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Relaxation Processes for Ferromagnetic Resonance in Thin Films

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Ferromagnetic-resonance linewidth measurements have been made for two hundred Ni–Fe alloy films (77% Ni) 150–3200 Å thick at frequencies from 1–9 Gc/sec with the static field in the film plane. To avoid dispersion effects samples with the smallest linewidth (ΔH_{min}) were selected for each thickness. For film thickness less than a frequency-dependent critical thickness D_ω, ΔH_{min} is independent of film thickness. For thicker films where $D > D_\omega$, ΔH_{min} increases linearly with film thickness. The observed D_ω values (about 1000 Å) are in good agreement with predictions based on magnon scattering involving spin waves degenerate with the uniform mode. Because of the magnetostatic mode modification of the spin-wave dispersion relation for thin films there are no spin-wave states degenerate with the uniform mode for $D < D_\omega$ and magnon scattering is not allowed. The applicability of two different magnon processes, *s–d* exchange and two-magnon scattering, is discussed. Neither mechanism provides a completely satisfactory explanation of the data. The present data indicate: (1) For $D > D_\omega$, the linewidth is a linear function of film thickness and a magnon process is important. (2) For $D < D_\omega$, a magnon process is not important. (3) The anisotropy dispersion makes a contribution to ΔH, which is significant and may mask the above effects if the dispersion is large.

SEVERAL investigations of the ferromagnetic resonance linewidth in thin films, with the field parallel to the film plane, have undertaken to characterize the losses associated with resonance. Goser has demonstrated that eddy-current losses are important only if the film thickness D is greater than the skin depth δ for resonance with the static magnetic field in the plane of the film (parallel resonance).[1] For parallel resonance and $D < \delta$, Goser found that the linewidth (ΔH) is independent of film thickness,[2] while Soohoo[3] and Berteaud *et al.*[4] reported that ΔH is linearly proportional to D. Soohoo attributed the linear dependence to the *s–d* exchange interaction[5] between the ferromagnetic and conduction electrons while Berteaud suggested a two-magnon process in which the uniform mode scatters into degenerate magnons within the spin-wave manifold. Such a two-magnon process is in accord with recent resonance studies at high-microwave power levels,[4,6] which have been explained in terms of magnon–magnon scattering and cannot be explained by *s–d* exchange. Nelson[7] has shown the importance of the film sample by reporting data which indicate that the resonance linewidth increases with magnitude dispersion of the uniaxial anisotropy. In an attempt to separate the relaxation contribution from the dispersion contribution to the linewidth, measurements have been made for 200 Ni–Fe alloy films (77% Ni) with thickness from 150 Å to 3200 Å and at frequencies from 1–9 Gc/sec (parallel resonance).

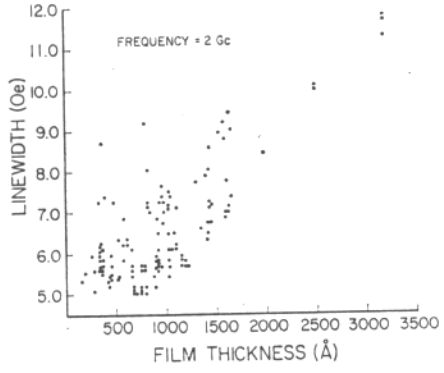

FIG. 1. Ferromagnetic-resonance linewidth as a function of film thickness for Ni–Fe alloy films at 2 Gc/sec with the static field in the film plane.

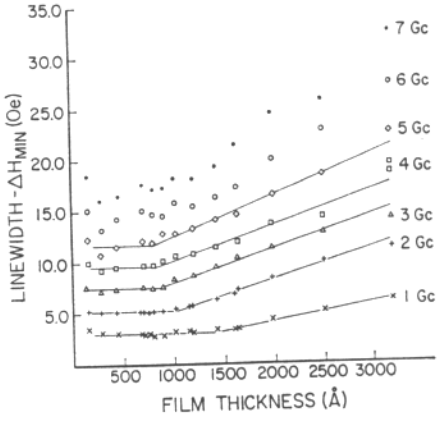

FIG. 2. Minimum-resonance linewidth for a specified film thickness as a function of film thickness for Ni–Fe alloy films with the static field in the film plane.

