Ferromagnetic resonance in a system composed of a ferromagnetic substrate and an exchange-coupled thin ferromagnetic overlayer

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The theory of Rado and Ament and the general exchange boundary conditions of Rado and Weertman have been used to discuss the magnetic field dependence of the absorption of microwave radiation by a composite system consisting of a thin ferromagnetic overlayer exchange coupled to a thick ferromagnetic substrate. The overlayer and substrate are assumed to interact through a surface exchange interaction of the form $E_{ex}=-J\mathbf{M}_A\cdot\mathbf{M}_B$. In the limit of weak to moderate coupling strengths, the overlayer ferromagnetic resonance (FMR) is shifted by an effective field of the form JM_B/d, where M_B is the substrate equilibrium magnetization and d is the overlayer thickness. Pronounced effects on the strength and position in magnetic field of the substrate absorption occur when the coupling parameter J is such that the overlayer and substrate FMR's occur at nearly the same value of applied magnetic field: The microwave absorption exhibits two peaks having comparable strengths. In the limit of very strong coupling ($J\sim10^{-4}$ cm) the magnetizations in the overlayer and in the substrate precess together to yield one absorption peak at a field value which is shifted from that corresponding to the isolated substrate FMR for an unpinned surface. The shift in peak position, as well as changes in the linewidth, is caused by an effective surface pinning due to the presence of the overlayer. This pinning can be described by an effective surface energy which contains contributions from the surface pinning energy at the free surface plus contributions which are proportional to the overlayer thickness and which depend on the difference in magnetization and on the difference in volume magnetocrystalline anisotropy fields between the substrate and overlayer materials.

INTRODUCTION

One would like to study the properties of very thin ferromagnetic metal films of variable composition and variable lattice parameters in order to compare those properties with first-principles calculations. Ideally, experiments on such specimens should be carried out with the films, a few atomic layers thick, suspended in a vacuum free from all external constraints. Realistically, very thin films must be supported on some kind of substrate and therefore both theory[1] and experiment have been directed towards the study of metallic overlayers,[2,3] interfaces,[4,5] and compositionally modulated structures.[6] The best characterized systems are those in which a single thin film has been grown on a polished bulk single-crystal substrate by molecular-beam epitaxy in ultrahigh vacuum. In a properly equipped system, a bulk crystal surface can be prepared which is smooth on an atomic scale over large areas and which is free from contamination. Moreover, in such a system, Auger electron spectroscopy, photoelectron spectroscopy, and low-angle electron diffraction are available to measure the cleanliness and quality of the substrate, as well as to monitor continuously the crystal structure, the crystalline perfection, and the purity of the epitaxial overlayer.

Arrott *et al.* have concentrated on the investigation of thin metal overlayers deposited by molecular-beam epitaxy on single-crystal metallic substrates.[7] They have recently reported the results of experiments on metallic overlayers grown on a single crystal of iron: The magnetic field at which ferromagnetic resonance (FMR) was observed in the iron was affected by the presence of a nickel overlayer but not by the presence of a manganese, manganese oxide, or a chromium layer.[8] In order to understand the results of those experiments, and in anticipation of further experiments of a similar type, we have been motivated to study the magnetic field dependence of the absorption of microwave radiation by a bulk ferromagnetic crystal whose surface has been covered by an overlayer of a second ferromagnetic crystal a few atomic layers thick. The two ferromagnetic materials are assumed to be exchange coupled at their interface by a surface energy per unit area of the form used by Hoffman, Stankoff, and Pascard[9] and by Hoffman:[10]

$$E_{ex}=-J\mathbf{M}_A\cdot\mathbf{M}_B\ , \tag{1}$$

where M_A,M_B are the magnetizations of the overlayer and of the bulk substrate.

THE MODEL

Consider the geometry illustrated in Fig. 1. A microwave field impinges at normal incidence from vacuum upon the surface of a ferromagnetic specimen consisting of a bulk crystal having a uniform magnetization density in equilibrium, $\mathbf{M}_B$, and covered by an overlayer, thickness d, of a second ferromagnetic material whose uniform magnetization density in equilibrium is $\mathbf{M}_A$. In this paper we shall explicitly consider the parallel configuration in which $\mathbf{M}_A,\mathbf{M}_B$ in equilibrium are parallel to the sur-

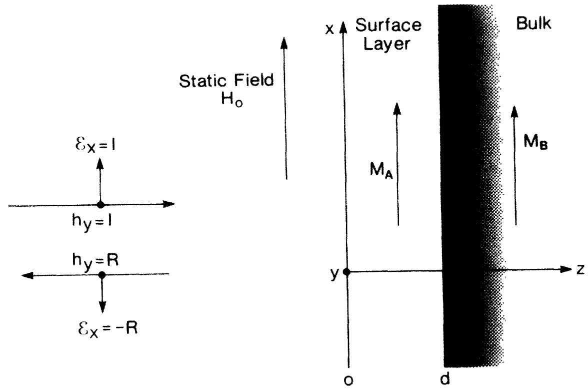

FIG. 1. The geometry used to calculate the response to incident microwave radiation of a bulk ferromagnet covered by a thin film of a second ferromagnet. The magnetizations in the two metals, M_A and M_B, are assumed to be uniform in equilibrium and parallel with the external field, H_0. The magnetizations in the film and in the bulk substrate are assumed to be coupled at their interface by an exchange energy of the form $E_{ex}=-J\mathbf{M}_A\cdot\mathbf{M}_B$.

face of the specimen, and are parallel to the external static field, $\mathbf{H}_0$ along a principle axis of the crystals: The generalization to the perpendicular configuration in which $\mathbf{H}_0$, $\mathbf{M}_A$, and $\mathbf{M}_B$ are perpendicular to the surface is straightforward. If the external field is taken to lie in any other direction, the problem becomes much more complicated because, in general, the equilibrium configuration does not correspond to a uniform magnetization either in the overlayer or in the bulk.[11]

The amplitude of the incident microwave magnetic field is a scaling factor which, for convenience in the computer calculation, is taken to be 1 Oe. With this convention, the total y component of the rf magnetic field amplitude at the surface of the specimen is $h_y \simeq 2$. This is because the rf surface impedance is so small, $z=e_x/h_y \sim 10^{-3}$, at the frequencies of interest here that the reflectivity is very nearly unity [recall that the ratio of the reflected amplitude of h_y to the incident amplitude of h_y is given by $R=(1-z)/(1+z)$].

The response of the model system of Fig. 1 to the incident rf microwave field can be calculated using the prescription of Ament and Rado:[12] Maxwell's equations for the electric and magnetic fields in the metals are combined with the Landau-Lifshitz equations of motion for the magnetizations, including exchange, and suitable boundary conditions on the rf electric fields, magnetic fields, and magnetizations are applied at the two boundary surfaces at $z=0$ and at $z=d$. The boundary conditions on the rf electric and magnetic field components are simple: the tangential components of **e** and **h** must be continuous across each interface. The boundary conditions on the rf magnetization components are more complex,[10,13] and are stated explicitly below. The solution of the full boundary value problem for the system shown in Fig. 1 requires the solution of a set of 10×10 equation for the nine unknown wave amplitudes in the metal (six in the overlayer, three in the bulk) and the reflected wave amplitude. The results are not particularly transparent. We have written a computer program which can be used to calculate the magnetic field variation of interesting quantities such as the microwave absorption coefficient, the derivative of the absorption, the wave vectors which characterize the solutions in each metal, and the spatial variation of the rf magnetization and magnetic field components. This program is very useful for the investigation of specific cases. However, in order to obtain an overview of the effect of exchange coupling between the two metals, it is useful to develop an approximate but analytical formalism. Before doing this we review the magnetic equation of motion and the boundary conditions appropriate to this problem.

The complication of having two magnetic systems leads to some difficulties in notation. We use M for vectors and magnitudes of the vectors, direction cosines for the components of the magnetization, and m for the complex amplitudes of $\exp(i\omega t)$. Thus for the overlayer magnetization

$$\mathbf{M}_A(z,t)=M_A[\alpha_1(z,t)\hat{\mathbf{x}}+\alpha_2(z,t)\hat{\mathbf{y}}+\alpha_3(z,t)\hat{\mathbf{z}}] ,$$

and for the substrate

$$\mathbf{M}_B(z,t)=M_B[\beta_1(z,t)\hat{\mathbf{x}}+\beta_2(z,t)\hat{\mathbf{y}}+\beta_3(z,t)\hat{\mathbf{z}}] .$$

A typical component is written as $M_B\beta_2(z,t)=m_B^y(z)\exp(i\omega t)$.

