as the cathode diameter, which is an indication that the spread in beam energy of the accelerated beam is not large. A weakness in both sets of experiments is the difficulty in measuring the spread in beam energy.

V. CONCLUSIONS

The relativistic motion of a charged particle in combined inhomogeneous, large-amplitude, oscillating electromagnetic fields and steady magnetic fields has been investigated theoretically and experimentally. It was found that large energy gains could be obtained for conditions different from the idealized situation studied by Roberts and Buchsbaum.[1] The experiments confirmed the analysis and showed that the effects of space charge, beam diameter, cavity loading, multipactor breakdown, and background gas ionization are not limitations at the power levels investigated. The 30-cm wavelength experiment demonstrated that continuous operation at the experimental power levels is possible.

ACKNOWLEDGMENTS

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Linewidth and Relaxation Processes for the Main Resonance in the Spin-Wave Spectra of Ni–Fe Alloy Films*

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Measurements of the position and linewidth of the main resonance in the spin-wave spectra of 80% Ni–20% Fe evaporated films 150 to 3200 Å thick at frequencies from 0.8 to 4.0 GHz, at room temperature and with the static magnetic field perpendicular to the film plane have been performed. The center field for resonance was independent of thickness and consistent with the Kittel resonance condition for the uniform precession. The linewidth was about 30 Oe (measured as the field separation of inflection points on the absorption curve), independent of film thickness and frequency. The linewidth data have been compared to previous data for resonance with the static field parallel to the film plane and interpreted in terms of relaxation processes for the uniform precession. In general, frequency-swept linewidths, not field-swept linewidths, are proportional to the relaxation rate and are the quantities which should be compared. The frequency-swept linewidth for perpendicular resonance is equal to that obtained for parallel resonance in films thinner than 500 Å. This result indicates that two-magnon scattering between the uniform precession mode and spin-wave states for which the exchange energy term is large (wavenumber k appreciably different from zero) does not contribute to the perpendicular resonance linewidth and is the origin of the linewidth increase with thickness for parallel resonance. It appears that scattering to states with $k \approx 0$ and exchange conductivity broadening are the most reasonable sources for the residual 30 Oe linewidth.

INTRODUCTION

Spin-wave resonance in thin ferromagnetic films was initially predicted by Kittel[1] and observed experimentally by Seavey and Tannenwald[2] shortly thereafter. Following this initial work, a large variety of spin-wave spectra have been reported and several models have been evoked to explain these different spectra.[3] In most of these studies, the emphasis has been on explaining the spacing and intensities of the various spin-wave resonances which occur at fields lower than that for the main resonance. Very little attention has been given to the properties of the main resonance. In this study, attention was focused exclusively on the linewidth and the position of the main resonance for 80% Ni–20% Fe thin films. The position of the resonance was observed to be independent of film thickness from 150 to 3200 Å. The linewidth, defined as the field separation between inflection points on the absorption curve, was about 30 Oe independent of thickness (150–3200 Å) and frequency (0.8–4.0 GHz).

EXPERIMENTAL

The nickel-iron alloy films were vacuum evaporated from a melt of 80% Ni and 20% Fe onto hot glass substrates at 300°C in a moderate vacuum of 10^{-6} Torr and in the presence of a uniform magnetic field parallel

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[1] C. Kittel, Phys. Rev. **110**, 1295 (1958).
[2] M. H. Seavey and P. E. Tannenwald, Phys. Rev. Letters **1**, 168 (1958).
[3] An excellent review of this work has been given by J. W. Hartwell, Interim Tech. Rept., Department of Electrical Engineering, Duke University, Durham, North Carolina, April, 1967, and J. W. Hartwell, Proc. IEEE **56**, 23 (1968).

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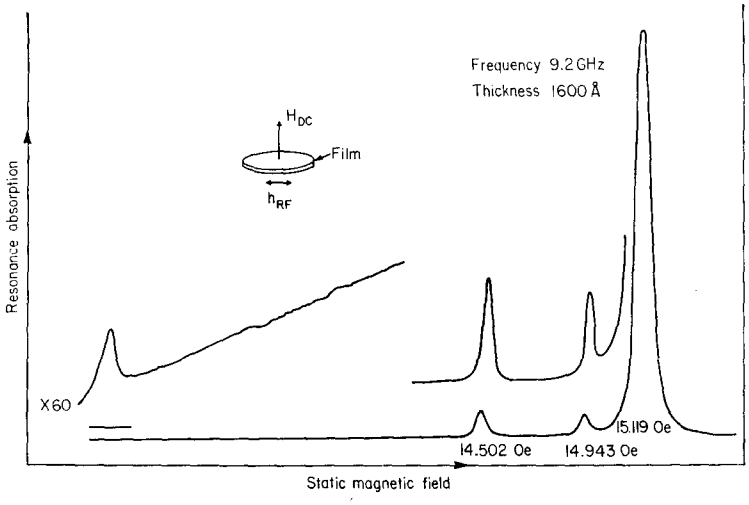

FIG. 1. Reflected microwave power as a function of static magnetic field for spin-wave resonance in a 1600 Å Ni–Fe film at 9.2 GHz.

to the plane of the substrate. Film composition was determined to be about 77% Ni using x-ray fluorescence techniques. Film thickness was determined magnetically, using a 20-Hz hysteresis loop tracer, and optically, using the Tolansky multiple beam interference technique. Linewidth measurements were performed utilizing a stripline section for microwave excitation, field modulation, and phase sensitive detection. The stripline was a conventional double-ground-plane system[4] designed to have an impedance of 50 Ω and provide a uniform microwave excitation field over the 1-cm diam sample mounted parallel to and against one ground plane. The stripline assembly was attached to a 12 in. diam lucite plate. This plate was mounted in the 2 in. gap of a 12 in. electromagnet so that the plane of the plate, the stripline ground plane, and the film plane were approximately normal to the static field direction and the direction of the microwave field was in the film plane. The plate was pivoted at its center and thumb screw adjustments were provided around its circumference for orienting the plate to align the film perpendicular to the static field direction. By adjusting the film position to maximize the field position of the main resonance, the film normal could be adjusted to $\pm 0.1°$ of the static magnetic field direction. The phase-sensitive detector output was displayed as a function of static applied field using an X–Y recorder and the linewidth ΔH was taken to be the field separation between the peaks of the absorption derivative. In the discussion to follow, this derivative linewidth will be referred to simply as linewidth.[5] All field measurements were made with a nuclear magnetic resonance spectrometer in conjunction with an electronic counter. With the above arrangement, resonance data was obtained at frequencies from 0.8 to 4 GHz. In addition, a microwave spectrometer at 9.2 GHz incorporating a cylindrical TE_{011} reflection cavity was used for rapid surveys of the spin-wave spectra of the films examined.

