In this first approximation, diffusion is important and variations in metastable concentration were ignored. The rate terms were found to be important in just the way suggested by Sec. II. The basic diffusion-type wave is slowed down, the frequency is reduced, and the wavelength is increased by rate terms which would cause the uniform plasma to be stable. If the rate terms of this type are of sufficient importance, no periodic behavior or wave motion of this type is possible. On the other hand, rate terms of the type which lead to instability of a uniform plasma also lead to higher phase velocity, higher frequency, and shorter wavelength, predictions which are in qualitative agreement with experiment.

The second approximate solution considered variations in all three concentrations but ignored diffusion. The wavelength, frequency, and phase velocity so obtained are dependent entirely on the rate terms. It was shown that use of the prototype rate terms leads to a real frequency. The wave number and phase velocity may be either positive or negative, depending upon the rate terms. A lower limit exists to the speeds allowable by striations moving in the direction opposite to the current flow.

Inclusion of all possibilities results in equations which have not yet been solved. Preliminary successes, however, are sufficiently promising to warrant further study based on the mechanism suggested.

The most important weaknesses in this theory of striations appears to be (1) the use of a small-perturbation theory and (2) lack of reliable expressions for the ionization and excitation rates. Less important deficiencies include (3) the approximation of constant current density, (4) the failure to include a P dependence (which affects the field strength) in the ionization and excitation rate terms, (5) the use of first-order diffusion theory, (6) the use of ambipolar type diffusion to describe ion and electron losses even when the concentrations differ, (7) the use of the loss term γN even when the concentration profile is probably not the J_0 Bessel function, and (8) neglect of the many possible components that may be present with sufficiently long lifetimes to be of significance, such as molecular ions and several species of metastables.

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Ferromagnetic Resonance in Thin Films of Permalloy*

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Microwave resonance measurements have been made in evaporated (82% Ni, 18% Fe) films of thickness 760 A to 1600 A. The longest relaxation, as measured by the line width, gives $T_2=3\times10^{-8}$ sec. The sample thickness was equal to or less than the skin depth, resulting in a Lorentzian-type line. Multiple resonances were obtained according to shape anisotropy theory.

THE original discovery of ferromagnetic resonance[1] was made in thin films of iron, nickel, and cobalt. Subsequent resonance experiments were mostly confined to bulk metals and the ferrites. Renewed interest has recently been shown in the magnetic properties of ferromagnetic films because of their likely single-domain structure and their consequent single-domain rotation magnetization process.[2–4] Evidence has been presented that the spin reversal time by domain rotation may be faster than 10^{-9} sec.[5] An ultimate limit must be set by damping of the motion. We have started an investigation of the damping as well as other features of the resonance at microwave frequencies.

The films, (82% Ni, 18% Fe) evaporated onto microscope slides, varied in thickness from 760 A to 1600 A. The microwave experiments were carried out using standard, well-known techniques.

Damping, as measured by the line width, turns out to be much smaller than previously observed in ferromagnetic metals or alloys. The longest relaxation time we observed occurred at 2800 Mc/sec with $T_2=3\times10^{-8}$ sec, where the magnetic field H was applied perpendicular to the plane of the film.

With H making other angles with the plane of the film at 9000 Mc/sec, and at temperatures down to 4.2°K, the full line width ΔH varies in no regular fashion. Some selected resonance curves are shown in Fig. 1. In all cases the lines had more of a Lorentzian shape than $\sqrt{\mu_R}$ shape, evidence of the fact that the sample thickness was approximately equal to or less than the skin depth on resonance. The appropriate electromagnetic calculations show that in this range line broadening with respect to the μ'' line is in the vicinity of 1.5. For a thick sample $(\Delta H)_{\sqrt{\mu_R}}/(\Delta H)_{\mu''}=2.5$, and the line would have a characteristic $\sqrt{\mu_R}$ shape.