MAGNETIC EQUATIONS OF MOTION AND BOUNDARY CONDITIONS

The Landau-Lifshitz equation of motion is used with the Gilbert form for the magnetic damping term.[14] For the overlayer, and for the parallel configuration of Fig. 1, this is

$$-\frac{1}{\gamma_A}\frac{\partial \mathbf{M}_A}{\partial t}=\mathbf{M}_A\times\left[\mathbf{H}_{\rm eff}-\frac{\Gamma_A}{M_A}\frac{\partial \mathbf{M}_A}{\partial t}\right] , \quad (2)$$

where γ_A is the gyromagnetic ratio for the overlayer. The damping coefficient is often written as

$$\frac{\Gamma_A}{M_A}=\frac{G_A}{\gamma_A^2 M_A^2} , \quad (3)$$

where G_A is the Gilbert damping parameter. For the model used here the effective field, $H_{\rm eff}$, contains seven terms:

$$\mathbf{H}_{\rm eff}=H_0\hat{\mathbf{x}}+h(z,t)\hat{\mathbf{y}}+\mathbf{H}_k-4\pi M_A\alpha_3(z,t)\hat{\mathbf{z}} + \frac{2A_A}{M_A^2}\frac{\partial^2\mathbf{M}_A}{\partial z^2}+\mathbf{T}_{0A}\delta(z)+\mathbf{T}_{dA}\delta(z-d) . \quad (4)$$

The terms are described as follows.

(1) The direction of the applied field, H_0, lies in the plane of the crystal film and is chosen as the x axis.

(2) The direction of the microwave field, $h(z,t)$, lies in the plane of the film, perpendicular to the applied field, and is chosen as the y axis.

(3) The anisotropy field H_k depends on the direction of the magnetization with respect to the crystal axes. For

the overlayer we make the simplifying assumption that the x axis is a [100] direction for a cubic crystal. Then the anisotropy field H_k can be taken in that direction as a constant to first order in small quantities. $H_k = 2K_1/M$, where K_1 is the cubic anisotropy constant. Alternatively the anisotropy field could be chosen to have components $-2K_1\alpha_2/M_A$ and $-2K_1\alpha_3/M_A$ in the y and z directions, respectively. Both formulations give the same torques to first order. If the overlayer has its [001] axis perpendicular to the film and the dc field is in the [110] direction, the anisotropy field would be chosen with components $2K_1\alpha_2/M_A$ and $-K_1\alpha_3/M_A$ in the y and z directions, respectively. A full treatment of the effects of anisotropy and magnetostriction on FMR is found in Ref. 15.

(4) The magnetizing field $4\pi M_A\alpha_3\hat{\mathbf{z}}$ arises because the z component of the magnetic induction $\mathbf{B}(z,t)$ must vanish at every point in the present case where there is translational invariance in the x and y directions; $\partial B_z/\partial z = 0$ and there is no uniform field in the z direction.

(5) The exchange field arises from the excess exchange energy density which can be expressed as[16]

$$E_{\rm ex} = \frac{A}{M^2}[(\nabla\cdot\mathbf{M})^2 + (\nabla\times\mathbf{M})^2] , \quad (5)$$

where A is the exchange stiffness constant, which for a nearest-neighbor interaction $-2J\mathbf{S}_i\cdot\mathbf{S}_j$ in the simplest lattice structures, is given by[17]

$$A = c\frac{JS^2}{a_{\rm NN}} , \quad (6)$$

where $a_{\rm NN}$ is the nearest-neighbor distance and c depends on the lattice type; $c=1$ for sc, $c=\sqrt{3}$ for bcc, and $c=2\sqrt{2}$ for both fcc and ideal hcp.

(6) The model assumes a surface anisotropy field[11] which arises from a surface anisotropy energy density of the form

$$E_s = K_y\alpha_2^2 + K_z\alpha_3^2 , \quad (7)$$

which leads to the surface field

$$\mathbf{T}_{0A} = -\frac{2}{M_A}(K_y\alpha_2\hat{\mathbf{y}} + K_z\alpha_3\hat{\mathbf{z}}) \quad (8)$$

which acts to restore the magnetization toward the x axis for positive values of K_y and K_z. A possible origin of such a surface anisotropy could be the reconstruction[18] of the free surface (e.g., in a 2×1 structure) giving rise to an inplane Dzialoshinski-Moriya (DM) interaction.[19] The DM interaction is first order in the spin-orbit coupling in contrast to the bulk anisotropy which is second order.

The surface fields give rise to surface pinning. Hard pinning occurs when the surface field completely determines the magnetization direction at the surface. Intermediate pinning occurs when the magnetization direction is determined by a balance between the surface torque and the exchange torque which appears when there is a finite derivative of the magnetization at the surface. In the absence of a surface field, the normal derivatives of the magnetization must vanish at a planar surface. As shown some time ago by Rado and Weertman,[13] this can be seen by integrating over an infinitesimally small region at the surface. This gives the boundary condition for the top surface

$$\frac{2A}{(M_A)^2}\frac{\partial\mathbf{M}_A}{\partial z}\bigg|_0 = -\mathbf{T}_{0A} . \quad (9)$$

(7) The interfacial exchange energy density, Eq. (1), produces equal and opposite torques on adjacent layers of the substrate and overlayer. The surface fields are evaluated in the limit of small α_2, α_3, β_2, and β_3. The field acting on the overlayer is

$$\mathbf{T}_{dA} = -JM_B[(\alpha_2-\beta_2)\hat{\mathbf{y}} + (\alpha_3-\beta_3)\hat{\mathbf{z}}]\,|_d \quad (10a)$$

and on the substrate

$$\mathbf{T}_{dB} = JM_A[(\alpha_2-\beta_2)\hat{\mathbf{y}} + (\alpha_3-\beta_3)\hat{\mathbf{z}}]\,|_d . \quad (10b)$$

Clearly, as they must, these fields vanish if the magnetizations are parallel, irrespective of their orientations. For large coupling, very small deviations from parallelism give rise to large fields. The large coupling limit should correspond to the case in which the exchange interaction is intermediate between the exchange interactions in the overlayer and in the substrate. As above, the surface fields are balanced by normal derivatives of the magnetization on both sides of the interface.

$$\frac{2A_A}{M_A^2}\frac{\partial\mathbf{M}_A}{\partial z}\bigg|_d = \mathbf{T}_{dA} , \quad (11a)$$

$$\frac{2A_B}{MB^2}\frac{\partial\mathbf{M}_B}{\partial z}\bigg|_d = -\mathbf{T}_{dB} . \quad (11b)$$

That the torques are equal and opposite results in the pleasingly symmetric relation

$$\frac{2A_A}{M_A}\frac{\partial\mathbf{M}_A}{\partial z}\bigg|_d = \frac{2A_B}{M_B}\frac{\partial\mathbf{M}_B}{\partial z}\bigg|_d \quad (12)$$

The equations of motion for the problem of a ferromagnetic overlayer on a ferromagnetic substrate include: (1) the overlayer equations, Eq. (2) with the effective field defined by Eq. (4) which has terms elaborated in Eqs. (8) and (10); (2) the substrate equations which are similar to Eq. (2) after changing subscripts from A to B and replacing the α's with β's; (3) the magnetic boundary conditions given in Eqs. (9) and (11); (4) Maxwell's equations including the effects of eddy currents; and (5) the usual boundary conditions for the electric and magnetic fields.

To proceed further we write the equations for the overlayer for the linearized response to a time variation $\exp(i\omega t)$:

$$\frac{i\omega}{\gamma_A}m_A^y + (B_A + i\omega\Gamma_A)m_A^z - \frac{2A_A}{M_A}\frac{\partial^2 m_A^z}{\partial z^2} = \frac{-2K_z m_A^z}{M_A}\delta(z) - J[M_B m_A^z - M_A m_B^z]\delta(z-d) , \quad (13a)$$

$$(H_A+i\omega\Gamma_A)m_A^y-\frac{i\omega}{\gamma_A}m_A^z-\frac{2A_A}{M_A}\frac{\partial^2 m_A^y}{\partial z^2}=h_yM_A-\frac{2K_ym_A^y}{M_A}\delta(z)-J[M_Bm_A^y-M_Am_B^y]\delta(z-d)\ , \tag{13b}$$

where $H_A=H_0+2K/M_A$ and $B_A=H_0+2K/M_A+4\pi M_A$ for the field along the [100] direction in the plane of the film or $H_A=H_0-2K/M_A$ and $B_A=H_0+K/M_A+4\pi M_A$ for the field along the [110] direction, with the [001] axis perpendicular to the film in either case. The boundary equations for the outer surface become

$$A_A\left.\frac{\partial m_A^y}{\partial z}\right|_0=K_ym_A^y(0)\ , \tag{14a}$$

$$A_A\left.\frac{\partial m_A^z}{\partial z}\right|_0=K_zm_A^z(0)\ . \tag{14b}$$

The boundary conditions for the interface are

$$\left.\frac{2A_A}{M_A}\frac{\partial m_A^y}{\partial z}\right|_d=JM_AM_B\left[\frac{m_B^y(d)}{M_B}-\frac{m_A^y(d)}{M_A}\right]=\left.\frac{2A_B}{M_B}\frac{\partial m_B^y}{\partial z}\right|_d , \tag{15a}$$

$$\left.\frac{2A_A}{M_A}\frac{\partial m_A^z}{\partial z}\right|_d=JM_AM_B\left[\frac{m_B^z(d)}{M_B}-\frac{m_A^z(d)}{M_A}\right]=\left.\frac{2A_B}{M_B}\frac{\partial m_B^z}{\partial z}\right|_d . \tag{15b}$$

Equations (14) and (15) constitute a complete set of boundary conditions on the components of the magnetization; when combined with the continuity conditions on the tangential components of **e** and **h**, the response of the system to the incident microwaves is completely determined.

