Ferromagnetic-resonance spectrum of exchange-coupled ferromagnetic bilayers

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The technique of ferromagnetic resonance is used currently to extract quantitative information on the strength of the exchange coupling between ultrathin ferromagnetic films, possibly separated by a thin layer of nonmagnetic material. The data are analyzed frequently within a model that treats the magnetization within each film as a rigid, precessing moment. We comment on the limits of validity of this picture, and also on the nature of the boundary condition applicable at the interface between two exchange-coupled media.

I. INTRODUCTION

There is currently great interest in the nature of the exchange coupling between thin ferromagnetic layers, either in direct contact, or possible separated by thin layers of nonferromagnetic material. Examples are provided by Fe-Cr-Fe trilayers,[1] Fe-Cu-Fe trilayers,[2] and Fe-Ni bilayers.[3] While aspects of this topic were explored in the experimental[4] and theoretical literature many years ago,[5,6] the current upsurge of interest has its origin in the current ability to prepare very high-quality multilayers of ultrathin (few-atomic-layer) films, within which interface quality is as high as realized in semiconductor superlattice structures.

The ferromagnetic resonance spectrum of ultrathin bilayers is analyzed often within a simple model that supposes the magnetization inside each film precesses rigidly, influenced by surface and interfacial anisotropies, along with the interfilm exchange coupling. Such a picture also forms the basis of an effective medium theory of the response of superlattices.[7] A particularly careful and complete discussion of such analyses, along with data on Fe-Ni bilayers, can be found in Ref. 3.

Quite clearly, in the very-thin-film limit, there is no problem with modeling the magnetization of a film as a simple, rigid precessing magnetization vector, excited into motion by an external field. As the film thickness increases, however, there will be spatial gradients in the dynamic magnetization, and the simple picture just outlined requires modification. For a bilayer, the separation in frequency between the "acoustic" and "optical" modes of the structure will be controlled not only by the interfilm coupling, but by contributions within the constituent films. A full theory of the response of the structure is required before quantitative conclusions can be made.

The purpose of this Brief Report is to present a simple calculation which leads to a criterion that outlines the range of film thicknesses within which the simple rigid moment picture may be applied to the individual films. While we resort to a specific model, we believe the criterion stated below is more general, and can provide a "rule of thumb" for validity of such a picture. Also, we comment on the structure of the boundary condition at the interface between two exchange-coupled media.

II. THE CALCULATION

We consider an explicit model of a bilayer, in the form of a sequence of planes that stack to form an fcc structure. There is an interface between two materials that coincides with the xy planes; each is an fcc film with identical lattice constant a_0. The interface is parallel to a (100) plane, and the separation between adjacent (100) planes is $a_0/2$. In the lower half space, we have Heisenberg ferromagnet A, in which the spins S_A interact via nearest-neighbor exchange J_A. The upper half space contains ferromagnet B, within which nearest-neighbor spins S_B are coupled by exchange J_B. Across the interface, nearest neighbors interact via the interface exchange J_I. A Zeeman field $\mathbf{H}_0$ is parallel to $\hat{\mathbf{z}}$, and we introduce also single-site anisotropies of the form $-K_{A,B}(S_{A,B}^{(z)})^2$ within each interface at the boundary between the materials. We do ignore dipolar interactions between the spins, which, of course, enter importantly for the systems studied experimentally. This does enable us to carry through an analysis in an elementary manner, to obtain a simply stated criterion in the end.

One considers long-wavelength disturbances in the spin system on each side of the interface. With dipolar, coupling ignored, only $S^+=S^x+iS^y$ enters. From the microscopic equations of motion one finds, with frequencies in magnetic field units,

$$\frac{\partial S_{A,B}^+}{\partial t}=(H_0-D_{A,B}\nabla^2)S_{A,B}^+ , \tag{1}$$

where $D_{A,B}=a_0^2 J_{A,B}S_{A,B}$. Equation (1) must be supplemented by two boundary conditions at the interface. These may be derived from the microscopic equations of motion. With $H_{A,B}^{(s)}=2S_{A,B}K_{A,B}$ the effective pinning fields experienced by the spins in the interface, we find at $z=0$ one has

$$4J_I(S_A S_B^+ - S_B S_A^+) = H_A^{(s)}S_A^+ + 2a_0 S_A J_A\frac{\partial S_A^+}{\partial z} - 2a_0 S_A J_I\frac{\partial S_B^+}{\partial z} \tag{2}$$

and

$$4J_I(S_BS_A^+-S_AS_B^+)$$
$$=H_B^{(s)}S_B^+-2a_0S_BJ_B\frac{\partial S_B^+}{\partial z}+2a_0S_BJ_I\frac{\partial S_A^+}{\partial z}\ . \quad (3)$$

If we compare with the statements discussed by earlier authors,[3,8] taking due account of the difference in notation, one finds the last terms on the right-hand sides of Eqs. (2) and (3) are missing. These terms must, in fact, be present. Suppose we set $H_A^{(s)}=H_B^{(s)}=0$, $S_A=S_B$, and $J_A=J_B=J_I$. Then we have an extended single film with no internal interface. Equations (2) and (3) place no constraint on $S^+(\mathbf{r})$ for this case, while if the last term is omitted we have the unphysical constraint $\partial S^+/\partial z=0$ at a mathematical plane in a homogeneous crystal. These last terms will enter very importantly, in practice whenever the exchange J_I across the interface is comparable to that $J_{A,B}$ within the films. Clearly, the boundary condition introduced some years ago by Hoffman[8] is incorrect.