MAIN RESONANCE MODE IDENTIFICATION

A representative absorption curve, obtained with the reflection cavity spectrometer at 9.2 GHz for a 1600 Å film, is shown in Fig. 1. The films exhibited the usual spectra characterized by a strong peak, the main resonance, and a series of weaker resonances at lower values of static field.

The linewidth and associated relaxation processes for the main resonance are expected to be closely related to the nature of the mode associated with the resonance. If the resonance corresponds closely to the uniform precession, the linewidth should be connected with relaxation processes for the uniform precession. If the resonance corresponds to a standing spin-wave mode, as expected for films with strong spin pinning at the film surfaces[1] or for films with a large-volume inhomogeneity in the magnetization through the film thickness,[6] the linewidth should be connected with spin-wave relaxation processes. The nature of the main resonance mode can be determined by examining the thickness dependence of the field at the resonance peak. For a standing spin-wave mode, the resultant exchange field associated with the variation in the magnetization precession amplitude through the thickness increases with decreasing thickness and results in a lowering of the required external field for resonance. For the uniform precession, there is no such exchange field and the external field for resonance should be independent of thickness.

It is not possible to draw any general conclusions

[4] Symposium on Microwave Strip Circuits, IRE Transactions, Vol. MTT-3, No. 2, March 1955.

[5] With the present experimental arrangement, the derivative of the absorption is obtained as a function of applied static field. The values of the derivative linewidth reported here can be converted to the usual half-power linewidth of the absorption curve by multiplying ΔH by $\sqrt{3}$, if the lineshape is assumed Lorentzian. A lineshape analysis for several resonance curves indicated that the lines are near Lorentzian in shape and that the $\sqrt{3}$ conversion is accurate to better than $\pm 15\%$.

[6] P. E. Wigen, C. F. Kooi, M. R. Shanabarger, and T. D. Rossing, Phys. Rev. Letters 9, 206 (1962).

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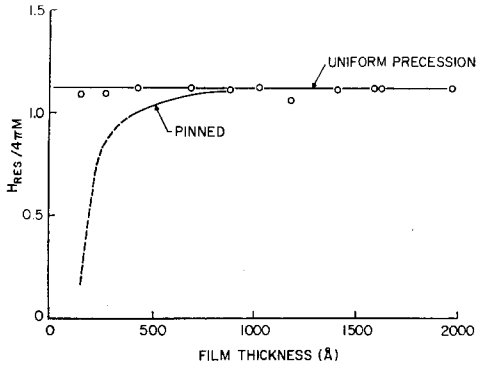

FIG. 2. Thickness dependence of the center field H_{res} for the main resonance in the spin-wave spectra of Ni–Fe alloy films with 20% Fe at 4.0 GHz with the static magnetic field perpendicular to the film. The H_{res} values have been normalized to the average saturation induction $\langle 4\pi M \rangle$. The open circles correspond to measured values, the solid lines to the value predicted from the Kittel resonance condition for the uniform precession and the values expected for a film with strong surface spin pinning.

concerning the nature of the main resonance from the literature. In an early investigation by Seavey and Tannenwald,[7] the saturation induction $4\pi M$ and g value were shown to be essentially independent of film thickness from 100 to 1000 Å, which indicate that the position of the resonance is independent of film thickness. On the other hand, Blades has reported a strong thickness dependence for the position of the main resonance from 100 to 1600 Å,[8] and concluded that pinning at the metal-to-glass interface was the spin constraint required to explain the data. Frait and Mitchell have also concluded that partial spin pinning is operative.[9] In general, it appears that a large number of strong spin-wave resonances in the spectra are indicative of strong pinning and/or a large volume inhomogeneity in $4\pi M$, while less pronounced spectra with only a few weak resonances are indicative of weak pinning and small-volume inhomogeneity. The weak spin-wave modes evident in Fig. 1 suggest that the latter conclusion is applicable to the films used in this study.

In order to clearly determine the nature of the main resonance (uniform precession or standing spin-wave mode) for the films used in the present study, the field for resonance H_{res} was carefully measured as a function of film thickness. These data, normalized to the average saturation induction $\langle 4\pi M \rangle$, are shown in Fig. 2. The average saturation induction for each sample was determined from the center field for uniform mode resonance observed with the static magnetic field parallel to the film plane (parallel resonance). The normalization procedure was found necessary in order to reduce the scatter in H_{res} due to variations in $\langle 4\pi M \rangle$ from sample to sample. The rms fluctuation in $\langle 4\pi M \rangle$ was 450 Oe. The data in Fig. 2 clearly show that the field for resonance is not a function of thickness down to 150 Å. For comparison, the theoretical field for resonance as a function of thickness for the surface spin-pinning model is also shown in Fig. 2 (pinned curve). The results indicate that the main resonance corresponds very closely to the uniform precession (upper curve) and that surface spin pinning is negligible for the films investigated.

