Magnetic resonance in multilayer films

Robert M. White
Xerox Research Center, 3333 Coyote Hill Road, Palo Alto, California 94304

Conyers Herring
Department of Applied Physics, Stanford University, Stanford, California 94305 and Xerox Research Center, 3333 Coyote Hill Road, Palo Alto, California 94304

(Received 31 January 1980)

The ferromagnetic resonance frequency for films having a nonuniform magnetization is derived. It is shown that for both normal and in-plane polarizations a film in which the exchange coupling extends throughout the whole depth resonates at the same frequency as a uniform film with a magnetization $\langle M^2\rangle/\langle M\rangle$, where $M(y)$ is the depth-dependent magnetization and the angular brackets denote averages over depth. Anomalously high apparent magnetizations can result if such a film has regions of reversed magnetization.

A number of interesting effects have been reported on bimetallic films containing short-wavelength (less than 40 Å) one-dimensional compositional modulations. For example, foils of Au-Ni and Cu-Pd exhibit[1] appreciable increases in their elastic moduli relative to homogeneous foils of the same average composition. Another example involves multilayer films of In-Ag and Sn-Ag where the superconducting transition temperatures were found[2] to depend upon the number of layers. Such films also exhibit interesting magnetic properties. Cu-Ni films, in particular, were reported[3] to contain regions in which the magnetization, as inferred from ferromagnetic-resonance experiments, was significantly larger than that of pure Ni. Although such an enhanced magnetization could conceivably occur if there were large concentrations of divalent nickel produced, for example, by oxidation, there does not seem to be any evidence for this. The purpose of this comment is to elucidate what kind of an average of the depth-dependent magnetization is measured in ferromagnetic resonance on layered materials; we shall show that this average can exceed the maximum magnetization in any part of the film, though only if the local magnetizations of different regions are not all of the same sign.

The conclusion regarding the magnetization in Ref. 3 was deduced from ferromagnetic resonance using the Kittel resonance expression, which, for the applied field H_0 parallel to the film, is

$$\omega/|\gamma| = [H_0(H_0+4\pi M)]^{1/2} \quad . \tag{1}$$

This expression applies to a *homogeneous* sample. In an inhomogeneous sample one must consider the appropriate average dipolar field acting on the magnetization.

The equation of motion, including exchange, is

$$\frac{d\vec{M}}{dt} = -|\gamma|\vec{M}\times(\vec{H}+\alpha\nabla^2\vec{M}) \quad , \tag{2}$$

where α is a phenomenological exchange parameter.

With an assumed time dependence of the form $\exp(i\omega t)$ the transverse components satisfy

$$i\omega M_x = -|\gamma|M_yH_z + |\gamma|M_zH_y - |\gamma|\alpha M_y\nabla^2M_z + |\gamma|\alpha M_z\nabla^2M_y \quad , \tag{3a}$$

$$i\omega M_y = -|\gamma|M_zH_x + |\gamma|M_xH_z - |\gamma|\alpha M_z\nabla^2M_x + |\gamma|\alpha M_x\nabla^2M_z \quad . \tag{3b}$$

Let us average these equations throughout the thickness of the film, denoting the averages by angular brackets. The terms with ∇^2 will average to zero; indeed, since these represent the averages of the exchange torques exerted by the film on itself, they must vanish even if a more general expression than $\alpha\vec{M}\times\nabla^2\vec{M}$ is used for them. Now let us further assume the thin planar geometry shown in Fig. 1, so that $H_x=0$ and, since $\vec{\nabla}\cdot\vec{B}=0$, $H_y=-4\pi M_y$. With a uniform dc field $H_z=H_0$. Equations (3) for the free-precession modes of the system then become

$$i\omega\langle M_x\rangle = -|\gamma|H_0\langle M_y\rangle - 4\pi|\gamma|\langle M_zM_y\rangle \quad , \tag{4a}$$

$$i\omega\langle M_y\rangle = |\gamma|H_0\langle M_x\rangle \quad . \tag{4b}$$

Finally, let us assume that the spins in the film are fairly strongly exchange coupled to each other. (If successive magnetic layers are not exchange coupled, they will resonate independently of each other since by Maxwell's equations the H in any layer is not influenced by the M's of different layers.) Thus if $M_z=M_0(y)$, we can, to a good approximation, take the small-amplitude precession to have the form $M_x=\theta_xM_0(y)$, $M_y=\theta_yM_0(y)$, where θ_x, θ_y are independent of y. Equations (4) then give a simple