SIMPLIFIED TREATMENT OF THE OVERLAYER

In order to obtain a simpler formulation of the problem of the effect of exchange coupling on the response of the overlayer and of the bulk, the equations of motion (13) for the overlayer magnetization are integrated over an interval which extends from just inside the front surface ($z=\epsilon$) to just inside the rear surface ($z=d-\epsilon$) where ϵ is an infinitesimal. Divide the resulting equations by the thickness, d, and define

$$M_Y=\frac{1}{d}\int_0^d m_A^y(z)dz\ , \tag{16a}$$

$$M_Z=\frac{1}{d}\int_0^d m_A^z(z)dz\ . \tag{16b}$$

The resulting equations for the average magnetization components M_Y, M_Z are the following:

$$\frac{i\omega}{\gamma_A}M_Y+(B_A+i\omega\Gamma_A)M_Z-\left.\frac{2A_A}{dM_A}\frac{\partial m_A^z}{\partial z}\right|_d+\left.\frac{2A_A}{dM_A}\frac{\partial m_A^z}{\partial z}\right|_0=0\ , \tag{17a}$$

$$(H_A+i\omega\Gamma_A)M_Y-\frac{i\omega}{\gamma_A}M_Z-\left.\frac{2A_A}{dM_A}\frac{\partial m_A^y}{\partial z}\right|_d+\left.\frac{2A_A}{dM_A}\frac{\partial m_A^y}{\partial z}\right|_0=\frac{M_A}{d}\int_0^d h_y(z)dz\ . \tag{17b}$$

The surface terms contribute nothing to the integrals because the surfaces have not been included in the range of the integration. However, the boundary conditions, Eqs. (14) and (15), which have been derived from the surface terms, can be used to eliminate the surface derivatives from Eqs. (17). Moreover, if the overlayer is very thin compared with the spatial variation of the fields and magnetization, i.e., if d is very small compared with the rf skin depth, one can write

$$m_A^y(0)\simeq m_A^y(d)=M_Y\ , \tag{18a}$$

$$m_A^z(0)\simeq m_A^z(d)=M_Z\ , \tag{18b}$$

and

$$\frac{1}{d}\int_0^d h_{y(z)dz}\simeq h_y(A)\ . \tag{18c}$$

Combining Eqs. (14), (15), (17), and (18) gives the desired equations which relate the response of the overlayer to the driving rf magnetic field and to the magnetic response of the bulk material:

$$i\left[\frac{\omega}{\gamma_A}\right]M_Y+\left[B_A+\frac{2K_z}{dM_A}+\frac{JM_B}{d}+i\omega\Gamma_A\right]M_Z=\frac{JM_A}{d}m_B^z(d)\ , \tag{19a}$$

$$\left[H_A+\frac{2K_y}{dM_A}+\frac{JM_B}{d}+i\omega\Gamma_A\right]M_Y-i\left[\frac{\omega}{\gamma_A}\right]M_Z=h_y(A)M_A+\frac{JM_A}{d}m_B^y(d)\ . \tag{19b}$$

Equations (19) are just the equations of motion for a uniform magnetization with driving terms from the surface magnetization of the substrate as well as from the incident microwave radiation. If these equations are solved for M_Y and M_Z as functions of m_B^y, m_B^z, and $h_y(A)$, one obtains pinning conditions for the substrate magnetization which do not explicitly contain the overlayer magnetization components. As an example, we write out the boundary condition Eq. (15b) using an obvious symbolic notation:

$$\frac{2A_B}{M_B}\frac{\partial m_B^z}{\partial z}\bigg|_d = JM_A m_B^z(d) - JM_B M_Z\{m_B^y(d), m_B^z(d), h_y(A), D\} \tag{20}$$

where D is the resonant denominator given by

$$D=\left[\frac{\omega}{\gamma_A}\right]^2-\left[B_A+\frac{2K_z}{dM_A}+\frac{JM_B}{d}+i\omega\Gamma_A\right]\times\left[H_A+\frac{2K_y}{dM_A}+\frac{JM_B}{d}+i\omega\Gamma_A\right]. \tag{21}$$

These pinning conditions are peculiar in two respects:

(a) They contain not only the derivative of a particular substrate magnetization component plus a term proportional to that same magnetization component, but they also contain a term proportional to the driving rf magnetic field and a term proportional to the other component of the substrate magnetization.

(b) The contributions to the substrate pinning from the terms like JM_BM_Z will depend upon how nearly the condition is met for ferromagnetic resonance of the overlayer (real part of $D=0$). The effective pinning of the substrate magnetization components due to exchange coupling with the overlayer will be particularly important when the substrate and overlayer resonances occur at nearly the same value of applied magnetic field. Moreover, the effective pinning parameter for the substrate magnetization can become negative for a particular range of coupling strength. A negative pinning parameter favors an enhanced amplitude for the nonpropagating spin-wave mode at fields larger than the FMR field, and can lead to a second, high-field absorption peak in addition to the main FMR absorption peak.[20–22] This point will be illustrated below in the calculation for the particular case of a 50-Å-thick nickel overlayer on a bulk iron single crystal with various choices of coupling.

FURTHER COMMENTS

Any pinning at the surface of the thin overlayer film appears in the equations of motion for M_Y, M_Z like a bulk magnetocrystalline anisotropy term. This result has been previously obtained by Rado.[11] As pointed out by Rado, any surface pinning of the overlayer shifts the FMR field for the thin layer by an amount which is inversely proportional to its thickness.

Exchange coupling to the bulk substrate introduces an effective field, similar to the surface pinning term, which shifts the position of the overlayer FMR field by an amount proportional to the bulk magnetization, and inversely proportional to the overlayer thickness, d. Ferromagnetic coupling, $J>0$, shifts the resonance to lower magnetic fields.

For very small J, the magnetic coupling to the substrate becomes unimportant in the driving terms, and the overlayer responds to the driving rf microwave field as if it were an isolated film having an additional magnetocrystalline anisotropy field of JM_B/d. The criterion for very small J can be estimated if we assume that the substrate response, in the case that the substrate is not in resonance, is roughly $\beta_2(d)=h_y(A)/H_B$, where H_B is the effective dc field acting at the interface. Then the driving term in Eq. (19b) from the substrate coupling, $JM_A m_B^y(d)/d$, can be neglected with respect to the microwave field term $h_y(A)M_A$ if $(JM_B/dH_B)\ll 1$. Under these conditions, (JM_B/d), the shift in the overlayer resonance field from the effect of the coupling to the substrate, would be small, but still detectable for a linewidth that also is small compared with H_B.

STRONG COUPLING

For a strong coupling the substrate and overlayer magnetizations at the interface become locked together so that their angular deviations from equilibrium are substantially the same: $\alpha_2(d)\approx\beta_2(d)$ and $\alpha_3(d)\approx\beta_3(d)$. Since the angular deviations from equilibrium are the same, this implies that one can write

$$\frac{m_B^y(d)}{M_B}=\frac{m_A^y(d)}{M_A}\simeq\frac{M_Y}{M_A} \tag{22a}$$

and

$$\frac{m_B^z(d)}{M_B}=\frac{m_A^z(d)}{M_A}\simeq\frac{M_Z}{M_A}\,. \tag{22b}$$

These relations can be used together with 19(a), 19(b), and 15(a), 15(b) to write pinning equations for the substrate, correct to order d, which involve only substrate magnetization components:

$$\frac{2A_B}{M_B}\frac{\partial m_B^y}{\partial z}\bigg|_d=\left[\frac{2K_y}{M_B}\right]m_B^y(d)+\frac{dM_A}{M_B}\left[-h_y(A)M_B+(H_A+i\omega\Gamma_A)m_B^y(d)-\left[\frac{i\omega}{\gamma_A}\right]m_B^z(d)\right], \tag{23a}$$

$$\frac{2A_B}{M_B}\frac{\partial m_B^z}{\partial z}\bigg|_d=\left[\frac{2K_z}{M_B}\right]m_B^z(d)+\frac{dM_A}{M_B}\left[i\left[\frac{\omega}{\gamma_A}\right]m_B^y(d)+(B_A+i\omega\Gamma_A)m_B^z(d)\right] . \tag{23b}$$

Note that the interface exchange strength has dropped out of these pinning equations.

