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Ferromagnetic resonance of exchange-coupled magnetic layers

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The ferromagnetic resonance-line shapes, fields, and intensities of exchange coupled magnetic multilayers are calculated as a function of exchange coupling and number of layers. We find that the number of magnetic excitations equals the number of layer pairs that make up the layered structure. The magnetic dispersion of these excitations is easily calculable from the theoretical formulation developed earlier. It is suggested that the multitude of ferromagnetic resonance lines in magnetic superlattices observed experimentally elsewhere may be explained in terms of an earlier calculation involving surface magnetic anisotropy fields only.

INTRODUCTION

The fabrication of new artificial materials has stimulated scientific interest in the basic properties of coupled layers. From a scientific point of view this means that it may now be possible to study the fundamental interaction between ions which do not form thermodynamically stable materials. The principal issue of this emerging science is the predictability and detection of so-called superlattice effects. By superlattice effects we mean effects which cannot be described solely in terms of single-layer effects. A superlattice effect usually involves the excitation of multilayers coupled by a common interaction between layers. For example, in magnetic superlattices (as we are considering in this paper) the predominant coupling between layers is either the magnetostatic or exchange interaction, depending upon the separation between layers.

Magnetostatic coupling has been shown¹ to influence the dispersion of magnetostatic waves in magnetic superlattices. Experimental efforts have been initiated² to detect these coherent waves in superlattice structures in which the separation between magnetic layers is on the order of 0.1 to 1 μm . For atomic-scale separations exchange coupling is the predominant interaction between layers. In this limit it has been demonstrated^{3,4} that static field properties may be directly affected. In this paper we show that dynamic field properties of magnetic superlattices are also directly affected by exchange coupling between layers. In particular, we consider the ferromagnetic resonance (FMR) of coupled magnetic layers of iron and iron alloy. We believe that the technique of FMR is useful for the investigation of exchange effects in magnetic superlattices.

The calculation of the FMR frequencies in metallic media usually involves the calculation of the surface impedance Z_s , from which the FMR frequencies, linewidths, etc., may be determined.⁵ The calculation of the FMR frequencies of a multilayered metallic structure was considered previously.⁶ In this⁶ model the calculation involved the combination of *all* the boundary equations into a set of coupled algebraic equations to be solved for the internal electromagnetic field amplitudes. We find this method mathematically unappealing, since the algebraic complexity increases as the number of layers that make up

the structure increases.

We have devised a formulation by which the algebraic complexity does not increase with the number of layers in a superlattice, that is, a multilayered structure consisting of identical pairs of layers. The external magnetic field is normal to the film plane. A detailed derivation of the formulation will be given elsewhere. However, we will outline here the method used in determining the effect of ferromagnetic exchange on the FMR of iron-iron alloy multilayered structure. The effect of antiferromagnetic exchange coupling will be considered elsewhere. FMR calculations of this kind are timely in view of recent experimental work^{7,8} on magnetic superlattices. FMR data⁸ on Co-Cr multilayers show a multitude of lines which have not yet been explained. We suggest that these lines are a manifestation of phenomena similar to those described here.

We find, for example, in our calculation that in the limit of small exchange or no coupling there are two FMR lines whose field positions can be predicted by a simple theory appropriate to a single layer. One line, H_+ , corresponds to the iron layer and the other, H_- , to the iron-alloy layer. As A_{12} , the exchange coupling between layers, is increased, $H_+ - H_-$ scales as A_{12} . Subsidiary or additional FMR lines appear for fields between H_+ and H_- , and as a rule the number of subsidiary lines *equals* the number of pair layers (iron-iron alloy layer) which make up the layered structure. In addition, we find that the FMR fields of the subsidiary lines are evenly spaced in magnetic field. We ascribe the excitation of these subsidiary lines to the many ways by which the surface magnetic anisotropy field can be varied at each surface. In contrast, in this calculation the mechanism for varying the surface fields from surface to surface is due to the variation in exchange coupling between layers; the variation in surface fields in Co-Cr layered structure⁹ may be growth induced or related only to interfacial effects.

