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AN ALTERNATIVE MODEL TO THE TWO-MAGNON MAGNETIC RELAXATION PROCESS IN PERMALLOY FILMS

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The thickness dependence of the linewidth difference for parallel and perpendicular ferromagnetic resonance in permalloy films at x-band and room temperature is calculated for the exchange conductivity-constant damping theory and is compared with experiment. The results are in good agreement for thin ($d < 800$ Å) and thick ($d > 1500$ Å) films. The data show a somewhat greater difference than the theory for intermediate thickness. The results indicate that a previously proposed two-magnon interpretation for the observed difference may be inappropriate.

IN A RECENT experimental study of the ferromagnetic resonance (FMR) linewidth in permalloy films[1], a striking increase with thickness for the *difference*, $\alpha = \Delta\omega_{\parallel}/\gamma - \Delta\omega_{\perp}/\gamma$, between the in-plane effective field linewidth,[2] $\Delta\omega_{\parallel}/\gamma$, and the perpendicular effective field linewidth, $\Delta\omega_{\perp}/\gamma$, was reported. A tentative explanation of this increase in terms of a two-magnon relaxation was proposed. The extent to which such an explanation may be valid depends critically on that part of the difference, which can be accounted for by intrinsic damping and exchange-conductivity. This paper reports the results of a calculation of precisely this contribution to the linewidth difference versus thickness, for a suitable choice of damping, conductivity, and other relevant parameters.[3,4] The results indicate that virtually all of the observed linewidth difference for small thickness ($d \leq 800$ Å) and large thickness ($d > 1500$ Å) can be explained by exchange-conductivity and a constant damping. The observed difference for 800 Å $< d <$ 1500 Å is greater than that indicated by the theory, but the results suggest that even this excess is not compatible with a two-magnon interpretation.

In our model, we calculate the total FMR linewidth for in-plane[3] and perpendicular[4] resonance in permalloy films as a function of thickness. As in previous calculations,[4] The Landau–Lifshitz equation of motion with damping is coupled with Maxwell's equations, and hence we obtain both the exchange-conductivity broadening as well as the Landau–Lifshitz contribution to the linewidth. The calculations allow for abritrary pinning conditions at the two film surfaces. We have found recently[3] that the films[5] can be characterized by a uniaxial surface anisotropy K_s with the hard axis normal to the film plane and that K_s is thickness dependent. For the present paper and for simplicity, the calculations are made for two values of K_s (0.1 and 1.0 ergs/cm^2) where, in both cases, K_s is assumed to be the same at both surfaces and independent of film thickness. The values of $4\pi M = 11{,}210$ Oe, $A = 1.143 \times 10^{-6}$ erg/cm, and $g = 2.10$ were obtained from previous work on 75% Ni – 25% Fe films made at NRL.[6] The values of the Landau–Lifshitz damping parameter, $\lambda = 7.5 \times 10^7$ Hz, and the conductivity, $\sigma = 0.7 \times 10^5$ $(\Omega\text{cm})^{-1}$, were obtained by a procedure illustrated

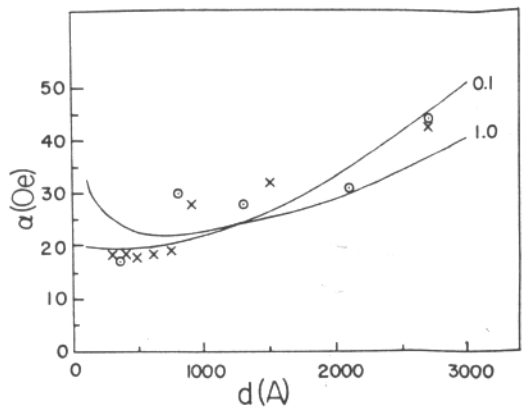

FIG. 1. The difference, α, between the effective field linewidth in the parallel and perpendicular orientations as a function of thickness, d. The solid curves are calculated assumming surface anisotropy values of 0.1 and 1.0 erg/cm^2. The x's represent the experimental data obtained from the C.N.R.S. films and open circles are data obtained from the NRL films.