The bulk magnetization components must satisfy the appropriate torque equations [similar to (2) with appropriate change of subscripts]. It is within the spirit of simplicity already used to reach 23(a) and 23(b) to neglect the relatively small exchange fields within the bulk [at 9.56 GHz, and at resonance $(2A_B/M_B)k^2 \approx 110$ Oe compared with $H_B=400$ Oe and $B_B=23\,000$ Oe.] It is also reasonable to neglect damping terms so that, for purposes of estimating the effective pinning terms, one may write

$$\frac{i\omega}{\gamma_B}m_B^y(z)+B_B m_B^z(z)=0 , \tag{23c}$$

$$H_B m_B^y(z)-\frac{i\omega}{\gamma_B}m_B^z(z)=M_B h_y(z) . \tag{23d}$$

These last equations may be used to eliminate the cross terms from 23(a) and 23(b) in order to obtain pinning conditions that involve only the derivative of a component plus a term proportional to that same component. Finally, one can note that by continuity, $h_y(d)$ in the substrate must equal $h_y(A)$; moreover, $\gamma_A \simeq \gamma_B$ (for the case of a nickel overlayer on an iron substrate $\gamma_B/\gamma_A=0.95$). Using these approximations and Eqs. 23(c) and 23(d), one can rewrite the pinning equations 23(a) and 23(b) in the form

$$\frac{2A_B}{M_B}\frac{\partial m_B^y}{\partial z}\bigg|_d=\left[\frac{2K_y}{M_B}\right]m_B^y(d)-\frac{dM_A}{M_B}(H_B-H_A)m_B^y(d) , \tag{24a}$$

$$\frac{2A_B}{M_B}\frac{\partial m_B^z}{\partial z}\bigg|_d=\left[\frac{2K_z}{M_B}\right]m_B^z(d)-\frac{dM_A}{M_B}(B_B-B_A)m_B^z(d) . \tag{24b}$$

Recall the definitions of the fields H_A, H_B, B_A, and B_B from Eqs. (13): the difference (H_B-H_A) is just the difference in effective anisotropy fields between the substrate and the overlayer, and the difference (B_B-B_A) involves the difference between their magnetizations as well as the difference in anisotropy fields. For the specific case of a (001) nickel overlayer having its equilibrium magnetization along a cube axis deposited on a (001) iron substrate whose equilibrium magnetization lies along a [110] direction, one has

$$(H_B-H_A)=-\frac{2K_B}{M_B}-\frac{2K_A}{M_A}=1.03 \text{ kOe} ,$$

and

$$(B_B-B_A)=4\pi(M_B-M_A)+\frac{K_B}{M_B}-\frac{2K_A}{M_A}=17.87 \text{ kOe} ,$$

where the parameters from Table I have been used to evaluate the expressions.

It might at first be supposed that the terms in Eqs. (24) proportional to the thickness would be negligible for films sufficiently thin that the spatial variation of its magnetization can be neglected. However, using the above example, and a film 50 Å thick, it is easy to see that the term in H_B-H_A contributes an amount to the surface pinning equivalent to $K_y \simeq -0.12$ erg/cm^2 and the term in B_B-B_A contributes an amount equivalent to $K_z \simeq 2.18$

TABLE I. Parameters used to calculate the magnetic field dependence of the absorption of rf radiation by an iron substrate covered by a layer of "nickel." The parameters for iron are appropriate for a single crystal at 77 K having a [100] axis normal to the surface and the external field applied in the plane parallel with a [110] axis. "Nickel" parameters are those for room-temperature nickel except that K_1 has been chosen to shift the nickel FMR field well away from the FMR field for iron at 9.56 GHz.

Parameter	Iron (M_B along [110])	"Nickel" overlayer
Saturation magnetization M (kOe)	$M_B=1.756$	$M_A=0.489$
$4\pi M$ (kOe)	$4\pi M_B=22.07$	$4\pi M_A=6.14$
g factor	2.09	2.187
Exchange stiffness (erg/cm)	2.0×10^{-6}	1.0×10^{-6}
Gilbert damping parameter (Hz)	2.0×10^{8}	2.45×10^{8}
Resistivity (Ω cm)	3.3×10^{-6}	7.22×10^{-6}
Magnetocrystalline anisotropy constants	$K_1=5.3\times10^{5}$	$K_1=-4.0\times10^{5}$
(erg/cm^3)	$K_2=0$	$K_2=0$
Resonant field at 9.56 GHz (kOe)	1.005	2.945
Resonant field at 73 GHz (kOe)	16.48	22.63

ergs/cm^2. These are very substantial values, and are in excess of those required to explain most experiments carried out on bulk metals.[23–25] Moreover, thin epitaxial crystal films are often in a state of strain because of the mismatch between the lattices of the overlayer and bulk materials. A homogeneous strain of 1% in nickel, for example, can produce an effective volume anisotropy energy[26,27] characterized by $K_1^{\text{eff}} \simeq 2\times10^6$ erg/cm^3. It is apparent that strains of a few percent in the overlayer could result in appreciable pinning of the substrate magnetization for overlayer thicknesses of order 100 Å.

An interesting feature of the substrate pinning equations, either Eqs. (23) or (24), is that any pinning at the overlayer surface is transferred directly to the substrate in the limit of strong exchange coupling. It has been shown by Gradmann's group[4,5] that epitaxial ferromagnetic metal layers are often characterized by surface-energy parameters K_y, K_z of order 0.2 erg/cm^2: this is sufficient to produce pronounced shifts in the field at which substrate FMR occurs.

INTERMEDIATE PINNING

It was mentioned above that the exchange coupling between the overlayer and substrate could lead to very strong pinning effects on the substrate absorption for small and intermediate values of the coupling parameter, J, if the overlayer resonance occurred at nearly the same value of the applied field as the substrate resonance. This was a consequence of the resonant denominator, Eq. (21), which occurs in the effective boundary conditions for the substrate magnetization. For simplicity, neglect volume anisotropy terms and assume that the overlayer pinning parameters K_y, K_z are zero, i.e., the magnetization at the overlayer-vacuum interface is free to precess. Neglect the damping term, $i\omega\Gamma_A = i(\omega/\gamma_A)(G_A/\gamma_A M_A)$, and write the condition that the overlayer resonates at the field, H_0, at which the substrate resonates

$$\left[\frac{\omega}{\gamma_A}\right]^2 = \left[H_0 + \frac{JM_B}{d}\right]\left[H_0 + 4\pi M_A + \frac{JM_B}{d}\right] . \tag{25}$$

It is interesting that the condition (25) can be satisfied by two values of the coupling parameter, J. The two values of J in question are just those which shift the resonance fields for the uncoupled overlayer to the value H_0, the resonant field for the substrate. The equation from which one can calculate the resonant fields for the uncoupled overlayer is analogous to Eq. (25)

$$\left[\frac{\omega}{\gamma_A}\right]^2 = H(H + 4\pi M_A) , \tag{26}$$

neglecting magnetocrytalline anisotropy and surface pinning for simplicity. For a given value of (ω/γ_A), Eq. (26) has two solutions: one solution, H_1, is positive and corresponds to a realizable laboratory magnetic field; the other solution, H_2, corresponds to a negative magnetic field and is not realizable in practice. However, the effect of exchange coupling to the bulk is to introduce the effective field JM_B/d. If JM_B/d is positive, corresponding to ferromagnetic coupling, both H_1 and H_2 are shifted to *lower* fields. Thus for $J>0$, the overlayer exhibits only one resonant field for positive magnetic fields, and eventually even that resonant field is shifted to values less than zero and becomes inaccessible to experiment. On the other hand, a negative value of J shifts the resonant fields H_1 and H_2 to more positive values. Eventually, for sufficiently strong negative coupling, both H_1 and H_2 will be positive and therefore the overlayer will exhibit ferromagnetic resonances at two accessible values of the applied field. It should be clear from this discussion that a ferromagnetic coupling between the overlayer and substrate can be expected to have a strong effect on the substrate resonance only if the uncoupled overlayer FMR occurs at a larger field than the substrate FMR. However, antiferromagnetic coupling can lead to large pinning effects regardless of whether the overlayer resonance occurs at a lower or a higher field than the substrate resonance. It must be borne in mind that in order to observe large effects for either case, the value of J required to shift the overlayer resonance into coincidence with the substrate resonance must not be so large that the overlayer and substrate magnetizations become locked together.

All of the above points have been checked using a computer to solve the full boundary value problem for an iron crystal having an overlayer of a metal similar to nickel. Before describing those results it is useful to estimate the range of values for the surface-exchange parameter J that one might expect based upon the magnitude of the volume-exchange stiffness parameter, A.

ESTIMATE OF THE INTERFACIAL EXCHANGE COUPLING PARAMETER

For the continuum model one can connect J for the interface in the limit of strong coupling with a typical bulk value of A through the relation

$$J = \frac{2A}{M_A M_B b} \approx 10^{-4}\ \text{cm} , \tag{27}$$

where b is the separation of the layers. We have used a value $b = 1.8$ Å, M_A and M_B corresponding to Ni and Fe (see Table I), and a value of $A \approx 10^{-6}$ erg/cm which is intermediate between Ni and Fe. This follows from Eqs. (1) and (5) by considering what happens in the bulk if adjacent layers make an angle θ with one another, say in a twist. The excess exchange energy per unit volume $A(\text{curl}\,\mathbf{M}/M)^2$ is $A(\theta/b)^2$. Therefore the excess exchange energy per unit area for a pair of adjacent layers is $A\theta^2/b$. From the expression $-JM_AM_B$, the same twist gives an excess exchange energy per unit area of $JM_AM_B\theta^2/2$. As is shown explicitly from the computer calculations below, the values of J which lead to quite interesting effects from intermediate coupling are two orders of magnitude smaller than that estimated from Eq. (27).

One might well expect that good epitaxy between Fe and Ni would produce something close to the above estimate. Once the coupling is strong it becomes quite difficult to distinguish between different degrees of strong coupling. An FMR experiment could be used to deduce values of the exchange coupling parameter for intermediate and weak coupling. The experiments of Hoffman[10] on permalloy films coated on both sides by nickel suggest $J \sim 10^{-7}$ cm, which is quite a small value.

