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Spin wave frequency shifts in exchange coupled ferromagnet/antiferromagnet structures: Application to Co/CoO

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Co/CoO structures have been studied almost exclusively through measurements of hysteresis, and display an enhanced and strongly temperature dependent effective in-plane anisotropy. A recent experimental study demonstrated an alternate way of investigating effects related to the coupling across the interface by measuring frequencies of long wavelength spin waves associated with the Co film. A large increase in frequency of the low frequency spin wave in the Co was observed as the temperature was lowered through the Neél temperature of CoO. We show how these frequency shifts can be understood as an effective interface anisotropy introduced by strong exchange coupling across the Co/CoO interface. This means that spin waves in the Co also include energy contributions from the larger anisotropies experienced by spins in the CoO. The theory is presented and discussed for the Co/CoO interface and other structures. © *1997 American Institute of Physics.* [S0021-8979(97)47008-1]

INTRODUCTION

The magnetic coupling between Co and CoO has been studied almost exclusively with measurements of hysteresis.[1–4] In contrast, a recent experimental study[5] suggests an alternate way of investigating effects related to the coupling across the Co and CoO interface. In this study of long wavelength spin waves associated with the Co film, a huge increase in frequency of the spin wave mode associated with the Co film was observed as the temperature was reduced below room temperature. Such an effect suggests the influence of coupling to the antiferromagnet CoO which has a Neél temperature of 293 K.

The present paper explores the origin of large frequency shifts in a single and double interface geometry via two different mechanisms. For the single interface, the frequency shift is due to the exchange coupled anisotropies. In a sandwich multilayer structure, we obtain frequency shifts which do not require anisotropies in the antiferromagnet but which are dependent on the interface coupling strength.

FREQUENCY SHIFTS FROM COUPLING AT FERROMAGNET/ANTIFERROMAGNET INTERFACES

The Co film is assumed to have minimal anisotropy, but there are in-plane and out-of-plane anisotropies in the antiferromagnetic CoO film. Because of the exchange coupling at the interface, a spin wave in the Co must also drive the interface spins in the antiferromagnetic CoO. Even though the driving frequency is far from the antiferromagnetic resonance, the large anisotropies in the CoO therefore affect the frequency of the Co spin wave. This can provide a significant shift for the frequency of the low-frequency spin wave. As one approaches the Neél temperature of the antiferromagnet, the effect disappears since effective coupling and the anisotropy in the antiferromagnet are both zero at that point.

We calculate the frequencies using a microscopic theory described in Ref. 6. The frequency shifts exist because of the interface and thus decrease as the thickness of the Co film increases. We therefore consider thin films of only a few atomic layers. Our first example for a single interface represents a single thin Co film exchange coupled to a thin CoO film. A field H_0 is applied along the uniaxis of the CoO in-plane anisotropy. For simplicity, we consider structures where the equilibrium directions of the magnetic moments are only along the ±field directions.

The spins in layer i, $\mathbf{S}_i$, see an effective field $\mathbf{H}_i$:

$$\mathbf{H}_i=\frac{1}{g\mu_B\hbar}(J_{i,i-1}\mathbf{S}_{i-1}+J_{i,i+1}\mathbf{S}_{i+1})+H_i^{\mathrm{in}}(S_i^z/S)\mathbf{z}$$
$$+(H_i^{\mathrm{out}}+4\pi M)(S_i^y/S)\mathbf{y}+H_0\mathbf{z}. \tag{1}$$

Here $J_{i,i-1}$ is the exchange coupling constant between planes i and $i-1$, H_i^{in} is the in-plane anisotropy field and H_i^{out} is the out-of-plane anisotropy field. The applied field H_0 is in-plane and along the z axis. In the long wavelength limit, out-of-plane fluctuations (in the y direction) of the magnetization produce demagnetizing fields $4\pi M_y$. The dipolar terms may be combined with the out of plane anisotropy acting on an individual layer.

The equations of motion for the spins in layer i can then be written $d\mathbf{S}_i/dt=\gamma\mathbf{S}_i\times\mathbf{H}_i$ where γ is the gyromagnetic ratio. Because of the exchange terms, the spins in layer i are coupled to the spins in the layers above and below. One generally further assumes that the excitation amplitudes (s_x and s_y) are small and the equations are linearized by neglecting terms quadratic in these variables. It is straightforward to solve numerically the coupled equations of motion if the number of layers is not too large. Useful analytical approximations for larger systems in certain special cases are described in Ref. 7.