OUTLINE OF CALCULATION

In Fig. 1 we present the structure to be considered. We assume normal incidence of the electromagnetic wave and symmetrical excitation of the layered structure. The

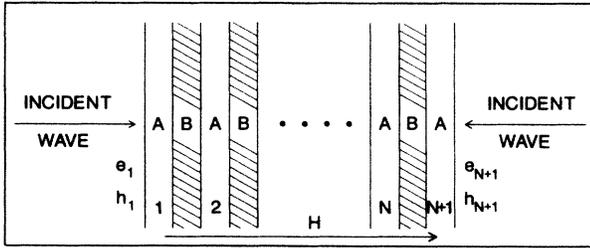


FIG. 1. The multilayered structure consists of ferromagnetic layers A and B. The structure is symmetrically excited by the electromagnetic field. H is the external magnetic field.

quantity of interest is the surface impedance, Z_s , of the first and last layers. The real part of the surface impedance is related to the FMR absorption⁵ of the structure. Z_s has been calculated for the case of no magnetic interaction between magnetic layers. We may write the boundary conditions at a given surface as⁶

$$\sum_{n=1}^4 [Z_n^{(L)} h_n^{(L)} \exp(-jk_n^{(L)} t) - Z_n^{(R)} h_n^{(R)} \exp(-jk_n^{(R)} t)] = 0, \quad (1)$$

$$\sum_{n=1}^4 [h_n^{(L)} \exp(-jk_n^{(L)} t) - h_n^{(R)} \exp(-jk_n^{(R)} t)] = 0, \quad (2)$$

$$\sum_{n=1}^4 [S^{(L)} h_n^{(L)} \exp(-jk_n^{(L)} t) + A_{12} Q_n^{(R)} h_n^{(R)} \exp(-jk_n^{(R)} t)] = 0, \quad (3)$$

$$\sum_{n=1}^4 [S^{(R)} h_n^{(R)} \exp(-jk_n^{(R)} t) - A_{12} Q_n^{(L)} h_n^{(L)} \exp(-jk_n^{(L)} t)] = 0. \quad (4)$$

The first two equations represent the continuity equations in the electric and magnetic electromagnetic fields, respectively. In the case where the medium to the left of the surface [superscript (L)] is free space the terms in the bracket with superscript (L) are replaced by e_1 and h_1 in Eqs. (1) and (2), respectively, where e_1 is the electric field and h_1 the magnetic field at the first layer. In the case where the medium to the right of the surface [superscript (R)] is free space, again the terms in the bracket with superscript (R) are replaced by e_L and h_L in Eqs. (1) and (2), respectively, where e_L and h_L are the surface fields at the last layer. The last two equations are the two spin boundary conditions at the surface common to the two magnetic layers. At the first layer Eq. (4) may be omitted and $A_{12} = 0$ in Eq. (3), since there is no exchange interaction between the first layer and free space. A_{12} is defined as the ferromagnetic exchange coupling parameter between two magnetic layers. It is assumed that the exchange coupling exists only between surface magnetic moments so that the static moments at the surface are parallel to each other. Hence, the exchange coupling only affects the microwave properties of the layered structure. Similarly, at the last layer Eq. (3) is omitted and $A_{12} = 0$

in Eq. (4). When the surface is *not* common with free space all of the four equations must be used. Z_n is the characteristic impedance of the layer and is equal to $jk_n c / 4\pi\sigma$, where c is the velocity of light, σ is the conductivity, and k_n is the allowable propagation constant in the magnetic layer. There are four normal modes⁹ of k_n . Only two give rise to magnetic resonance; the other two correspond to the antiresonant modes. We choose only the two resonant modes of propagation. The electromagnetic waves propagate in two directions so that we may write $k_3 = -k_1$ and $k_4 = -k_2$. For each k_n value there correspond two internal field amplitudes. Thus, for a given layer there are four internal field amplitudes. The coefficient S is deduced from the spin boundary conditions¹⁰ [Eqs. (3) and (4)], and is defined as

$$S_n = jQ_n k_n A$$

and

$$Q_n = \frac{1}{4\pi} \left[1 - \frac{j}{2} \delta^2 k_n^2 \right], \quad \delta^2 = \frac{c^2}{2\pi\sigma\omega}.$$