EXPERIMENTS WHICH COULD DETERMINE J

Equations (19) for the response of the average overlayer magnetization components M_Y, M_Z have been derived for the case in which the equilibrium magnetization and static field are parallel to the plane of the specimen (parallel configuration). Analogous expressions can be easily derived for the case in which the equilibrium magnetizations and external field are perpendicular to the specimen surface (perpendicular configuration). The resulting conditions for ferromagnetic resonance have a familiar form if one neglects surface pinning [i.e., $K_y = K_y = 0$ in Eq. (7)]:

$$\left[\frac{\omega}{\gamma_A}\right]^2 = \left[H_0 + \frac{JM_B}{d}\right]\left[H_0 + 4\pi M_A + \frac{JM_B}{d}\right] \quad \text{(parallel configuration)}\,, \tag{28a}$$

$$\frac{\omega}{\gamma_A} = H_0 - 4\pi M_A + \frac{JM_B}{d} \quad \text{(perpendicular configuration)}\,, \tag{28b}$$

Exchange coupling between the overlayer and the substrate introduces an effective anisotropy field that could, in principle, be measured using Eqs. (28) and the frequency dependence of the FMR fields for both the perpendicular and the parallel configurations. Of course, these experiments would be feasible only for small and intermediate values of the exchange coupling such that the overlayer and substrate magnetizations were not effectively locked together.

CALCULATIONS FOR A SPECIFIC EXAMPLE

To explore the effects of the strength and sign of J on FMR for thin ferromagnetic overlayers on a ferromagnetic substrate we adopt a model that is relevant to the experiments of Heinrich *et al.*[8] Their results, as we shall see, are for the strong coupling limit. A principal purpose of this paper is to investigate a full range of possibilities for the coupling as well a various choices of surface anisotropies in anticipation of what might be observed if the interaction between the Ni and Fe were modified, e.g., by depositing an intermediate nonmagnetic layer that would transmit a weaker exchange interaction. The geometry of Heinrich *et al.* had a 5 nm Ni overlayer grown epitaxially on the (001) surface of Fe with the field along the Fe [110] direction. The Ni overlayer had a strong effect on the iron FMR line at 77 K, but not at room temperature. The Ni overlayer appears to have a body-centered cubic structure. If this conclusion is further supported, it means that this is a new phase of Ni for which the properties are yet to be obtained. For the sake of calculations, we have used values appropriate for face-centered cubic Ni. The anisotropy of fcc Ni is negative and very rapidly varies with temperature below 200 K. We have chosen a value of $K_1 = -4\times10^5$ erg/cm^3 corresponding to Ni at approximately 140 K. In the model the applied field is along the [100] direction of fcc Ni. This puts the resonance frequency of Ni well above that of Fe which is useful for demonstrating the effects of varying the interfacial exchange coupling. For an epitaxial bcc Ni overlayer the field would be along the [110] direction. To obtain the same resonance frequency at 9.56 GHz the anisotropy constant for bcc nickel would be $K_1 = 4.8\times10^5$ erg/cm^3, positive, as it is in bcc Fe where $K_1 = 5.3\times10^5$ erg/cm^3. In the model, we have used the properties listed in Table I. The magnetic field dependence of the microwave absorption and its modification due to an exchange-coupled overlayer are calculated using the full formalism: Maxwell's equations with the usual boundary conditions plus the Landau-Lifshitz equations, Eq. (13) for the overlayer and a similar set for the substrate, and the boundary conditions, Eqs. (14) and (15).

The results of the calculations for the absorption derivative at a frequency of 9.56 GHz are shown in Figs. 2, 3, 9, and 10 for ferromagnetic exchange coupling ($J > 0$), and for an overlayer 50 Å thick. For this thickness the spatial variation of the magnetization across the film was less than 10%. The magnetic field dependence of the absorption derivative is shown in Fig. 2 for small values of J. For no exchange coupling the "nickel" resonance occurs at 2.945 kOe and the iron resonance occurs at 1.005 kOe. As the coupling is increased, the nickel resonance shifts to lower fields because of the effective internal field JM_B/d. This field is substantial: for $J = 5\times10^{-7}$ cm it gives a shift of 1.756 kOe. As the nickel resonance shifts closer to the iron resonance its strength increases due to the driving effect of the precessing magnetization in the iron. At the same time, the iron resonance shifts slightly down in field and becomes somewhat weakened due to the pinning effects of the nickel overlayer. Moreover, the iron response at the field corre-

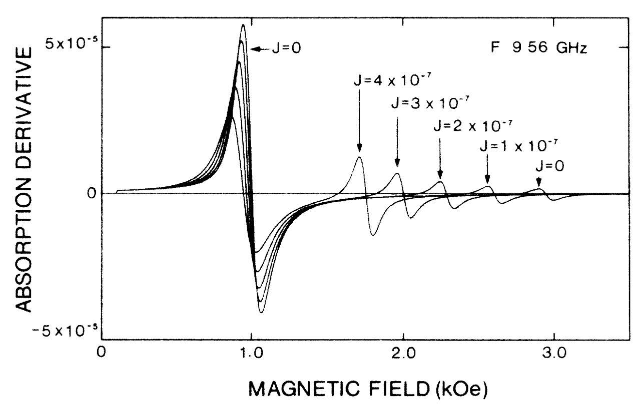

FIG. 2. Variation with magnetic field of absorption derivatives at 9.56 GHz for a system composed of a 50 Å thick "nickel" overlayer exchange coupled with an iron single-crystal substrate (see Table I). The value of the exchange coupling parameter in cm, J, is indicated on each curve. The high-field peaks are located at 2.945, 2.608, 2.293, 2.005, and at 1.755 kOe for $J = 0,1,2,3,4\times10^{-7}$ cm.

sponding to the nickel resonance is beginning to be enhanced by the increasing strength of the nonpropagating spin wave. This is brought out clearly for the case $J=5\times10^{-7}$ cm for which the nickel resonance has been shifted to a value 1.19 kOe—close to the iron resonance. The absorption now consists of two strong peaks [Figs. 3(a) and 3(b)]: the low-field peak corresponds to the usual resonance, but shifted down in field because of pinning caused by the nickel overlayer; the high-field peak corresponds to enhanced absorption due to a nonpropagating spin wave. At any value of the external field, the iron supports three waves of the form e^{-kz}: their wave vectors are shown in Figs. 4(a), 4(b), and 4(c) for a range of magnetic fields of interest for this problem. The wave vector k_1 [Fig. 4(a)] corresponds to a nonpropagating spin wave whose magnitude is relatively large and relatively independent of the value of the magnetic field. This wave has a very small amplitude relative to the other two waves (approximately 10^{-4}:1), consequently it has little effect on the field dependence of the absorption. The wave vector k_2 [Fig. 4(b)] corresponds, for fields below resonance, to a propagating wave. It gradually transforms, through the resonance, into a wave which has equal real and imaginary parts for large field values. Wave vector k_3 [Fig. 4(c)] corresponds to a wave having comparable real and imaginary components for fields less than the resonance field, but it transforms into a nonpropagating wave for large magnetic fields. The magnetic field dependence of the amplitudes of the two important waves in the iron for no coupling to the nickel layer ($J=0$) is shown in Fig. 5. The usual FMR absorption peak occurs at the field where

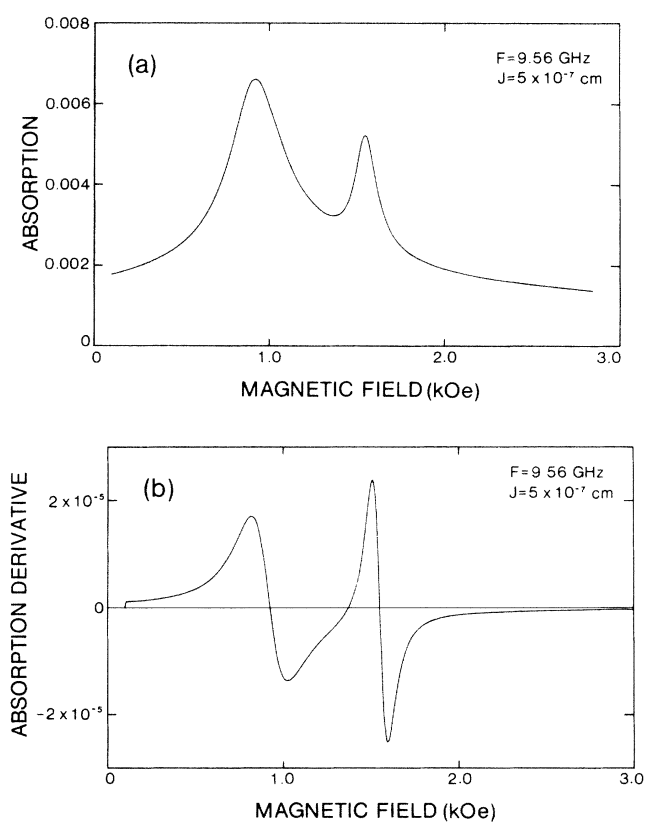

FIG. 3. Variation with magnetic field of the absorption (a) and absorption derivative (b) at 9.56 GHz for a system composed of a 50 Å thick "nickel" overlayer exchange coupled with an iron single-crystal substrate (see Table I). The exchange coupling is ferromagnetic and has a strength $J=5\times10^{-7}$ cm. The low-field absorption maximum occurs at 0.926 kOe and the high-field maximum occurs at 1.548 kOe.

