMR spectra at various frequencies, a definitive identification of the modes is not possible at the moment. So the interpretation just presented is still tentative. Further variable frequency FMR and Brillouin scattering experiments will be carried out shortly.

ACKNOWLEDGMENTS

The authors are grateful to the referee who reviewed this paper for many comments and suggestions on the first manuscript. This work was supported by the Brazilian Federal agencies PADCT, FINEP, and CNPq and by the state agencies FACEPE and FAPERGS.

[1] R. W. Erwin, J. J. Rhyne, M. B. Salamon, J. Borchers, S. Sinha, J. E. Cunningham, and C. P. Flyn, Phys. Rev. B **35**, 6808 (1987).

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

[3] M. N. Baibich, J. M. Broto, A. Fert, F. Nguyen van Dan, F. Petroff, P. Etienne, G. Creuzet, A. Friederich, and J. Chazelas, Phys. Rev. Lett. **61**, 2472 (1988).

[4] S. S. P. Parkin, N. More, and K. P. Roche, Phys. Rev. Lett. **64**, 2304 (1990).

[5] J. J. Krebs, P. Lubitz, A. Chaiken, and G. A. Prinz, Phys. Rev. Lett. **63**, 1645 (1989).

[6] A. Layadi and J. O. Artman, J. Magn. Magn. Mater. **92**, 143 (1990).

[7] Y. Yafet, Phys. Rev. B **36**, 3948 (1987).

[8] D. M. Edwards, J. Mathon, R. B. Muniz, and M. S. Phan, Phys. Rev. Lett. **67**, 493 (1991).

[9] P. Bruno and C. Chappert, Phys. Rev. Lett. **67**, 1602 (1991).

[10] C. A. dos Santos, B. Rodmacq, M. Vaezzadeh, and B. George, Appl. Phys. Lett. **59**, 126 (1991).

[11] B. Rodmacq, Ph. Mangin, and Chr. Vettier, Europh. Lett. **15**, 503 (1991).

[12] B. Rodmacq, B. George, M. Vaezzadeh, and Ph. Mangin, Phys. Rev. B **46**, 1206 (1992).

[13] R. Zuberek, H. Szymczak, R. Krishman, and M. Tessier, J. Phys. (Paris) C **8**, 1761 (1988).

[14] P. E. Wigen, Z. Zhang, L. Zhou, and M. Ye, This conference; also P. E. Wigen and Z. Zhang, Braz. J. Phys. **22**, 267 (1992).