LINEWIDTH FOR THE MAIN RESONANCE

In Fig. 3, the linewidth $\Delta H_\perp$ for resonance with the static magnetic field perpendicular to the film plane is displayed as a function of frequency for a 150 Å film. For comparison, the parallel linewidth $\Delta H_{||}$, obtained with the static magnetic field parallel to the film plane and reported previously,[10] is also shown as a function of frequency for the same film. Two points concerning Fig. 3 should be emphasized. First, the perpendicular linewidth $\Delta H_\perp$ is considerably larger than the parallel resonance linewidth $\Delta H_{||}$. Second, $\Delta H_\perp$ is independent of frequency while $\Delta H_{||}$ increases linearly with frequency. Similar data were obtained for films up to 3200 Å thick. In Fig. 4, the thickness dependence of the perpendicular linewidth is shown for resonance at 4 GHz. Again, parallel resonance data are shown for comparison. As in Fig. 3, $\Delta H_\perp$ is considerably larger than $\Delta H_{||}$. Furthermore, the perpendicular linewidth does not exhibit the increase with thickness which is characteristic of the parallel resonance linewidth.[11] The data presented in Figs. 3 and 4 can best be summarized as follows: While $\Delta H_{||}$ increases almost linearly with both film thickness and frequency, the perpendicular

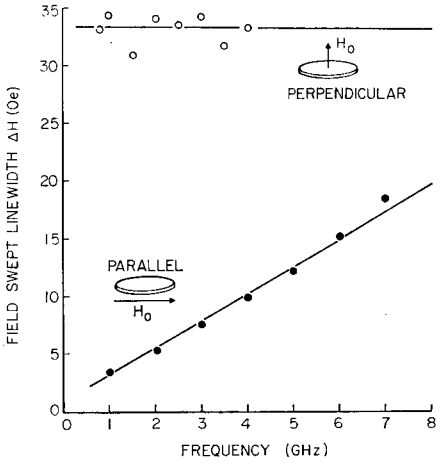

FIG. 3. Field-swept linewidth (field difference between maximum and minimim excursions of the absorption derivative) as a function of frequency for parallel and perpendicular resonance in a 150 Å film.

[7] M. H. Seavey and P. E. Tannenwald, J. Appl. Phys. **29**, 292 (1958).
[8] J. D. Blades, *Proceedings of the International Conference on Magnetism, Nottingham 1964* (The Institite of Physics and the Physical Society, London), p. 309.
[9] Z. Frait and E. N. Mitchell, in. Ref. 8, p. 316.
[10] C. E. Patton, C. H. Wilts, and F. B. Humphrey, J. Appl. Phys. **38**, 1358 (1967).
[11] Similar results for $\Delta H_{||}$ and $\Delta H_\perp$ were reported for resonance at 9.3 GHz by A. J. Berteaud and H. Pascard, J. Appl. Phys. **36**, 970 (1965).

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linewidth is larger and constant at approximately 30 Oe, independent of both thickness and frequency.[12] It has been found that two effects can be used to explain the linewidth data summarized in Figs. 3 and 4: (1) the effect of geometry on the relationship between the linewidth ΔH and the relaxation rate for the uniform precession, and (2) the effect of geometry on the two-magnon scattering contribution to the relaxation rate. In the analysis to follow, it will be shown that (1) the apparent lack of connection between $\Delta H_{||}$ and $\Delta H_{\perp}$ in Figs. 3 and 4 is due to geometry and (2) the relaxation rates for parallel and perpendicular uniform precession resonance are related in a consistent manner which involves the possibility of two-magnon scattering contributions to the linewidth in each case.

TWO-MAGNON SCATTERING

First consider the connection between linewidth and the uniform precession relaxation rate for parallel and perpendicular resonance. For the present purposes, this relaxation rate η can be defined as the inverse time constant for the decay of the uniform precession amplitude after the microwave field exciting the magnetization motion has been turned off. In the appendix, the Gilbert modification of the Landau–Lifshitz equation is used to calculate the linewidth ΔH obtained by sweeping the magnetic field as in the usual resonance experiment, the linewidth $\Delta(\omega/\gamma)$ obtained by sweeping frequency at a fixed field and the relaxation rate η. The frequency-swept linewidth in field units is obtained by dividing $\Delta\omega$ by the gyromagnetic ratio γ. It is shown that in general $\Delta(\omega/\gamma)=(2/\sqrt{3})\eta/\gamma$ but that $\Delta H=(2/\sqrt{3})\eta/\gamma$ only if the sample exhibits rotational symmetry about a direction parallel to the applied static field. This symmetry requirement is satisfied for perpendicular resonance ($\Delta H_{\perp}$) but not for parallel resonance ($\Delta H_{||}$). In other words, $\Delta H_{\perp}$ provides a valid measure of the relaxation rate $\eta_{\perp}$ for perpendicular resonance but $\Delta H_{||}$ is not a meaningful measure of the relaxation rate $\eta_{||}$ for parallel resonance. In order to make a meaningful comparison of the resonance losses for the two configurations, it is necessary to compare frequency-swept linewidths, not field-swept linewidths, since the frequency-swept linewidth is always a valid measure of the relaxation rate. As shown in the Appendix, the frequency-swept linewidth $\Delta(\omega/\gamma)$ is related to the field-swept linewidth ΔH by

$$\Delta(\omega/\gamma)_{\perp}=\Delta H_{\perp} \qquad \text{(perpendicular resonance)} \quad (1a)$$

and

$$\Delta(\omega/\gamma)_{||}=[(\gamma^2\pi M/\omega)^2+1]^{1/2}\Delta H_{||}. \qquad \text{(parallel resonance)} \quad (1b)$$

For 80% Ni–20% Fe films with $4\pi M\approx 10^4$ G at 4 GHz, Eq. (1b) reduces to $\Delta(\omega/\gamma)\approx 3.6\Delta H$, so that the correction factor for parallel resonance is quite large.