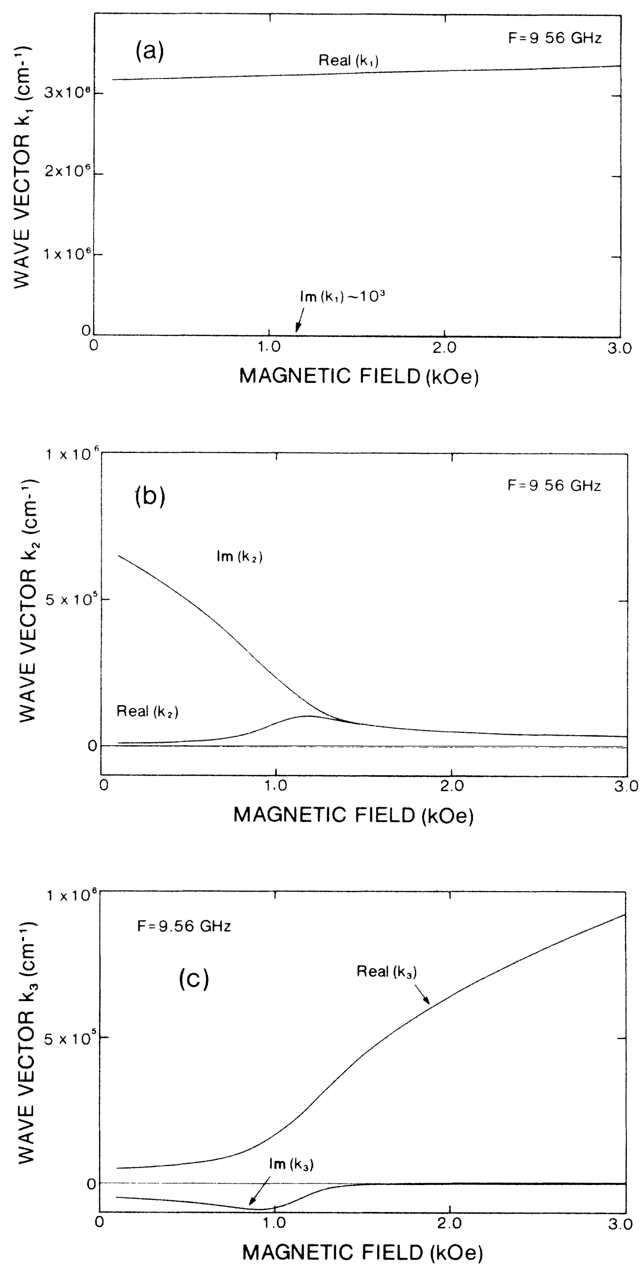

FIG. 4. The variation with magnetic field at 9.56 GHz of the three wave vectors which are used to describe the spatial variation of the rf magnetic field component, h_y, in iron (see Table I): $h_y=\sum_{n=1}^{3} h_n e^{-k_n z}$. Wave vector k_1 is the nonpropagating spin wave: the corresponding wave amplitude, h_1, is very small and for practical purposes may be neglected. Wave vectors k_2, k_3 correspond to waves having a mixed spin-wave and electromagnetic character: the amplitudes of the corresponding waves are relatively large.

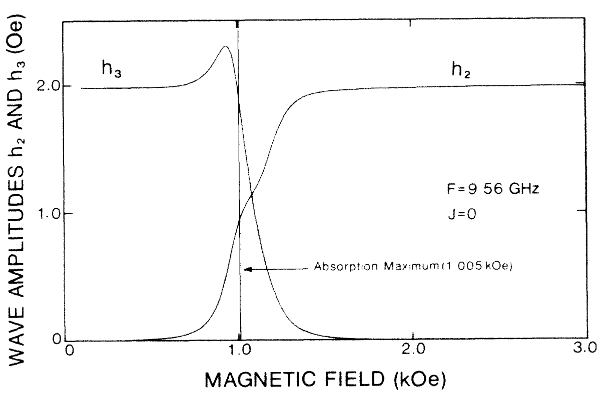

FIG. 5. The variation with magnetic field at 9.56 GHz of the iron wave amplitudes h_2 and h_3 which correspond to the wave vectors k_2 and k_3 of Fig. 4 for no exchange coupling ($J=0$) between the iron single crystal and a 50 Å thick "nickel" overlayer (see Table I). The magnitudes of the wave amplitudes are shown in the figure: their phases vary with magnetic field but have not been shown.

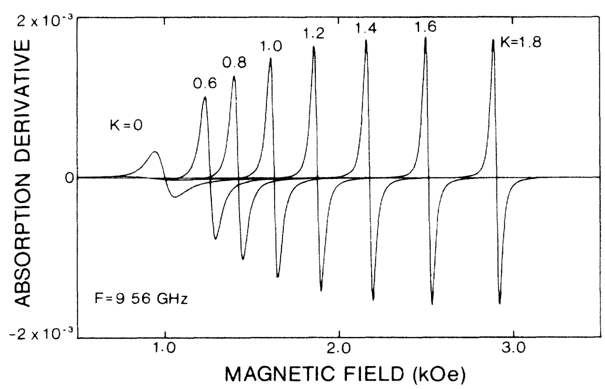

FIG. 7. The effect of front surface pinning on the absorption of 9.56 GHz microwave radiation by the iron single crystal described in Table I. Rado-Weertman spin pinning conditions have been used in the form $Adm/dz+|K|m=0$, where m stands for either of the components m_y, m_z. These pinning conditions correspond to a uniaxial surface energy having a hard axis along the direction of the equilibrium magnetization.

there are comparable amplitudes of the two waves, and where both waves have mixed electromagnetic and spin-wave character. These amplitudes can be contrasted with the case in which the iron is exchange coupled with the nickel overlayer and $J=5\times10^{-7}$ cm (Fig. 6). Note the pronounced increase in the amplitude h_3 and the decrease in the wave amplitude h_2 near 1.55 kOe—the field corresponding to the high-field absorption peak of Fig. 3. In this case the pinning effects due to the nickel have generated a surface excitation whose absorption is comparable to the normal FMR absorption at the lower field. It is important to note that the position of the surface mode in magnetic field is dependent upon the coupling torques. This is illustrated in Fig. 7 for the case of no nickel overlayer, but for which it is assumed that the bulk iron is

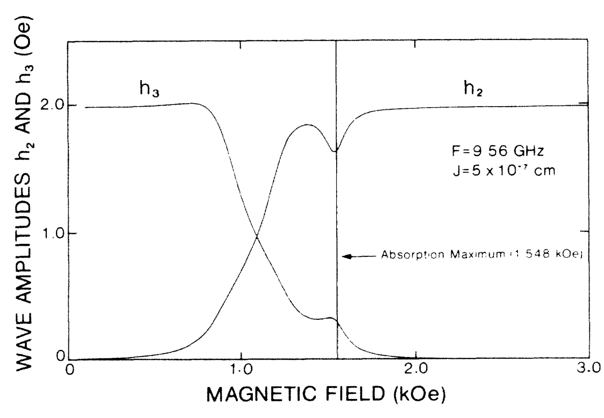

FIG. 6. The variation with magnetic field at 9.56 GHz of the iron wave amplitudes h_2 and h_3 which correspond to the wave vectors k_2 and k_3 of Fig. 4 when the 50 Å thick "nickel" overlayer is coupled to the iron crystal by a ferromagnetic exchange interaction of strength $J=5\times10^{-7}$ cm.

subjected to surface pinning of various strengths. For the simple case of Fig. 7 in which the pinning parameter is taken to be the same for both m_B^y and m_B^z, and K is taken to be negative corresponding to a hard axis along M_s, one has Rado-Weertman boundary conditions in the form

$$A_B\frac{dm_B}{dz}+|K|m_B=0\ . \tag{29}$$

Thus, for that magnetic field such that the real part of the nonpropagating spin wave satisfies

$$kA_B=|K|\ , \tag{30}$$

the amplitude of the nonpropagating spin wave becomes relatively large, and the absorption exhibits the resonances shown in Fig. 7. The field dependence of the wave amplitudes for the two strong modes is shown in Fig. 8 for the case $|K|=1.0$ erg/cm^2. Note the strong decrease in the amplitude of the electromagneticlike wave, h_2, and the strong increase in the amplitude of the nonpropagating spin-wave-like amplitude, h_3, at a field of 1.670 kOe corresponding to the strong absorption maximum shown in Fig. 7 for $|K|=1.0$ erg/cm^2.

It should, perhaps, be explicitly pointed out that most of the absorption shown in Fig. 3(a) is due to the bulk material. At the absorption peaks the response of the nickel becomes large, but the overlayer is too thin (50 Å) compared with the rf penetration into the iron ($\sim$500 Å at resonance) to contribute more than a few percent to the total absorption.