We now apply the above to the analysis of a model bilayer, supposing $H_A^{(s)}=H_B^{(s)}=0$. As a model of Fe-Cr-Fe or Fe-Cu-Fe when the Fe films couple antiferromagnetically, we take $J_A=J_B=J$, $S_B=-S_A=-S$, and $J_I=-|J_I|$. At the outer surfaces, $z=-L_A$ and $z=+L_B$, we let $(\partial S_A^+/\partial z)_{-L_A}=(\partial S_B^+/\partial z)_{L_B}=0$. Since the left-hand side of Eq. (3) is equal but opposite in sign to that in Eq. (2) we have at the interface

$$\left[\frac{\partial S_A^+}{\partial z}\right]_0=-\left[\frac{\partial S_B^+}{\partial z}\right]_0\ . \quad (4)$$

We have also from either Eq. (2) or Eq. (3),

$$S_B^++S_A^+|_0=-\frac{a_0}{2}\left[\frac{J}{|J_I|}-1\right]\frac{\partial S_A^+}{\partial z}\bigg|_0\ . \quad (5)$$

For a mode of frequency Ω, with due account of the boundary condition at the outer surfaces, we have $S_A^+=a\cos[\kappa(L_A+z)]$ and $S_B^+=b\cos[\kappa(L_B-z)]$, where $\kappa=[(\Omega-H_0)/D]^{1/2}$. Application of Eq. (4) gives $b=+a\sin(\kappa L_A)/\sin(\kappa L_B)$. For the structures of interest, where the interfilm coupling is transmitted through an intervening film, we have $|J_I|\ll J_F$. We then write $(J/|J_I|-1)\cong J/|J_I|$ and Eq. (5) gives

$$\kappa\sin(\kappa L_A)\sin(\kappa L_B)=\frac{2|J_I|}{Ja_0}\sin[\kappa(L_A+L_B)]\ , \quad (6)$$

from which the mode frequencies are determined.

Note that $\kappa\equiv 0$ is a solution of Eq. (6). This is the "acoustic" mode, where all spins move in phase. Its frequency is independent of J_I or J.

In the thin-film limit, we search for another mode where the magnetization is uniform across the film. We suppose $\kappa L_A\ll 1$ and $\kappa L_B\ll 1$. We then have a solution with

$$\kappa^2=\frac{2|J_I|}{Ja_0}\left[\frac{1}{L_A}+\frac{1}{L_B}\right]=\frac{4|J_I|}{J_Fa_0^2}f\ , \quad (7)$$

where $f=(a_0/2)(1/L_A+1/L_B)$ is the fraction of the spins in the sample which reside in the interface. Rearranging, and noting $D=a_0^2JS$ gives the frequency of this mode as

$$\Omega=H_0+4|J_I|Sf\ . \quad (8)$$

This is the "optical mode" excited in a ferromagnetic resonance experiment. The quantity $4|J_I|S$ is the magnitude of the exchange field felt by a single spin in the interface, by virtue of exchange coupling to its neighbors on the other side. The frequency difference between the "optical" and the "acoustical" modes thus provides a simple and direct measure of the exchange across the interface.

The frequency splitting between the optical and acoustical modes provides a direct measure of J_I only when the assumed conditions $\kappa L_A\ll 1$ and $\kappa L_B\ll 1$ are satisfied. Suppose, for simplicity, that $L_A=L_B=L$. Then $\kappa=(4|J_I|/a_0JL)^{1/2}$ for the optical mode, and the condition $\kappa L\ll 1$ requires

$$\frac{2L}{a_0}\ll\frac{J}{2|J_I|}\ . \quad (9)$$

When this condition is violated, the notion that one can view the precessing magnetization within a film as uniform breaks down, and a full analysis is required. Recall that we have assumed $|J_I|\ll J$.

III. SUMMARY

We have tried to outline, within a simple model, the regime of film thicknesses within which the magnetic response of multilayer media may be analyzed through use of a picture that treats the precessing magnetization within a given film as spatially uniform. When the interfacial exchange J_I is small compared to that within the films, a condition encountered when the exchange is transmitted through a nonferromagnetic layer between the two ferromagnets, we obtain the statement displayed in Eq. (9).

In the course of our discussion, we note the presence of terms in the boundary condition applicable at the interface evidently absent from the earlier work of Hoffman. They play a minor role in the limit $|J_I|\ll J$, but are required in general.

In a number of the trilayers examined to date, the exchange $|J_I|$ transmitted through the nonferromagnetic film is typically a few percent of that within the ferromagnetic films. We may then expect the breakdown of the uniform precessing magnetization model when the film is 10 or 15 layers thick.

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