In Fig. 5, the frequency-swept linewidths corresponding to the linewidth data of Fig. 4 are shown as a function of film thickness for resonance at 4 GHz. The scale is the same as in Fig. 4. The points for perpendicular resonance are unchanged, since $\Delta H_{\perp}=\Delta(\omega/\gamma)_{\perp}$, but the points for parallel resonance are shifted upward by a factor of 3.6. Figure 5 clearly shows that $\Delta(\omega/\gamma)$ (and hence the relaxation rates) for parallel and perpendicular resonance are nearly equal for very thin films (thicknesses $D<500$ Å). The frequency-swept linewidth and relaxation rate for perpendicular resonance remain at this value of 30 Oe

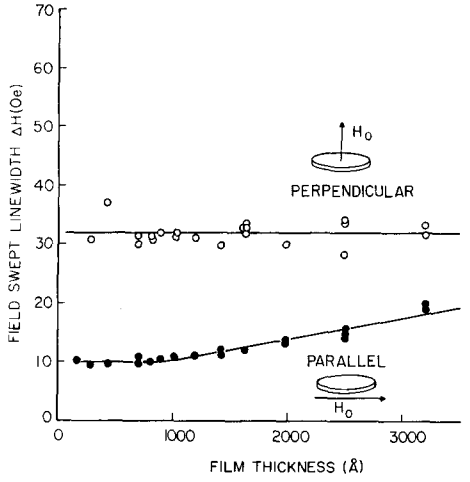

FIG. 4. Field-swept linewidth (field difference between the maximum and minimum excursions of the absorption derivative) as a function of film thickness for parallel and perpendicular resonance at 4.0 GHz.

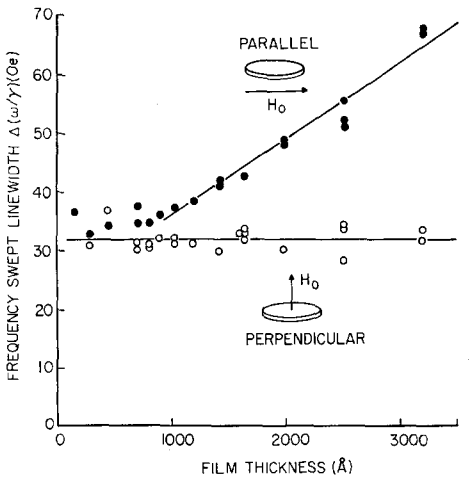

FIG. 5. Frequency-swept linewidth as a function of film thickness for parallel and perpendicular resonance. The values of $\Delta(\omega/\gamma)$ were obtained from the linewidth data in Fig. 4 as explained in the text.

[12] It is interesting to note that as early as 1957 P. E. Tannenwald and M. H. Seavey, Jr., Phys. Rev. **105**, 377 (1957) reported $\Delta H_{\perp}=43$ Oe for a 1000 Å film at 9.1 GHz and 33 Oe for a 960 Å film at 2.8 GHz.

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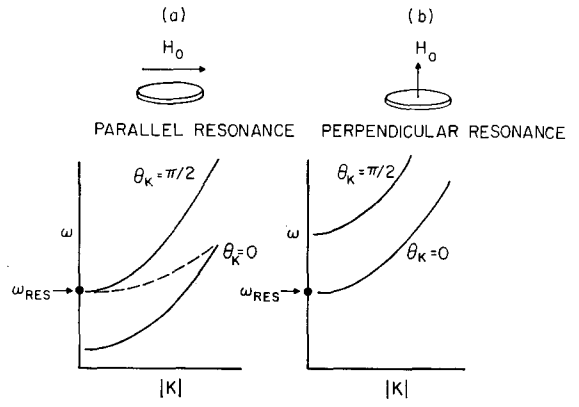

FIG. 6. Magnon frequency ω as a function of wavevector magnitude $|\mathbf{k}|$ for films biased to ferromagnetic resonance with the static field $\mathbf{H}_{res}$ parallel [Fig. 6(a)] or perpendicular [Fig. 6(b)] to the film plane. The $\theta=0$ branch corresponds to $\mathbf{k}$ parallel to $\mathbf{H}$ and $\theta=\pi/2$ corresponds to $\mathbf{k}$ perpendicular to $\mathbf{H}$. The dotted line indicates the modification of the $\theta=0$ branch in the limit of small film thickness (<500 Å) for parallel resonance due to magnetostatic interactions.

and do not change with increasing thickness. In contrast, $\Delta(\omega/\gamma)$ for parallel resonance increases monotonically with thickness. Almost identical results would be expected at other frequencies. The perpendicular linewidth $\Delta H_\perp$ is independent of frequency and $\Delta(\omega/\gamma)_\perp=\Delta H_\perp$. The frequency dependence of the $[(\gamma 2\pi M/\omega)^2+1]^{1/2}$ term in Eq. (1b) compensates for the increase in $\Delta H_{||}$ with ω (Fig. 3) and results in a $\Delta(\omega/\gamma)_{||}$ which is also frequency independent.

The equivalence of $\Delta(\omega/\gamma)_{||}$ and $\Delta(\omega/\gamma)_\perp$ in the thin-film limit and the thickness dependence of the frequency-swept linewidth for parallel and perpendicular resonance can be explained by considering magnon dispersion relations for the two geometries and examining the possibility of two-magnon scattering contributions to the relaxation rate in each case. The relevant dispersion relations are shown in Fig. 6. Spin-wave frequency ω_k is shown as a function of wavevector magnitude $|\mathbf{k}|$ for values of the static magnetic field $\mathbf{H}$ necessary to bias the film to ferromagnetic resonance. Allowed spin-wave states are contained in the region between the $\theta=0$ branch ($\mathbf{k}$ parallel to $\mathbf{H}$) and $\theta=\pi/2$ branch ($\mathbf{k}$ perpendicular to $\mathbf{H}$) of the dispersion relation, called the spin-wave manifold. For parallel resonance [Fig. 6(a)] the uniform precession frequency ω_{res} falls on the $\theta=\pi/2$ branch of the manifold at $|\mathbf{k}|=0$. Due to the increased magnetostatic contribution to the spin-wave energy for small film thickness, the $\theta=0$ branch is modified considerably as the film thickness is reduced.[13,14] For D less than about 500 Å, magnetostatic interactions severely modify the $\theta=0$ branch of the manifold as indicated by the dotted line in Fig. 6(a).[15] In the thin-film limit ($D<500$ Å), only low-k magnon states ($k\approx 0$) are degenerate with the uniform precession and only these states can provide a two-magnon scattering contribution to the linewidth. As the thickness is increased, the $\theta=0$ branch of the manifold approaches the bulk limit shown in Fig. 6(a), the number of states degenerate with ω_{res} increases, and a larger scattering contribution to the linewidth is possible. The observed linewidth increase with thickness for parallel resonance has been explained on the basis of such scattering.[10] The corresponding situation for perpendicular resonance is shown in Fig. 6(b). Here, ω_{res} falls on the lower $\theta=0$ branch of the manifold at $|\mathbf{k}|=0$. Magnetostatic interactions do not strongly influence the number of magnon states degenerate with the uniform precession for perpendicular resonance, and the two-magnon scattering contribution to the linewidth can come only from low-k states. There is no increase in the number of degenerate states with thickness and no increase in the scattering contribution to the linewidth with thickness is expected.