As noted above, and shown in Figs. 3(a) and 3(b), a value $J=5\times10^{-7}$ cm for the strength of the ferromagnetic exchange coupling between the overlayer and the iron substrate is sufficient to produce a very strong perturbation in the character of the magnetic field dependence of the absorption of microwave energy at 9.56 GHz. Further increase of the coupling strength causes the high-field absorption peak to increase in strength and the low-field absorption peak to decrease in strength, until only

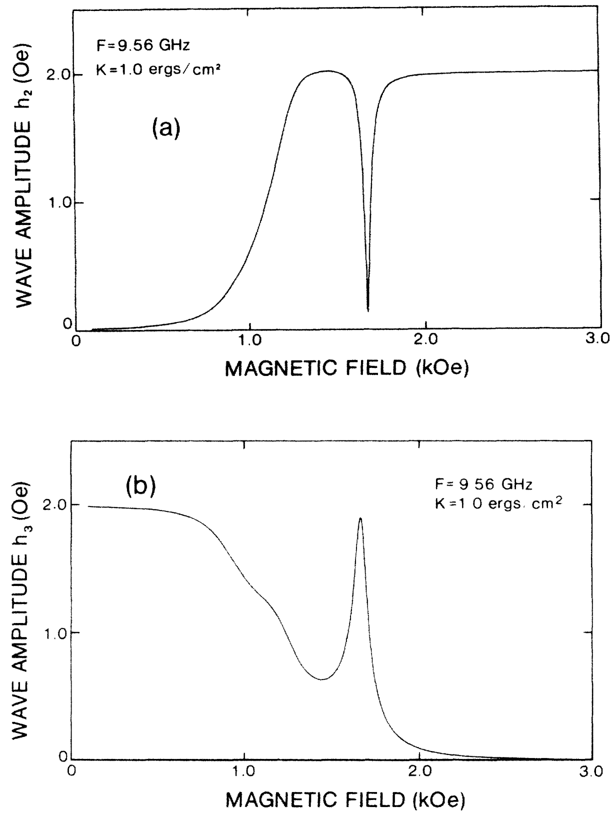

FIG. 8. Variation with magnetic field at 9.56 GHz of the wave amplitudes in iron for a pinning parameter $|K|=1.0$ erg/cm^2 (see Fig. 7). (a) The wave amplitude corresponding to k_2 of Fig. 4(b). (b) The wave amplitude corresponding to k_3 of Fig. 4(c). The minimum in h_2 and the peak in h_3 occur at 1.670 kOe, the value of the field for which the absorption is a maximum.

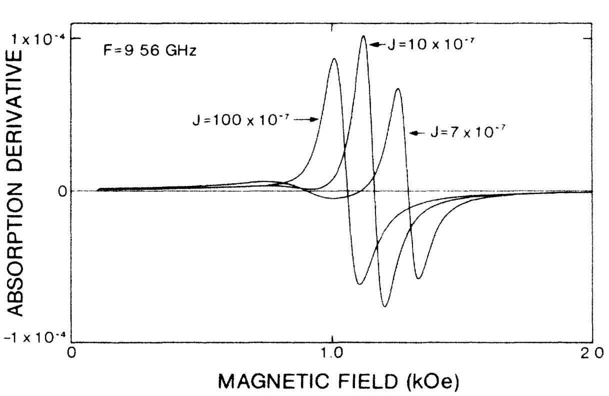

FIG. 9. Variation with magnetic field of absorption derivatives at 9.56 GHz for a system composed of a 50 Å thick "nickel" overlayer exchange coupled with an iron single-crystal substrate (Table I). This figure is an extension of Fig. 2 to values of the exchange parameter, J, such that the "nickel" exchange shift, JM_B/d, has moved the nickel resonance to fields less than 0.5 kOe. The prominent absorption peaks occur at 1.296, 1.165, and at 1.060 kOe for $J=7$, 10, and 100×10^{-7} cm.

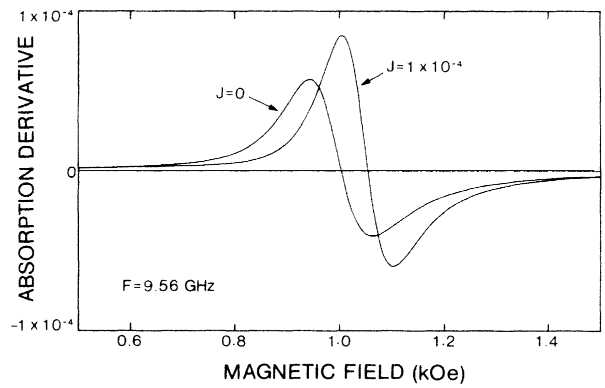

FIG. 10. Variation with magnetic field of absorption derivatives at 9.56 GHz for a system composed of a 50 Å thick "nickel" overlayer deposited on an iron single-crystal substrate (Table I). The case $J=0$ corresponds to no coupling between the "nickel" and the iron. The case $J=1.0\times10^{-4}$ cm corresponds to very tight coupling between the magnetizations in the two materials: the magnetization vectors in the two materials are locked together at the interface by the ferromagnetic exchange interaction. Absorption maxima occur at 1.005 kOe for $J=0$, and at 1.054 kOe for $J=1.0\times10^{-4}$ cm.

one absorption peak remains for very strong coupling between the overlayer and substrate magnetizations. This effect on the absorption derivative of increasing the coupling parameter is shown in Figs. 9 and 10. In Fig. 10 the absorption derivative for very large ferromagnetic exchange coupling between the overlayer and substrate is compared with that for no coupling between them. The absorption peak for very strong coupling is similar to that for no coupling, but the resonance field has been shifted from 1.005 to 1.054 kOe. This 50 Oe shift is a consequence of the thickness dependent, effective surface anisotropy terms as discussed above in connection with Eqs. (23) and (24).

A series of absorption curves can also be generated for negative values of J, corresponding to antiferromagnetic coupling between the nickel overlayer and the iron substrate, Figs. 11 and 12. For antiferromagnetic coupling the nickel resonance initially at 2.945 kOe is driven to higher-field values: the absorption at this high-field resonance is essentially due to the nickel layer, and it rapidly decreases as $|J|$ increases because the driving term in Eq. (13) proportional to the precessing iron magnetization is out of phase with the rf field, h_y. However, the nickel resonance[28] initially at -5.81 kOe is also driven towards higher-field values as the antiferromagnetic coupling is increased. Just as was the case for ferromagnetic coupling, the nickel overlayer interacts very strongly with the iron resonance when the two FMR fields become comparable, and this interaction leads to mutual pinning. This mutual pinning results in two absorption peaks (Fig. 12): one peak corresponds to the usual FMR absorption peak shifted to a lower field, and the other peak corresponds to the excitation of a nonpropagating spin wave. For large anti-

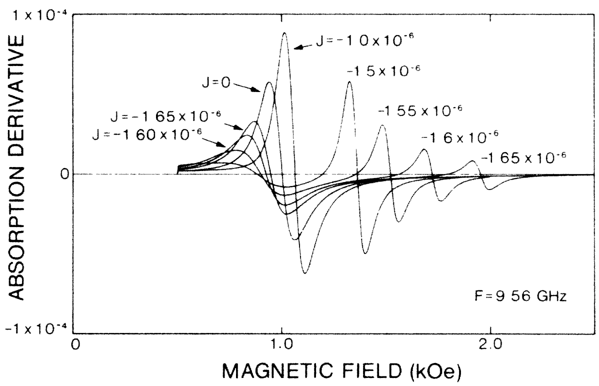

FIG. 11. The variation with magnetic field of absorption derivatives at 9.56 GHz for a system composed of a 50 Å thick "nickel" overlayer deposited on an iron single-crystal substrate (see Table I). The magnetizations at the interface are coupled by an exchange interaction of the form $E_{ex}=-J\mathbf{M}_A\cdot\mathbf{M}_B$: negative J corresponds to antiferromagnetic coupling. The low-field absorption peaks occur at 1.005, 1.065, 0.866, 0.903, 0.928, and at 0.949 kOe for $|J|=0$, 1, 1.5, 1.55, 1.60, and 1.65×10^{-6} cm. The high-field peaks occur at 2.945, off-scale (and very small), 1.364, 1.521, 1.723, and at 1.954 kOe for $|J|=0$, 1, 1.5, 1.55, 1.60, and 1.65×10^{-6} cm.

ferromagnetic coupling the field variation of the absorption derivative becomes the same as for large ferromagnetic coupling and is indistinguishable from the curve for $J=1.0\times10^{-4}$ cm shown in Fig. 10.

The same general pattern of variation of the absorption curves with strength of coupling between the nickel overlayer and iron substrate is found at higher frequencies except that a greater coupling strength is required to generate a strong absorption peak corresponding to the excitation of the nonpropagating spin wave. Calculations carried out for a frequency of 73 GHz are shown in Figs. 13, 14, and 15. At 73 GHz the uncoupled FMR occurs at

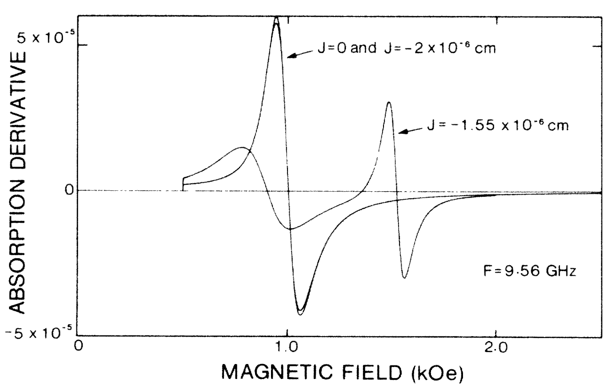

FIG. 12. The variation with magnetic field of absorption derivatives at 9.56 GHz for a 50 Å thick "nickel" overlayer exchange coupled to an iron substrate (see Table II). This diagram is an extension of Fig. 11. For $J=0$ and $J=-2.0\times10^{-6}$ cm the absorption peak occurs at 1.005 kOe. The absorption peaks for $J=-1.55\times10^{-6}$ cm occur at 0.903 kOe and at 1.521 kOe.