In comparison with the calculation of Ref. 10, it may be noted that in the expression for S_n we have put the surface uniaxial anisotropy parameter¹⁰ K_s equal to zero. We note that A_{12} plays a role similar to that of K_s in Eqs. (3) and (4). The exchange within a given layer is defined as the exchange stiffness constant and is equal to A .

Finally, t defines the surface location within the layered structure. For example, $t = 0$ corresponds to the free-space-magnetic-layer surface and $t = N(d_1 + d_2) + d_2$ corresponds to the magnetic-layer-free-space surface, where N is the number of pair layers, d_1 is the thickness of the iron layer, and d_2 the thickness of the iron alloy layer. There are $8N + 6$ equations, $8N + 4$ field amplitudes, and four surface-field variables (e_1, h_1, e_L , and h_L). The first two equations in this set of equations contain e_1 and h_L . For example, for $N = 0$ there are six equations, four internal-field variables, and four surface fields. Four equations contain e_1, h_1, e_L , and h_L , since we require the surface fields to be continuous across the surface. The remaining two equations are the spin boundary conditions at the surfaces of the *single layer*. The spin boundary conditions do not contain e_1, h_1, e_L , and h_L . For $N = 1$ they imply three layers (one pair layer and one single layer) and 14 equations, for example.

The object of this calculation is to be able to relate e_1 and h_1 to e_L and h_L or

$$\begin{bmatrix} e_1 \\ h_1 \end{bmatrix} = [A] \begin{bmatrix} e_L \\ h_L \end{bmatrix}, \quad (5)$$

where $[A]$ is a 2×2 matrix.⁵

We have developed a scheme to do this. The object is to relate at each surface the field amplitudes associated with the layer to the right of the surface in terms of field amplitudes corresponding to the layer positioned to the left of the surface using Eqs. (1)–(4). This then allows us to write the first three equations connected with the first layer in the structure in terms of field amplitudes associated with the right-hand layer. We repeat this by sequentially considering the next surface positioned to the right of the

previous surface. Eventually the set of three equations corresponding to the first layer are a function of only the four field amplitudes associated with the last layer exposed to free space. Great simplification is achieved, since now there are six equations and four field amplitudes⁵ rather than $8N+6$ equations and $8N+4$ variables. Using this process it may be possible to relate e_1 and h_1 to e_L and h_L , as shown in Eq. (5). Irrespective of the number of layers the number of equations reduces to six as described above. Hence, the complexity of the calculation does not increase with the number of layers. Equation (5) is of the proper form to derive⁵ the surface impedance, Z_s , of the whole structure.

RESULTS AND DISCUSSION

In Fig. 2 we plot $\text{Re}[Z_s]$ as a function of the external field, H . The FMR field is recognized as the field for which $\text{Re}[Z_s]$ is a maximum. We see in Fig. 2 that there are two resonance lines. One is associated with the iron layers ($4\pi M_s = 21\,500$ G) and the other with the iron-alloy layers ($4\pi M_s = 21\,000$ G). The thickness of each layer is 80 \AA and it is purposely chosen to be greater than the exchange coherence length.¹¹ The layers are assumed to be metallic with $\sigma = 5.8 \times 10^5 \text{ Scm}^{-1}$ and with an exchange stiffness constant value of $A = 1.9 \times 10^{-6} \text{ ergs/cm}$. The Landau-Lifshitz damping parameter was chosen to be $\lambda = 1 \times 10^7 \text{ Hz}$ for both layers. These values are typical for iron and iron-rich alloys. The two FMR lines tend to "repel" each other as the exchange coupling A_{12} between layers is increased (see inset in Fig. 2). The difference in FMR field between the two lines scales approximately with A_{12} .