If two-magnon scattering is the explanation for the increase in $\Delta(\omega/\gamma)_{||}$ with thickness, it is expected that $\Delta(\omega/\gamma)_\perp$ would be independent of thickness and equal to the value of $\Delta(\omega/\gamma)_{||}$ for $D<500$ Å. This expectation corresponds very closely to the experimental situation summarized in Fig. 5. At any thickness, the difference $[\Delta(\omega\gamma)_{||}-\Delta(\omega/\gamma)_\perp]$ represents the linewidth contribution due to scattering to spin-wave states with k appreciably different from zero, states which are not allowed in the thin-film limit due to magnetostatic interactions. The residual thickness independent 30 Oe linewidth corresponding to $\Delta(\omega/\gamma)_\perp$ for 150–3200 Å thickness and to $\Delta(\omega/\gamma)_{||}$ in the thin-film limit can be attributed to (1) low-k scattering and (2) other processes which do not involve two-magnon scattering.

Insofar as there are low-k states degenerate with ω_{res}, it is quite possible that a considerable portion of the residual linewidth is due to low-k scattering. Schlömann has shown that for coarse grained inhomogeneities, such as those found in polycrystalline yttrium iron garnet with grain sizes on the order of microns, the perpendicular resonance linewidth due to low k scattering is nonzero.[16] No corresponding analysis has been carried out for evaporated films with grain sizes on the order of 100 Å for which the coarse grain approximation is not appropriate. Wigen has considered the linewidth contribution due to low-k scattering which arises from fluctuations in the local magnetization along directions parallel to the film plane.[17] He

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[14] K. J. Harte, Technical Rept. No. 364, Lincoln Lab., MIT, Lexington, Massachusetts, August 27, 1964.
[15] In a more quantitative analysis, any portion of the manifold which is modified by magnetostatic energy terms should be represented as a series of discrete states in the dispersion diagram. For the present discussion, only the factors concerning the existence of states degenerate with ω_{res} are considered and this refinement has been omitted.
[16] E. Schlömann, J. Phys. Chem. Solids **6**, 242 (1958).
[17] P. E. Wigen, Phys. Rev. **133**, A1557 (1964).

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estimates that the linewidth due to such fluctuations is approximately equal to $H_p^2/4\pi M$, where H_p is the rms value of the internal field inhomogeneity. If the present 30 Oe residual linewidth is assumed to be due entirely to planar inhomogeneity broadening, $H_p \approx 500$ Oe. Wigen's analysis of spin-wave resonance data indicates that H_p is approximately 300 Oe. In the absence of a precise estimate of H_p for the films used in this study, no quantitative conclusions concerning the low-k scattering to the residual 30 Oe linewidth are possible. A concise theoretical treatment of the two-magnon scattering linewidth in films, involving both low-k and high-k states, and more complete information concerning film properties, including surface roughness, grain size, magnetization fluctuations, and any other sources of scattering, are required before a more quantitative analysis of the data in terms of scattering will be possible.

OTHER LINEWIDTH MECHANISMS

In the preceding discussion, only the two-magnon scattering contribution to the relaxation rate and $\Delta(\omega/\gamma)$ has been considered. The possible contributions of other processes to the residual $\Delta(\omega/\gamma)$ of 30 Oe have not yet been considered. A large number of other mechanisms have been proposed to explain ferromagnetic resonance linewidths in metals, insulators, and films. It is appropriate to briefly indicate which of these processes may be important in connection with the present data.

Relaxation processes peculiar to metallic ferromagnets and their applicability to thin films have been reviewed by Comly[18] and will not be discussed in detail here. Two such processes, eddy-current losses and s–d exchange, have been suggested as contributors to thin-film linewidths and it is important to consider the relevancy of these processes to the present data.

Smith[19] has calculated the contribution to the damping from eddy-current losses for parallel resonance assuming a uniform microwave field through the film and uniform precession of the magnetization with the precession cone in the form of a flat ellipse with **M** essentially in the film plane. Smith predicted that the linewidth should vary linearly with conductivity and frequency, and quadratically with film thickness and that the eddy-current contribution to the linewidth would be comparable to the relaxation loss contribution for $D \approx 3000$ Å. Schlömann[20] has calculated the eddy-current contribution to the parallel-resonance linewidth for a thin film against the metal wall of a microwave cavity with the microwave field parallel to the film plane, without invoking the assumptions of field and magnetization uniformity used by Smith, but also neglecting exchange. For film thickness D much less than the off-resonance skin depth δ, the theory agrees with Smith's result. For thick films, the linewidth approaches a constant value of about 1.4 times the linewidth in the absence of eddy-current losses. These calculations predict a linewidth thickness dependence which is much smaller than observed experimentally for parallel resonance.[10] The parallel-resonance linewidth temperature dependence[21] also indicates that eddy-current dissipation is not important.