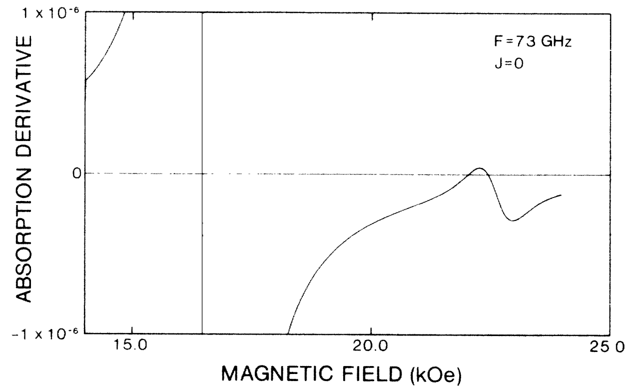

FIG. 13. The variation with magnetic field of absorption derivatives at 73 GHz for a system composed of a 50 Å thick "nickel" overlayer deposited on an iron single-crystal substrate (see Table I). There is no exchange coupling between the overlayer and substrate magnetizations at their interface. The iron resonance occurs at 16.48 kOe, the peak-to-peak derivative linewidth, ΔH, is 411 Oe, and the peak-to-peak strength is $S=2.92\times10^{-5}$. The nickel resonance occurs at 22.63 kOe, its linewidth is 680 Oe, and its strength is $S=3.24\times10^{-7}$. The iron resonance is shown in its entirety in Fig. 14.

16.48 kOe for the iron and at 22.63 kOe for the nickel: the nickel absorption is weak (Fig. 13)—the ratio of the peak-to-peak derivative amplitudes for iron and the nickel is 90.1. A value $J=1.75\times10^{-6}$ cm is required to give a shift of 6.15 kOe, the difference between the uncoupled resonance fields. As expected from that estimate, a value $J=2.0\times10^{-6}$ cm does produce a high-field absorption peak which is comparable to the low-field FMR peak, Fig. 14.

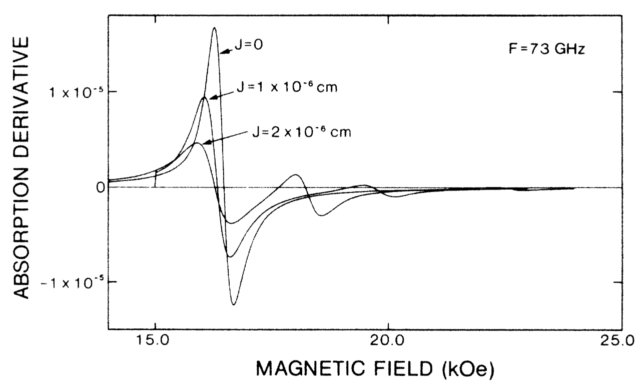

FIG. 14. The variation of absorption derivatives with magnetic field at 73 GHz for a system composed of a 50 Å thick "nickel" layer deposited on a single-crystal iron substrate (see Table I). The "nickel" and iron magnetizations are coupled at their interface by an exchange interaction of the form $E_{ex}=-J\mathbf{M}_A\cdot\mathbf{M}_B$. The low-field absorption peaks occur at 16.48, 16.34, and 16.29 kOe for $J=0$, 1.0×10^{-6}, and 2.0×10^{-6} cm. The high-field resonances (the "nickel" resonances) occur at 22.98, 19.81, and 18.58 kOe for $J=0$, 1.0×10^{-6}, and 2.0×10^{-6} cm.

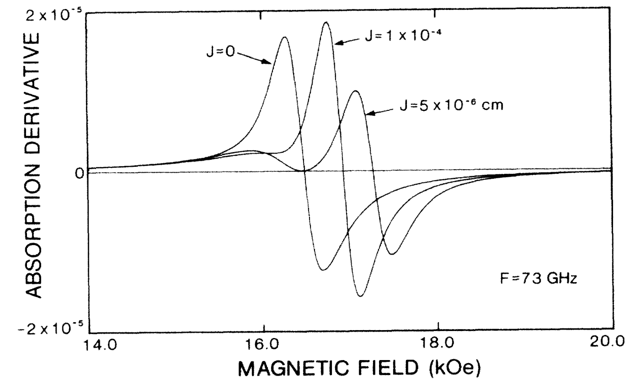

FIG. 15. A continuation of Fig. 14 to larger values of the strength of the ferromagnetic exchange coupling between the "nickel" overlayer and the iron substrate. The magnetic field variation of the absorption in the limit of no exchange coupling is shown for comparison. Absorption peaks occur at 16.48, 16.92, and at 17.27 kOe for $J=0$, 1.0×10^{-4}, and 5.0×10^{-6} cm. The low-field absorption anomaly of Fig. 14 has become very weak as the "nickel" and iron magnetizations become very strongly coupled.

From the point of view of experiment, it would clearly by desirable to make measurements at several frequencies because for small and intermediate values of J, increasing the frequency has much the same effect as decreasing the exchange coupling strength between the two ferromagnetic metals.

CONCLUSIONS

The magnetic field dependence of the absorption of microwave radiation by a thick specimen can be appreciably altered by exchange coupling with a thin overlayer of a second ferromagnetic metal. If the overlayer is formed on a clean surface of a single-crystal substrate by epitaxial growth in ultrahigh vacuum, it is likely that the magnetization in the overlayer will be so tightly coupled by the exchange interaction to the magnetization at the surface of the substrate that it precesses in phase with the substrate surface magnetization. Under those conditions no independent overlayer resonance is observable, and the substrate resonance will exhibit shifts due to effective pinning by the overlayer. The magnitude and sign of the effective pinning parameters which appear in the Rado-Weertman boundary conditions have a contribution from any pinning at the surface of the overlayer, and also contributions, proportional to overlayer thickness, from the difference in magnetization and the effective magnetocrystalline anisotropy fields between the substrate and overlayer materials.

Heinrich *et al.*[8] have recently reported the results of FMR measurements carried out on an iron single crystal covered by a 50 Å thick layer of nickel grown epitaxially on an iron (100) face. The lattice parameter observed for the nickel film was approximately 13% larger than would be expected for a face-centered cubic structure. Heinrich *et al.* are of the opinion that nickel grown epitaxially on a (100) face of iron forms in a body-centered cubic structure. The nickel overlayer produced little or no effect on the iron resonance at room temperature, but upon cooling the specimens the iron FMR was shifted to higher fields when coated with nickel relative to the FMR field observed for the uncoated iron crystal. The shift in FMR field increased as the specimen was cooled, and shifts between 70 and 170 Oe were observed at 77 K, the lowest temperature used. These observations are consistent with the hypothesis that the nickel overlayers were ferromagnetic at, or near, room temperature and that their magnetization was strongly exchange coupled with the iron magnetization.

Quantitative comparisons between the observations and theory is out of the question until the magnetic properties of the nickel overlayers can be determined, but the shifts and line narrowing observed at 77 K would be consistent with an effective negative surface pinning ranging from -0.2 to -0.4 erg/cm^2. It would be very interesting to investigate the shifts in the iron resonance field as a function of nickel overlayer thickness to determine whether one is dealing with an effect caused by volume anisotropy in the nickel, or the surface pinning of Ni.

Experiments on epitaxial films in which a thin nonmagnetic metal layer was grown between the substrate and the ferromagnetic nickel layer would clearly be of great interest since one might hope in that way to vary the strength of the exchange coupling between the two ferromagnetic metals.[29] This might open up the possibility of being able to measure the frequency dependence of the overlayer resonance, and therefore to determine its magnetic parameters, in addition to being able to investigate the range of the exchange interaction for two ferromagnetic materials separated by an intervening layer of metal.

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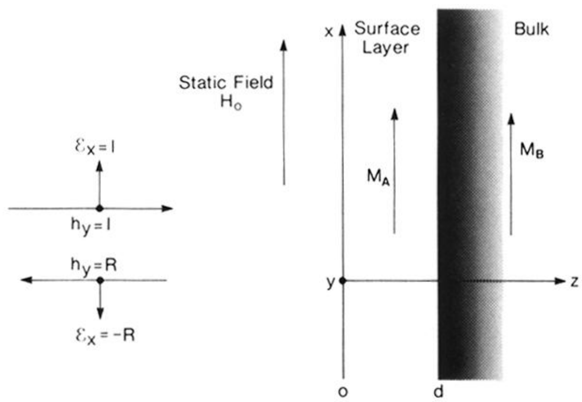

FIG. 1. The geometry used to calculate the response to incident microwave radiation of a bulk ferromagnet covered by a thin film of a second ferromagnet. The magnetizations in the two metals, M_A and M_B, are assumed to be uniform in equilibrium and parallel with the external field, H_0. The magnetizations in the film and in the bulk substrate are assumed to be coupled at their interface by an exchange energy of the form $E_{ex} = -J\mathbf{M}_A \cdot \mathbf{M}_B$.