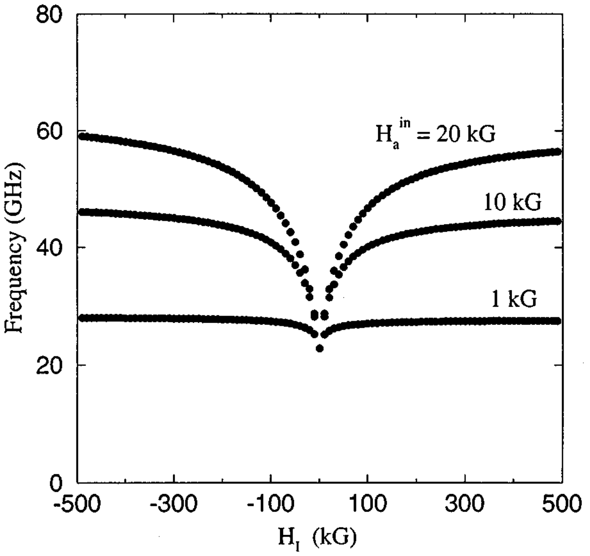

FIG. 1. Frequency as a function of interface exchange for different values of in-plane anisotropy in the antiferromagnet.

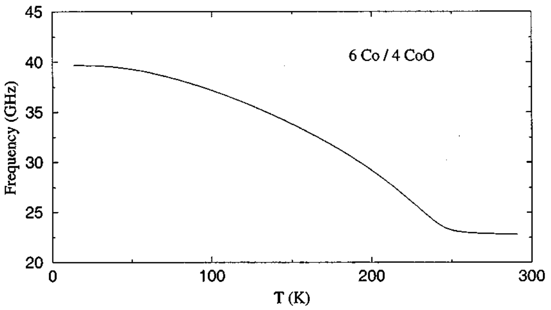

FIG. 2. Frequency of the lowest spin wave mode in a six layer Co/four layer CoO structure as a function of temperature. $H_I = -50$ kG and $H_a^{\mathrm{in}} = 2$ kG.

Our model parameters are not intended to represent a particular system, but are close to those for Co/CoO thin films.[5] For the ferromagnet, the exchange field is $H_{ex} = 1000$ kG and $M_s = 1.4$ kG. For the antiferromagnet $H_{ex} = 500$ kG and $M_s = 0.6$ kG. We take $S_a = S_b = 1$ and the gyromagnetic ratio $\gamma = 2.9$ GHz/kG. The applied field H_0 is 3 kG. Exchange J is contained in an effective field H_I.

We consider a six layer ferromagnetic film coupled to a four layer antiferromagnetic film. In Fig. 1 we plot frequency as a function of interface exchange for different values of the uniaxial in-plane anistropy. We note that anisotropy values in antiferromagnets can be quite large compared to those for typical ferromagnetic metals. For example, the uniaxial in-plane anisotropy in FeF_2 is on the order of 200 kG. The frequency increases with an increasing in plane anisotropy, increased interfacial coupling, and increasing CoO thickness. Similar effects are found for out-of-plane anisotropies, but the magnitude is significantly smaller.[7] Because out-of-plane anisotropy should not change the hysteresis curve, but does change the frequency, a comparison of spin wave frequencies and magnetization data might be able to provide a value for the out-of-plane anisotropy.

Interestingly, the high frequency spin wave modes associated with the Co film change much more rapidly than the lowest frequency modes as a function of interfacial exchange. These spin waves might be measured by a number of different techniques. For example Raman scattering has been used to measure spin wave modes in thin Fe films in the 500 GHz region. Similarly far-infrared spectroscopy has been used to study antiferromagnets in the same frequency range.

So far in the discussion, the examples have been made at low temperatures where the average spin moments in the antiferromagnet have their full magnitude. As the temperature is increased we approximate the effects of temperature on the spin wave frequencies by replacing the spin magnitudes by their thermal averaged values. It is expected that these values will generally vary from layer-to-layer in very thin structures. Using a self-consistent local mean field method, we calculate the average spin moment in each layer of the antiferromagnet for a given temperature.

The temperature dependent frequency of the lowest spin wave mode is presented in Fig. 2. The parameters for this calculation are $H_{ex} = 505$ kG, $S_{af} = 2$ which places the transition temperature for the CoO at 293 K. Because of finite size effects the effective transition temperature in the four layer antiferromagnet is lowered to about 250 K. This is consistent with the experimental data of Ref. 5. An in-plane anisotropy field of 2 kG for the antiferromagnet has also been included. We see that as the temperature is reduced, the frequency of the spin wave begins to rise around 250 K and has doubled its value by low temperatures. This is very similar to the recent experimental results in Ref. 5.