In Fig. 3 we fix the value of A_{12} to be 0.2 erg/cm^2 , but vary the number of pair layers (N) that make up the multilayered structure. We see that as N is increased, subsidiary absorption lines appear for fields in between the two main FMR field lines, as defined above. As a rule we find that the number of subsidiary lines is equal to N and the

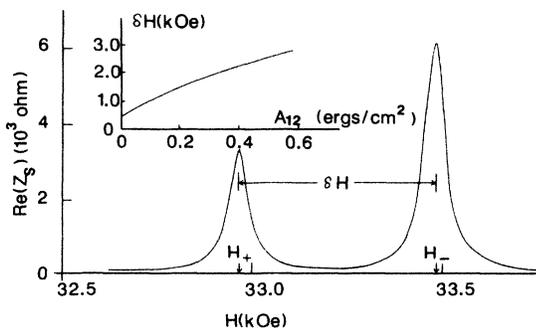


FIG. 2. The real part of the surface impedance Z_s is plotted as a function of the magnetic field H applied normal to the film plane. The operating frequency is fixed at 35 Hz. In the inset the difference in FMR fields, δH , between the two main lines is plotted as a function of A_{12} , exchange coupling. For $A_{12} = 0$, $\delta H = 4\pi\Delta M$, where ΔM is the change in saturation magnetization between the two ferromagnetic layers. For this calculation $N = 2$, the number of pair layers.

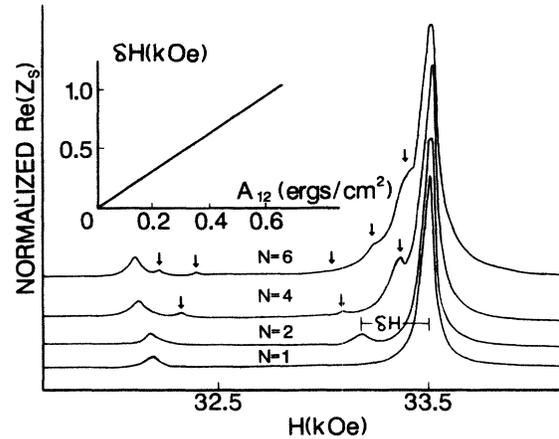


FIG. 3. $\text{Re}(Z_s)$ is plotted as a function of H for various values of N . In the inset the difference in FMR fields between the main FMR line and one subsidiary line is plotted as a function of A_{12} ($N = 2$).

absorption strength scales roughly as $1/N$. In order to quantify this part of the calculation, we plot in the inset of Fig. 3 the FMR field of one subsidiary line and the main iron line as a function of A_{12} for $N = 2$. We find that the difference in FMR fields between the main and subsidiary line is proportional to A_{12} . Repeating this calculation at various values of N does not change this conclusion.

The phenomena that we are describing in this paper may be explained as follows. The excitations of the subsidiary lines is a manifestation of the many ways in which the microwave magnetic field at the surface may vary at the surface. The number of ways equals the number of interfaces contained in the layered structure. The strength or magnitude of the surface magnetic field depends on A_{12} and the amplitude of the surface moments at adjacent layers [see Eqs. (3) and (4)]. These calculations imply that the effective surface field due to the exchange coupling is different from surface to surface, since the surface magnetic moment varies from surface to surface. Hence, the FMR of each layer occurs at fields slightly different from its neighbor.

From the experimental efforts⁸ we note that FMR measurements on Co-Cr show a multitude of FMR lines. We believe these multiple lines are a reflection of the many possible ways by which the surface magnetic fields vary at each layer. We suggest the source of the surface fields may be due to interfacial effects rather than exchange coupling between layers, since there is no exchange coupling between the magnetic layers. If we were to compare our calculations to the experimental results of Ref. 8, we would put $A_{12} = 0$ and $K_s \neq 0$ into Eqs. (1)–(4) at each surface. For this case the calculational results of Ref. 5 are sufficient (allowing K_s to vary at each Co surface).

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