 ©1980 The American Physical Society

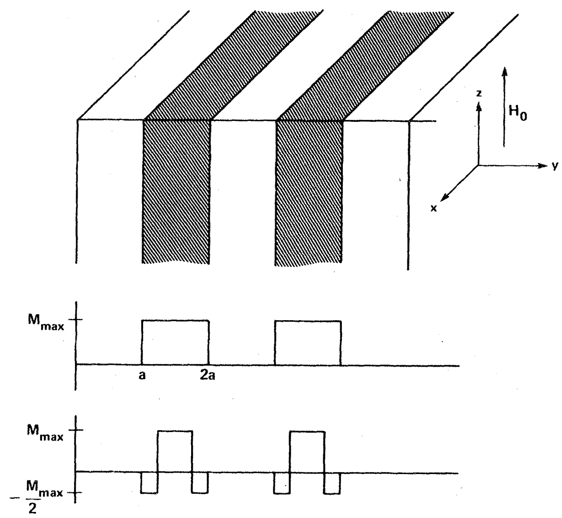

FIG. 1. Bimetallic film showing two idealized magnetization distributions.

equation for ω whose solution is

$$\omega/|\gamma| = [H_0(H_0 + 4\pi\langle M_0\rangle\eta)]^{1/2} , \quad (5)$$

where $\eta = \langle M_0^2\rangle/\langle M_0\rangle^2$.

The conclusions of Ref. 3 were strongly supported by the observation that the resonance measured with H_0 normal to the film, interpreted using the equation

$$\omega/|\gamma| = H_0 - 4\pi M , \quad (6)$$

yielded values of M identical to those inferred from resonance with H_0 transverse and interpreted by Eq. (1). For this case, one can again average the equations of motion analogous to Eq. (3) and obtain, for a stratified, but well-exchange-coupled film, the resonant frequency

$$\omega/|\gamma| = H_0 - 4\pi\langle M_0\rangle\eta , \quad (7)$$

with the same η as that in Eq. (5).

What values are possible for η? If the magnetization has a simple square-wave dependence as shown in Fig. 1, then

$$\langle M_0^2\rangle = \tfrac{1}{2}M_{max}^2; \ \langle M_0\rangle = \tfrac{1}{2}M_{max}; \ \eta = 2$$

and $4\pi\langle M_0\rangle\eta = 4\pi M_{max}$. In this case, if the resonance data are interpreted in terms of Eq. (1) the meaning of M is clear. More generally, it can be shown that if $M_0 \geq 0$ for all y, $\eta\langle M_0\rangle \leq M_{max}$: the η factor could not explain apparent M values exceeding the maximum for bulk alloys of any composition. However, suppose the magnetization has negative regions as illustrated in Fig. 1: then $4\pi\langle M_0\rangle\eta = (\frac{5}{2})4\pi M_{max}$. In this case, the value of M obtained from Eq. (1) would be two-and-a-half times *larger* than the maximum magnetization actually occurring in this film.

At the present time, the cause of the anomalously large effective M values observed by Thaler *et al.*,[3] in their Cu-Ni films has not been established. These authors have noted that, although a strong uniaxial anisotropy opposing orientation out of the plane of the film would affect the resonant frequencies in the same manner as an augmented M_0, the most obvious cause for such an anisotropy, namely an alternating stress accompanying the formation of the coherent lattice, would have the wrong sign. Repeating our calculation with inclusion of such anisotropy fields shows that the apparent magnetization measured in a resonant experiment with either normal or parallel field geometry becomes $\eta\langle M_0\rangle + \langle K\rangle/2\pi\langle M_0\rangle$, where K is related to the anisotropy energy density ϵ_A by $\epsilon_A = K(y)\cos^2\alpha$, α being the angle of M to the film normal. Unless some source for a large positive K can be found, the possibility should be kept in mind that regions of reversed magnetization might be affecting the observed resonances. The antiparallel alignments would have to be attributed to exchange effects, rather than to purely magnetic forces, since the observations of Ref. 3 were made in fields of many kilogauss, which would be expected to overpower ordinary magnetostatic and anisotropy forces. While it may seem very speculative to envision such exchange effects, it is noteworthy that in compositionally modulated Pd-Fe films the observation[4] of a magnetization that *decreases* with decreasing temperature, at fields below 1 kOe, is very suggestive of moments aligned partially in opposition. In any event, quantitative interpretation of resonant frequencies in modulated ferromagnetic films should take into account the η factor in Eqs. (5) and (7).

[1]W. M. C. Yang, T. Tsakalakos, and J. E. Hilliard, J. Appl. Phys. 48, 876 (1977).
[2]C. G. Granquist and T. Claeson, Solid State Commun. 32, 531 (1979).
[3]Barry J. Thaler, J. B. Ketterson, and J. E. Hilliard, Phys. Rev. Lett. 41, 336 (1978).
[4]G. Dublon, M. P. Rosenblum, and W. T. Vetterling, IEEE Trans. Magn. (to be published).