The Ni–Fe alloy films were evaporated from a melt of 80% Ni and 20% Fe onto glass substrates at 300°C in a vacuum of 10^{-6} Torr, with a uniform magnetic

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[1] K. Goser, Arch. Elek. Ubertragung **19**, 384 (1965).
[2] K. Goser, Z. Angew. Phys. **18**, 511 (1965).
[3] R. F. Soohoo, Proc. Intern. Conf. on Mag., Nottingham 1964, p. 852.
[4] A. J. Berteaud and H. Pascard, J. Appl. Phys. **36**, 970 (1965).
[5] C. Kittel and A. H. Mitchell, Phys. Rev. **101**, 1611 (1965).
[6] J. B. Comly, T. Penney, and R. V. Jones, J. Appl. Phys. **34**, 1145 (1963).
[7] R. H. Nelson, J. Appl. Phys. **35**, 808 (1964).

field applied in the plane of the substrate. Linewidth measurements were performed at 25°C utilizing a nonresonant stripline section, field modulation, and phase-sensitive detection. The linewidth was taken to be the field separation between the peaks of the derivative curve. Data for the 200 samples at 2 Gc/sec are shown in Fig. 1. The large variation in ΔH for the same film thickness can be attributed to dispersion. In order to minimize the dispersion contribution to ΔH, samples with the smallest linewidth ($\Delta H_{\min}$) were selected for each thickness.[8] The thickness-dependence of $\Delta H_{\min}$ for frequencies from 1–7 Gc/sec is shown in Fig. 2. For film thickness less than a critical thickness D_ω, $\Delta H_{\min}$ is independent of film thickness. For $D>D_\omega$, $\Delta H_{\min}$ increases linearly with film thickness. Following Nelson,[7] the linewidth may be described phenomenologically in terms of the Landau–Lifshitz damping parameter α. Values of α, obtained from the data in Fig. 2, increase linearly with film thickness from 0.005 at 400 Å to 0.010 at 3200 Å.

The D_ω values indicated in Fig. 2 can be explained on the basis of the magnetostatic mode modification of the spin-wave dispersion relation as shown in Fig. 3. Damon and Eshbach[9] have shown that the bottom of the magnetostatic mode spectrum drops down to the bottom of the spin-wave manifold only for $k>2\pi/D$. For a thick film ($D>D_\omega$) the spin-wave manifold is essentially unchanged and there are a large number of states degenerate with the uniform mode. For very thin films ($D<D_\omega$) there are no allowed states degenerate with the uniform mode. This analysis can be applied

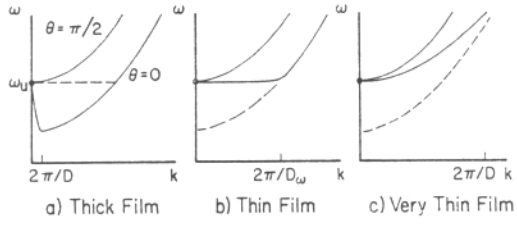
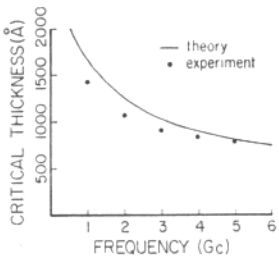


FIG. 3. Magnetostatic mode modifications of the spin-wave dispersion relation for (a) thick film, (b) thin film, and (c) very thin film. The angle θ is the angle between the static field and the spin-wave vector **k**.

[8] These minimum linewidth samples exhibited low dispersion, with Δ_{90} less than 0.1.

[9] R. W. Damon and J. R. Eshbach, J. Phys. Chem. Solids **19**, 308 (1961).

FIG. 4. Calculated and experimental values of the critical film thickness for magnon-scattering processes as a function of the uniform precession frequency ω_u. The theoretical curve was calculated assuming an exchange constant of 10^{-6} erg/cm and a saturation flux density of 10 000 G.



to both s–d exchange and the two-magnon interaction, since both involve magnon states degenerate with ω_u which are not allowed for $D<D_\omega$. The frequency-dependence of D_ω can be calculated from the spin-wave dispersion relation and is shown in Fig. 4 along with experimental values obtained from Fig. 2. The agreement between the theory and the data is quite good.

These results indicate that a magnon-scattering process is important for $D>D_\omega$. However, an explanation based on either s–d exchange or two-magnon scattering involves assumptions which are not clearly applicable in the present experiment. The s–d exchange process involves the rf excitation of spin waves with wave number equal to $2\pi/D$, with a significant variation of the microwave field across the film thickness. However, since δ was always at least ten times larger than D, the microwave-field variation through the film should be completely negligible.[10] If a two-magnon process is important, the linear dependence of $\Delta H_{\min}$ on film thickness indicates that the density of scattering centers increases with film thickness. Scattering at the film edges has been suggested as a possible mechanism by Berteaud.[4] By scratching through a 1600-Å film with a diamond scribe, the effective film-edge length was increased by 600% with only a 15% increase in ΔH at 2 Gc/sec. Therefore, the observed linear dependence (for $D>D_\omega$) cannot be explained by inhomogeneous scattering at the film edges.

The present data indicate: (1) For $D>D_\omega$, the linewidth is a linear function of film thickness and a magnon-scattering process is important. (2) For $D<D_\omega$, a magnon-scattering process is not important. (3) The anisotropy dispersion makes a contribution to ΔH which is significant and may mask the above effects if the dispersion is large.

[10] R. F. Soohoo, J. Appl. Phys. **31**, 218S (1960).