previously.[7] Using these values for the parameters, we con are the calculated and the experimental thickness dependence of α as shown in Fig. 1. The experimental data were obtained at room temperature and at x-band frequencies. The linewidth measurement on the NRL films is repeatable for a given thickness and it is accurate to ±2 Oe. The experimental[8] and theoretical[9] derivative absorption curves are approximately symmetrical. However, in reference 1 the half-power linewidth was used. In order to combine the two sets of data (NRL data and reference 1) in a consistent manner, we converted the half-power linewidth measurements into derivative absorption linewidth by multiplying the latter by 0.577. This conversion factor applies for a Lorentzian-shaped absorption curve which reasonably describes the absorption curve of a permalloy film. Figure 1 shows that for $K_s = 0.1$ erg/cm^2, the agreement between the experimental and calculated results is quite good particularly in view of the following: (1) The boundary conditions *can* vary[3] as the film thickness is varied. (2) The conductivity may vary over the thickness considered. (3) Data for films made in two different laboratories agree with each other as well as with the theory. This comparison shows that most, if not all, of the observed linewidth difference as a function of thickness is consistent with the exchange-conductivity theory with a constant Landau–Lifshitz damping.

The interpretation of the results of Fig. 1 are readily given. For very thin films with $0 < d < 800$ Å, the film conductivity is of little importance, since the thickness is small compared to the skin depth of approximately 1 μ (i.e. the r.f. fields in the film are rather uniform across the film thickness). Thus, $\Delta\omega_{\parallel}/\gamma$ and $\Delta\omega_{\perp}/\gamma$ depend only on λ and do not depend on σ or on d.[10] In this limit, we can easily estimate the difference in linewidth from an insulator type analytic expression for the linewidth:

$$\alpha \approx 1.15\frac{\lambda}{\gamma}(2\pi + \Delta H_i/M) \qquad (1)$$

where $\gamma = 1.85 \times 10^7$ Hz/Oe and $\Delta H_i = H_i^{(\parallel)} - H_i^{(\perp)}$. Here $H_i^{(\parallel)}$ and $H_i^{(\perp)}$ are the internal fields at resonance for the parallel and perpendicular resonance orientations. At 9.44 GHz for a 300 Å-film, $H_i^{(\parallel)} =$ 894 Oe and $H_i^{(\perp)} = 2766$ Oe. Equation (1) is valid for a Lorentzian-shaped resonance curve. Putting the above values in equation (1) gives $\alpha = 19$ Oe which is in reasonable agreement with the experimental value of 17 Oe. As the thickness is increased and the r.f. fields become non-uniform throughout the film thickness, the exchange-condustivity mechanism becomes more and more important and the linewidth for both orientations increases. The theoretical results show that this increase is greater for parallel than for perpendicular FMR. It is clear that the thickness dependence of the exchange-conductivity contributions to the linewidth should be different for the two orientations, simply because their corresponding internal fields for resonance are different.[12] Although it is not completely clear on an intuitive basis that the increase should be greater for parallel than for perpendicular resonance, it has been shown that a smaller internal field enhances the exchange-conductivity broadening effect.[13] As the film thickness increases beyond the skin depth, the exchange-conductivity contribution to the linewidth is maximized and increasing the thickness further does not increase the exchange-conductivity contribution. Thus the linewidth should level off with thickness. Although the calculations were carried out for thicknesses up to 3μ, the expected levelling off of the linewidth becomes complicated by the appearance of an additional, un-resolvable line which interferes with the main line. We are presently investigating this effect.

The disagreement between the theory and data *only* over an intermediate thickness region provides a further indication that a two-magnon type mechanism may be negligible. As previously discussed,[1] any two-magnon relaxation contribution would saturate at some maximum value rather than become zero for large thickness. Thus, if such a process were operative, all of the data points for the thicker films should lie significantly above the curve determined by the exchange-conductivity constant damping theory. Since the data and theory agree above $d = 2000$ Å the argument for the two-magnon processes in explaining the linewidth data is weakened. Nevertheless, quantitative predictions of the two-magnon relaxation mechanism as applied to this type of experiment would, of course, be quite useful in order to contrast the two models. Additional experimental data, particularly in the 800–1500 Å region, is also clearly needed.

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Die Dickenabbhängigkeit der Linienbreitendiffe renz für parallele und senkrechte ferromagnetische Resonanz in Permalloy-Filmen bei X-band-Frequenz und Zimmertemperatur wird für die Austausch-Leitungs-Theorie mit konstanter Dämpfung berechnet und mit Experiment verglichen. Die Ergebnisse stimmen für dünne ($d < 800$ Å) und dicke ($d > 1500$ Å) Filme gut überein. Für dazwischenliegende Dichten, zeigen die Daten eine Differenz, die etwas grösser ist, als der, die aus Theorie stammt. Die Ergebnisse weisen darauf hin, dass eine früher vorgeschlagene Zwei-Magnon-Interpretation für die beobachtete Differenz vielleicht ungeeignet sein mag.