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THEORY OF ANISOTROPIC BROADENING OF FMR LINES DUE TO MAGNETOELASTIC DIMENSIONAL RESONANCE IN THIN FILMS (*)

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Résumé. — Nous avons étudié l'effet des interactions magnétoélastiques sur la résonance ferromagnétique dans les couches minces, utilisant les constantes physiques du nickel. Le largeur de la raie de résonance est obtenue par la solution simultanée des équations de mouvement magnétoélastiques pour plusieurs conditions aux limites sur les spins et déplacements élastiques. Cette largeur de raie peut augmenter de plus de 50% en certains cas, quand une onde élastique est en résonance pour une épaisseur particulière de la couche. L'effet dépend fortement de l'angle d'aimantation, dû à l'anisotropie du magnétocouplage.

Abstract. — We have studied the effect of magnetoelastic interactions on ferromagnetic resonance in thin films, using physical constants appropriate to nickel. The resonance linewidth has been calculated by solving the coupled magnetoelastic equations of motion for various spin-pinning and elastic boundary conditions. We find that the linewidth may broaden by more than 50% in certain special cases where an elastic wave undergoes a thickness resonance. The effect is strongly dependent upon the magnetization direction due to the anisotropy of the magnetoelastic coupling.

We have studied the effect of magnetoelastic interactions on ferromagnetic resonance (FMR) in single-crystal thin films at K band. Our study is based on a formalism developed by Tiersten [1-3]. The physical constants used correspond to those of nickel, except for the conductivity, which is set equal to zero.

An infinite plate with (100) surfaces is placed in a rectangular Cartesian coordinate system with its axes along cube edges. We consider an arbitrary direction of the static magnetization \( \mathbf{M}_0 \) with respect to the coordinate axes. The internal static field \( \mathbf{H}_0 \) is defined as the vector sum of the applied field, demagnetizing field, and anisotropy field, and is, by definition, parallel to \( \mathbf{M}_0 \). A microwave field is then applied at normal incidence upon both surfaces and perpendicular to \( \mathbf{M}_0 \). The magnitude of \( \mathbf{H}_0 \) is determined such that the uniform-precession mode resonates at a given microwave frequency \( \omega_0/2 \pi = 25.92 \text{ GHz} \).

The behavior of the microwave components of the magnetization, \( \mathbf{m} \), and of the elastic displacement, \( \mathbf{u} \), are described by the linearized Landau-Lifshitz equations and elastic wave equations mutually coupled through the magnetoelastic interaction terms. The electromagnetic propagation is neglected so that Maxwell's equations reduce to the quasistatic field equations. In solving the coupled equations of motion, \( \mathbf{m} \) is conveniently expressed as the sum of a spatially independent part \( \mathbf{m}^0 \) (which corresponds to the uniform-precession mode) and a spatially dependent part \( \mathbf{m}' \). The equations of motion for \( \mathbf{m}^0 \) are separable from those for \( \mathbf{m}' \) and \( \mathbf{u} \), although they are coupled through boundary conditions. The solution for \( \mathbf{m}^0 \) yields an ordinary FMR spectrum. By assuming a plane wave solution with its propagation direction along the film normal, the equations of motion for \( \mathbf{m}' \) and \( \mathbf{u} \) yield a dispersion relation (angular frequency \( \omega \) vs propagation constant \( k \)), which is quintic in \( k^2 \). The quintic equation has been solved numerically, giving five pairs of roots, \( k^2 \). The general solution for \( \mathbf{m} \) is the sum of \( \mathbf{m}^0 \) and \( \mathbf{m}' \) which is a linear combination of ten independent solutions, whose coefficients are determined by the boundary conditions. If we impose symmetrical boundary conditions, ten coefficients can be related in pairs, leaving five independent unknowns. We consider two limiting cases of the spin boundary condition, spin-unpinned (SU) and spin-pinned (SP), and two limiting cases of the elastic boundary condition, traction-free (TF) and deformation-free (DF). The power absorption and its resonance linewidth are then calculated from the particular solution of \( \mathbf{m} \) which satisfies given boundary conditions.

We have found that the magnetoelasticity has an appreciable effect upon resonance linewidth only in certain special cases where an elastic wave undergoes a thickness resonance, but that in these cases the linewidth may increase by more than 50%. More specifically, the linewidth \( \Delta \omega_0/\gamma \) (\( \gamma \) is the gyromagnetic ratio) may broaden appreciably under the following conditions: (i) the film thickness \( L \) nearly equals an odd-integral number of half-wavelengths of either the longitudinal elastic (LE) or the transverse elastic (TE) wave at the FMR frequency \( \omega_0 \) under the SU-TF condition; (ii) \( L \) nearly equals a half-wavelength of either the LE or the TE wave at the crossover frequency \( \omega_c \) under the SP-TF condition; (iii) \( L \) nearly equals a full wavelength of either the LE or the TE wave at a frequency between \( \omega_0 \) and \( \omega_c \) under the SP-DF condition. The other limiting case, the SU-DF condition reduces to the uniform-precession problem since \( \mathbf{m}' \) and \( \mathbf{u} \) are zero everywhere, so that there is no magnetoelastic effect. The thickness range \( \Delta L \) over which the effect is significant is very small, and is given approximately by \( \Delta L = L(\Delta \omega_0/\gamma) \approx 0.03 L \).

On the basis of the results of the exact calculation outlined above, we have developed an approximate calculation, which is very simple to use and yet gives all of the essential information of the exact calculation. The results of the two methods have been checked in all the regions of interest for consistency. The idea of the approximate calculation is that of the five

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branches corresponding to five k's, we can neglect the ones which correspond to the non-propagating spin wave and the elastic waves which do not undergo a thickness resonance. In other words, the branches we need to consider are the ones corresponding to the propagating spin wave and the elastic wave which undergoes a thickness resonance. Therefore, the dispersion relation resulting from the approximate calculation becomes a quadratic equation in k² and can readily be solved analytically.

The linewidth of the uniform-precession mode, which constitutes the background linewidth, increases from 245 Oe to 261 Oe as the angle θ between M, and the film normal is varied from 0° to 90°. We have assumed the Landau-Lifshitz damping parameter A = 2.36 x 10¹⁰ rad/s. The amount of broadening due to the magnetoelastic thickness resonance depends strongly upon the angle θ because of the strong angular variation of the coupling between spin waves and elastic waves. In figure 1, we show the angular dependence of the linewidth for a given set of parameters, at three thicknesses for which three kinds of thickness resonance occur. It should be noted that the elastic damping of single-crystal nickel, upon which the amount of broadening also depends, is not known for the frequencies of interest. Weber [4] and Seavey [5] estimated ωrp = 37.7 (τp is the phenomenological phonon relaxation time) for permalloy at 60 GHz. We have, therefore, used this value for nickel as the best available estimate. It is interesting to note that ωrp for the k = 0 magnon at this frequency is 39.8.

In figure 2, we show, as an example, the linewidth at θ = 45° as a function of thickness around 1 015 Å, which corresponds to a half-wavelength of the LE wave, with the elastic damping as a parameter. It has been reported [6] that a characteristic linewidth increase of about 40 % at oblique angles is observed in single-crystal nickel platelets at K band. This observation is in qualitative agreement with curve L₁ of figure 1, if the platelets are about 1 000 Å thick, as they are believed to be. Although it is doubtful that all of the platelets are within 30 Å of each other, as they should be from figure 2, the above theory is the only model investigated so far that shows the observed linewidth peak at oblique angles even qualitatively.

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