These eddy-current calculations neglected exchange. Due to the finite penetration depth of the microwave field into a metal, the microwave excitation cannot be entirely uniform through the film, and resultant variations in the magnetization precession give rise to an exchange field which produces additional linebroadening. The first calculation of eddy-current damping including exchange was reported by Ament and Rado[22] for a static magnetic field parallel to the surface of a metal sample with $D \gg \delta$. The Ament–Rado eddy-current exchange-conductivity broadening mechanism has received considerable attention in conjunction with Rodbell's linewidth measurements on single-crystal iron whiskers and nickel platelets.[23] The smallest reported linewidth of 32 ± 2 Oe for an iron whisker at 9.09 GHz and 315°C is in good agreement with the Ament–Rado theory and compares favorably with the present residual $\Delta(\omega/\gamma)$. The reported nickel platelet linewidths range from 100 to 200 Oe. The order of magnitude agreement between the data of Rodbell and the present results suggest that the eddy-current exchange-conductivity mechanism may make a strong contribution to the thin-film linewidth.

A number of calculations concerning eddy-current exchange-conductivity broadening which are applicable to resonance in normally magnetized films have been reported. Gurevich[24] considered the case of negligible surface pinning and $D \gg \delta$, Pincus[25] and Kaplan[26] considered the case of finite thickness films, extending the original calculation of Kittel,[1] and Seavey[27] has treated the case of films with a variety of pinning assumptions and microwave field–film coupling arrangements. For the case which most nearly corresponds to the present experimental arrangement, namely, negligible surface spin pinning and microwave power incident on one side of the film with the other side abutting a con-

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[19] D. O. Smith, *Magnetism*, G. T. Rado and H. Suhl, Eds. (Academic Press Inc., New York, 1963), Vol. III, Chap. 10, pp. 506–7, 517.
[20] E. Schlömann, Proc. Am. Phys. Soc. **12** (Ser. II), 312 (1967).
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[27] M. H. Seavey, Jr., Lincoln Lab. Tech. Rept. No. 239, February, 1961.

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ductor, Seavey obtains a theoretical derivative linewidth of about 25 Oe for a 6500 Å thick film and $D/\delta=\frac{1}{2}$, corresponding to a frequency of about 28 GHz. These results strongly suggest that exchange conductivity provides a significant contribution to the present residual $\Delta(\omega/\gamma)$ of 30 Oe. Wigen has, in fact, reported that linewidths for the various spin-wave modes in the spin-wave spectra of thin films contain a large eddy-current contribution.[17] The conclusion was based on Kittel's theory[1] and the assumption that the main resonance corresponded to a spin-wave mode with $k=\pi/D$. As discussed in conjunction with Fig. 2, this assumption is not justified for the present data. Further difficulties exist in any positive interpretation of the present data in terms of exchange conductivity. The origin of the mechanism rests in the skin effect for metals at microwave frequencies and the line broadening would be expected to exhibit a dependence on thickness and frequency which are not observed. It is possible that, for $D\ll\delta$ as is the case in the present study, the linebroadening is not a strong function of these parameters. Further calculations of such linewidths as a function of thickness and frequency are necessary in order to clarify the applicability of exchange-conductivity to thin films. For the present, the apparent correlation between the available theoretical values and the data indicate that such a mechanism is a strong possibility.

Soohoo[28] has proposed that the Kittel–Mitchell s–d exchange interaction[29] makes a strong contribution to the parallel-resonance linewidth in thin films. However, in his application of the Kittel–Mitchell theory to resonance in films, Soohoo assumed that the resonance corresponds to the excitation of a standing spin-wave mode with $k=\pi/D$. A strong s–d exchange contribution of $\Delta H_{\|}$ is not consistent with the present and previously published data. It has been shown that in the present experiment the main resonance corresponds to the uniform precession, not a standing spin-wave mode. Furthermore, the model predicts an inverse dependence of linewidth on spin-wave number while Comly[18] has observed an increase in the spin-wave linewidth with k from parallel-pumping experiments. The s–d exchange interaction is definitely not the origin of the parallel-resonance linewidth thickness dependence. The magnon-scattering explanation is more appropriate. The s–d exchange interaction also does not appear to contribute to the residual $\Delta(\omega/\gamma)$ reported here.

The list of possible loss mechanisms for resonance in insulating ferromagnets is quite long and includes three magnon (splitting and confluence), valence exchange, slowly and rapidly relaxing impurity, Kasuya–LeCraw three-magnon, and Kasuya–LeCraw two-magnon-one-phonon processes. Sparks[30] has written an excellent review of resonance relaxation in insulators and the individual mechanisms will not be discussed here. However, two general remarks concerning the relevance of these processes to the present data are important. First, the linewidths predicted for these processes, calculated with parameters appropriate for Ni–Fe films,[18] are more than an order of magnitude smaller than the present experimental residual $\Delta(\omega/\gamma)$ of 30 Oe. Second, the linewidth contributions from the above mechanisms exhibit strong temperature and frequency dependences. From the present results, $\Delta(\omega/\gamma)$ is independent of frequency. The thin-film linewidth is also independent of temperature from 4.2°K to room temperature if surface oxidation effects are small.[21] It appears that the processes which are responsible for the small linewidths observed in insulating ferromagnets are not responsible for the large residual $\Delta(\omega/\gamma)$ observed in thin Ni–Fe films.

Finally, two factors which have been shown to influence the parallel-resonance linewidth in films, anisotropy dispersion and surface oxidation, should be considered. The author has previously reported that the room-temperature linewidth is strongly influenced by magnitude dispersion of the uniaxial anisotropy.[11,31] The data shown in Figs. 3 and 4 correspond to low-dispersion films[32] in order to simplify the comparison of the previous parallel-resonance results with the perpendicular-resonance data. Films with large dispersion exhibit $\Delta H_{\|}$ values which are larger than shown in Figs. 3 and 4. (See Ref. 11). In the present study of

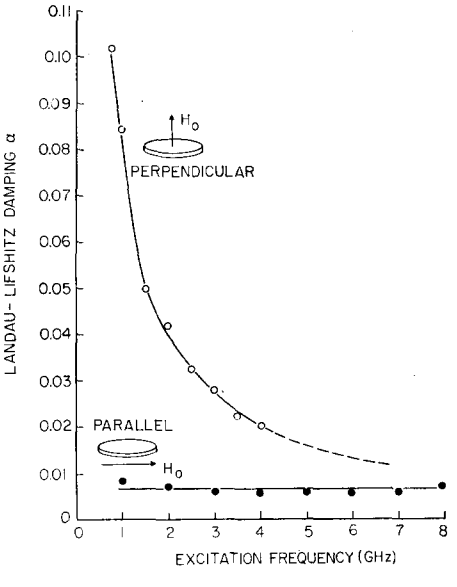

FIG. 7. Landau–Lifshitz damping α as a function of excitation frequency for parallel and perpendicular resonance in a 150 Å film.