FREQUENCY SHIFTS IN FERROMAGNET/ ANTIFERROMAGNET/FERROMAGNET SANDWICHES

A common experimental structure is a multilayer ''sandwich'' consisting of two ferromagnets separated by an antiferromagnetic film.[9] The system we study is similar to that in the previous section except that now there are no anisotropies. Coupling through the antiferromagnet is especially interesting because it is fundamentally different than simple antiferromagnetic coupling between ferromagnets.[10] With no applied field, the magnetizations in the ferromagnets will be antiparallel if the antiferromagnet has an even number of layers. In the presence of an external field, the magnetizations in the ferromagnets will cant toward the field direction. Since canting exists only because of antiferromagnetic order, we expect that the canting angle will be sensitive to temperature as well as field.

Our calculation method is different than the one used in the previous section, and allows us to find simultaneously the dynamic response and static ground state configuration. The idea is to solve the damped time dependent equations of motion directly using second order Runge–Kutta.[11] In order to do this, we use the fields defined in Eq. (1) but add a damping term of the form $\alpha \mathbf{S} \times \mathbf{S} \times \mathbf{H}$ to the equations of motion. The calculation then proceeds by allowing the variables $\mathbf{S}$ to relax to their time independent values. A Fourier analysis of time dependent data taken during the relaxation process gives the dynamic excitation frequencies.

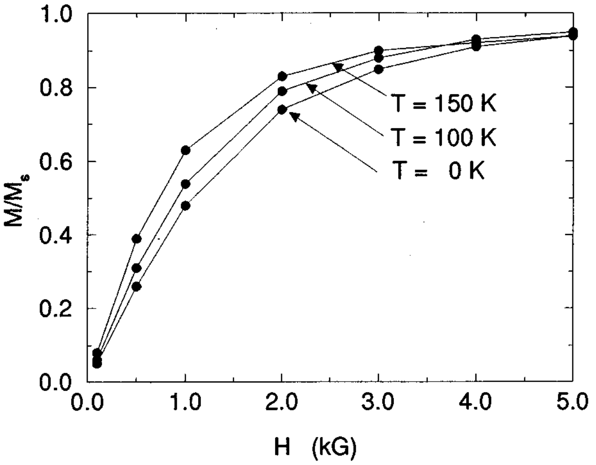

FIG. 3. Magnetization as a function of applied field for a four layer ferromagnet/four layer antiferromagnet/four layer ferromagnet sandwich structure. The effective interface exchange field is 7.5 kG $T=0$.

The magnetization of a four layer antiferromagnet sandwiched between two four layer ferromagnets is shown in Fig. 3 as a function of applied field. Results for different temperatures are presented, and the exchange constant of the antiferromagnet has been chosen to give a transition temperature around 200 K. At low temperatures, the effect of the antiferromagnet is large so that the magnetization does not saturate except at large fields. The structure becomes softer with increasing temperature and saturates at lower fields.

Low frequency spin waves in the two film structure are typically called acoustic or optic depending on the relative phase between the oscillating magnetizations in each ferromagnetic film.[12] The frequencies of these modes are shown in Fig. 4 as functions of temperature for the sandwich structure. The parameters are the same as in Fig. 3. The optic mode shows a strong decrease with temperature while the acoustic mode increases slightly. The acoustic mode frequency goes roughly as $[H(H+4\pi M\cos\theta)]^{1/2}$ where θ is the canting angle.[13] Since the product $M\cos\theta$ does not vary considerably at low temperatures, the acoustic mode is nearly constant at low temperatures.

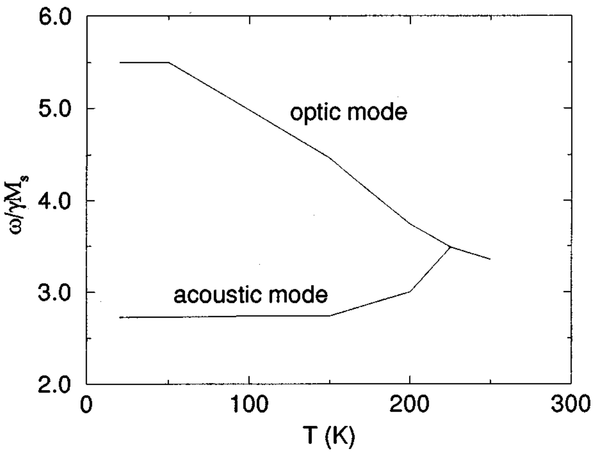

FIG. 4. Spin wave frequencies as a function of temperature for the sandwich structure of Fig. 3 with the applied field held constant at 1 kG. The two modes are degenerate above the transition temperature of the antiferromagnet.

As has been emphasized in the literature,[8] the antiferromagnet/ferromagnet interface can be quite complex. Nonetheless, we expect that our results will give a reasonable guide to the behavior in this and similar systems, such as Fe films with Cr overlayers at low temperatures.

ACKNOWLEDGMENTS

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