[28] R. F. Soohoo, in Ref. 8, p. 852.
[29] C. Kittel, and A. H. Mitchell, Phys. Rev. **101**, 1611 (1956).
[30] M. Sparks, *Ferromagnetic Relaxation Theory* (McGraw-Hill Book Company, New York 1964).
[31] C. E. Patton, thesis, California Institute of Technology, Pasadena, California, 157 (1967).
[32] The low-dispersion films correspond to the minimum linewidth samples of Ref. 10 with the dispersion parameter Δ_{90} less than 0.1.

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perpendicular resonance, however, it was found that dispersion made no significant contribution to $\Delta H_\perp$. The absence of a dispersion contribution of $\Delta H_\perp$ may be due to two factors. First, the dispersion contribution may be related to two-magnon scattering which does not contribute to $\Delta H_\perp$. Second, the effect of the uniaxial anisotropy on the resonance condition is probably quite small for films magnetized perpendicular to their plane in strong fields. It is suggested that these two factors combine to produce a perpendicular linewidth which is relatively insensitive to dispersion. Surface oxidation is known to have a strong influence on the parallel-resonance linewidth temperature dependence, but has little influence on the room-temperature linewidth.[21] Although no systematic study of the effect of oxidation on the perpendicular-resonance linewidth or the related temperature dependence of $\Delta H_\perp$ has been carried out, it has been assumed that the situation is comparable to that for parallel resonance and that oxidation is not responsible for the residual $\Delta(\omega/\gamma)$ reported here.

LANDAU–LIFSHITZ DAMPING

Even though the relaxation rates or frequency widths for parallel and perpendicular resonance are equal in the thin-film limit, the actual measured linewidths are quite different. The large differences in linewidth (see Fig. 3) have important consequences if the losses for resonance are interpreted in terms of Landau–Lifshitz damping. Both $\Delta H_{||}$ and $\Delta H_\perp$ are related to the damping α by

$$\Delta H = (2/\sqrt{3})\alpha\omega/\gamma \qquad (2)$$

if ΔH is the derivative linewidth and the lineshape is assumed Lorentzian. Equation (2) has been used to calculate $\alpha_\perp$ and $\alpha_{||}$ from the $\Delta H_\perp$ and $\Delta H_{||}$ data of Fig. 3 for a 150 Å film and the results are summarized in Fig. 7. The damping for parallel resonance is approximately constant at 0.005 while the damping for perpendicular resonance decreases from 0.09 at 800 MHz to less than 0.02 at 4 GHz. The large differences between $\alpha_{||}$ and $\alpha_\perp$ cannot be related to a difference in resonance losses for the two configurations. It has been pointed out that the relaxation rates for parallel and perpendicular resonance are the same in the thin-film limit. It appears that Landau–Lifshitz damping is not an appropriate parameter for the characterization of relaxation processes for ferromagnetic resonance in thin films. As demonstrated above, there is not a one-to-one correspondence between the damping and the relaxation rate. There is a one-to-one correspondence between the damping rate and the linewidth ΔH but the relationship between ΔH and relaxation rate [i.e., $\Delta(\omega/\gamma)$] depends on geometry. The relaxation rate or frequency width is the more appropriate parameter to use.

CONCLUSION AND SUMMARY

Measurements of the linewidth and position of the main resonance in the spin-wave spectra of Ni–Fe alloy films 150 to 3200 Å thick at frequencies from 0.8 to 4.0 GHz at room temperature, and with the static magnetic field normal to the film plane (perpendicular resonance) have been performed. The center field for resonance was observed to be independent of film thickness and consistent with the Kittel resonance condition for the uniform precession. The linewidth $\Delta H_\perp$ was found to be about 30 Oe, independent of film thickness and frequency. The observation of a thickness-independent field for resonance indicates that any surface spin pinning or volume inhomogeneities in the magnetization which are present must be small, and that the main resonance corresponds very closely to the uniform precession. Accordingly, the linewidth can be interpreted in terms of relaxation processes for the uniform precession. Geometry has an important influence on the interpretation of linewidth data in terms of relaxation rates. In general, frequency-swept linewidths, not field-swept linewidths, are proportional to the relaxation rate. The frequency-swept linewidth for perpendicular resonance is equal to that obtained for parallel resonance in films thinner than about 500 Å. This observation indicates that scattering to magnon states with wavenumbers appreciably different from zero does not contribute to the perpendicular-resonance linewidth and is the origin of the linewidth increase with thickness for parallel resonance. Scattering to low-k states is a possible contribution to the 30 Oe residual linewidth. Other linewidth mechanisms, previously suggested for insulators, metals, and thin films, have been considered. Apart from low-k scattering, exchange conductivity may provide a strong contribution to the 30 Oe linewidth, although further work is necessary before any positive conclusions will be possible. The other processes predict linewidths which are too small or have strong frequency and temperature dependences which are not observed in films.

The primary results of this investigation are: (1) the main resonance in the spin-wave spectra of Ni–Fe films is accurately predicted from the Kittel resonance condition for the uniform precession; (2) the linewidth for this resonance is independent of thickness, and this indicates that magnon scattering to states with k appreciably different from zero does not contribute significantly to the relaxation rate for perpendicular resonance; (3) the linewidth is probably related to low-k scattering and possibly to exchange-conductivity; (4) the linewidth is also independent of frequency and indicates that the intrinsic relaxation processes for ferromagnetic resonance in thin films are better characterized by a relaxation rate than by Landau–Lifshitz damping.

Note added in proof: The half-power spin-wave linewidth in Permalloy platelets at 17 GHz and tempera-

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tures from 4.2° to 300°K, as measured using parallel pumping techniques, is approximately 80 Oe [A. F. Milton, Bull. Am. Phys. Soc. Series II **3,** 502 (1968)], in good agreement with the present results. These results suggest that low-k scattering does not contribute appreciably to the present residual $\Delta(\omega/\gamma)$. A new s–d exchange calculation which includes the influence of s-spin relaxation [B. Heindrich, D. Fraitova, and V. Kambersky, Phys. Status Solidi **23,** 501 (1967)] indicates that the resultant linewidth may not be k-dependent, temperature dependent, or require a shielded s–d exchange integral. On the basis of this work, s–d exchange cannot be eliminated as a possible source of the residual $\Delta(\omega/\gamma)$ reported here.

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APPENDIX

If the Gilbert equation

$$d\mathbf{M}/dt=-\gamma(\mathbf{M}\times\mathbf{H})+(\alpha/M)(\mathbf{M}\times d\mathbf{M}/dt) \quad \text{(A1)}$$

is used to calculate the effective susceptibility tensor χ_{eff} defined by $\mathbf{m}=\chi_{\text{eff}}\mathbf{h}_{\text{rf}}$, where $\mathbf{m}$ is the time-dependent component of the magnetization $\mathbf{M}$, $\mathbf{h}_{\text{rf}}$ is the component of the internal field $\mathbf{H}$ corresponding to the externally applied microwave field at frequency ω, α is a phenomenological damping parameter, and the gyromagnetic ratio γ is taken to be positive for electrons, one obtains a resonance denominator of the form

$$[1-\omega^2(1+\alpha^2)/(XY)]-i\alpha\omega(X+Y)/(XY), \quad \text{(A2)}$$

where

$$X=\gamma[H_0+(N_x-N_z)M], \quad \text{(A3)}$$

and

$$Y=\gamma[H_0+(N_y-N_z)M]. \quad \text{(A4)}$$

Here H_0 is the static applied field in the z direction and (N_x, N_y, N_z) are the shape demagnetization factors for the sample, assumed to be an ellipsoid magnetized along a principal axis in the z direction. The half-power linewidth, corresponding to the difference in field values for the field-swept linewidth $\Delta H_{1/2}$ or frequency values for the frequency-swept linewidth $\Delta(\omega/\gamma)_{1/2}$ for which the imaginary part of the microwave susceptibility is equal to one-half its value at resonance, is obtained as the difference in field or frequency values for which the real and imaginary parts of Eq. (A2) are equal. The derivative linewidth (measured experimentally) can be obtained by dividing the half-power linewidth by $\sqrt{3}$, assuming a Lorentzian lineshape. For $\alpha^2\ll 1$, one obtains

$$\Delta(\omega/\gamma)=(1/\sqrt{3})\alpha[X+Y]/\gamma \quad \text{(A5)}$$

and

$$\Delta H=(2/\sqrt{3})(XY)^{1/2}/\gamma, \quad \text{(A6)}$$

with H_0 equal to H_{res}. If the Gilbert equation is solved for $\mathbf{h}_{\text{rf}}=0$ and $H_0=H_{\text{res}}$ with an assumed solution of the form $\mathbf{m}=\mathbf{m}_0e^{i\Omega t}$ where $\Omega=\omega+i\eta$ and η is the relaxation rate for the uniform precession, the existence of a nontrivial solution $\mathbf{m}_0$ requires that

$$\Omega=(XY)^{1/2}+i\alpha(X+Y)/2. \quad \text{(A7)}$$

The real part of Ω is the Kittel resonance condition $\omega_{\text{res}}=(XY)^{1/2}$. The relaxation rate η is equal to $\alpha(X+Y)/2$. From Eqs. (A5) and (A7) it can be seen that

$$\Delta(\omega/\gamma)=(2/\sqrt{3})\eta/\gamma=\Delta H(X+Y)/[2(XY)^{1/2}]. \quad \text{(A8)}$$

In general, the frequency-swept linewidth is a measure of the relaxation rate for the uniform precession, apart from a factor $2/(\gamma\sqrt{3})$. However, the field-swept linewidth is not a measure of η unless the z direction coincides with an axis of rotational symmetry for the sample so that $N_x=N_y$, $X=Y$, and $\Delta(\omega/\gamma)=\Delta H$. This condition is satisfied for perpendicular resonance ($N_x=N_y=0$) but not for parallel resonance ($N_z=0$, $N_y=1$). For these two special cases, Eq. (A8) reduces to Eqs. (1ab).[33]

The relation $\Delta(\omega/\gamma)=(2/\sqrt{3})\eta/\gamma$ can be derived more generally and is independent of the particular choice for the equation of motion for the magnetization, as long as the equation is linear and the magnetization $\mathbf{m}$ can be described by an equation of the form

$$\mathbf{m}(t)=\int_{-\infty}^{t}\phi(t'-t)\mathbf{h}_{\text{rf}}(t')\,dt', \quad \text{(A9)}$$

where $\phi(t'-t)$ represents the magnetization response at t due to an rf field at t', with a susceptibility of the form

$$\chi_{\text{eff}}(\omega)\propto 1/(\Omega_{\text{res}}-\omega) \quad \text{(A10)}$$

near resonance.[34] The frequency-swept linewidth is $(2/\sqrt{3})\eta\gamma$ from Eq. (A10). Equations (A9) and (A10) can be used to calculate ϕ and the magnetization response to an impulse field $h_{\text{rf}}=h_0\delta(t')$ can be obtained as

$$|\,m(t)\,|\propto e^{-\eta t} \qquad (t>0). \quad \text{(A11)}$$

Thus, $\Delta(\omega/\gamma)$ is equal to $(2/\sqrt{3})\eta/\gamma$, where η is the inverse time constant for the decay of the uniform precession amplitude.

[33] As shown by Eqs. (2–87 ab) of Ref. 18, the same results can be obtained from $\Delta(\omega/\gamma)=\partial(\omega/\gamma)/\partial H.\,\Delta H$ in the limit $H_{\text{res}}\gg\Delta H$.

[34] E. Schlömann (private communication).

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