From parallel and perpendicular orientations with respect to H, the magnetization $4\pi M$ and the g factor

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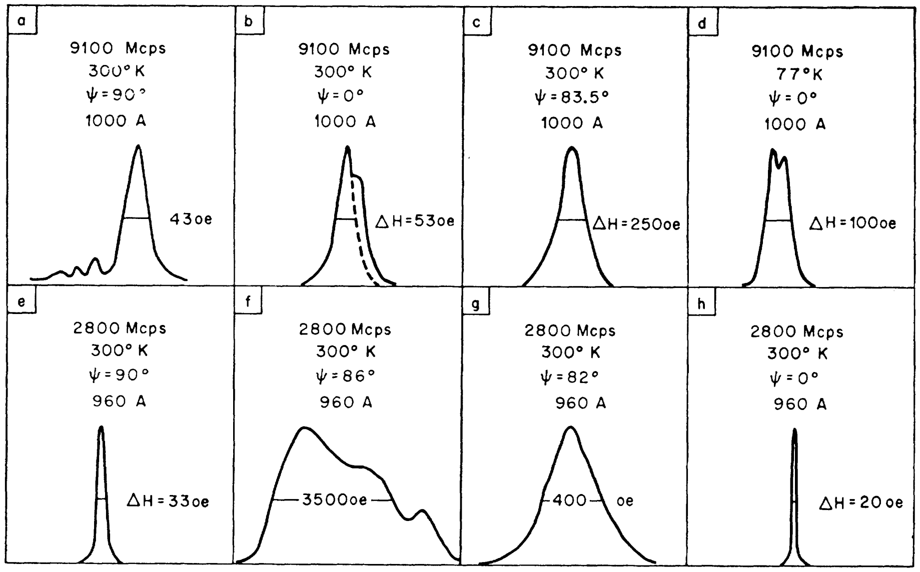

FIG. 1. Absorption curves taken under various conditions. The three subsidiary peaks in (a) disappear under high microwave power levels.

were computed. $4\pi M=9600$ gauss. The apparent g factor varies monotonically with film thickness from 2.04 for 760 A to 2.18 for 1400 A. Macdonald[6] and Griffiths[7] found a similar result and attributed it to strain on the side of the film in contact with the glass. Uniaxial anisotropy in the plane of the films was measured to be from 5 to 10 oersteds, the easy axis being along the direction in which a biasing H was applied during film deposition. Absolute permeabilities measured were of the order of $\mu''=500$, and calculated from the Bloch-Bloembergen relation checked within a factor of 2. A preliminary high-power experiment has shown that the film can be saturated under approximately the same conditions as ferrites. This was found to be the case by Bloembergen and Wang[8] for supermalloy but not for nickel.

Since a film has demagnetizing factors $N_x=N_z=0$, $N_y=4\pi$, there is an effective shape anisotropy field of

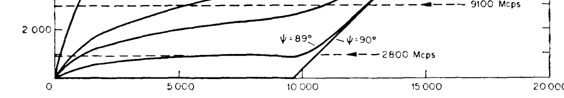

FIG. 2. Resonance conditions due to shape anisotropy. If the ordinate and abscissa are divided by $4\pi M=9640$, the plot will be normalized to units of $H/4\pi M$.

$4\pi M$ present which forces M to lie in the plane of the film. If the external H is applied so as to make some angle Ψ with the plane of the film, the magnetostatic equilibrium condition will give the position of the magnetization vector M. With increasing H, the energy minimum is moved out from the plane; it also becomes sharper and consequently may result in sufficient stiffness for M to resonate at a given microwave frequency. The results of such calculations, using the now well-known generalized resonance condition $\omega=\gamma/M\ \sin\theta(E_{\theta\theta}E_{\phi\phi}-E_{\theta\phi}{}^2)^{\frac{1}{2}}$, are shown in Fig. 2. The ordinate is the effective field necessary for resonance at a given angular frequency ω; the abscissa is H applied at the parametric angles Ψ. It is seen that at a fixed microwave frequency, represented by a horizontal line on the graph, the intersection point with any one of the Ψ curves gives the H necessary for resonance. Further, at certain frequencies, near-resonance can occur for a whole band of applied field values. This, for example, is the case at 2800 Mc/sec ($H_{\mathrm{eff}}=930$ oe) and $\Psi=89°$. The corresponding experimental data, e through h in Fig. 2, show a very narrow resonance at $\Psi=90°$ and $0°$ and extreme broadening at $\Psi=86°$. Qualitatively this is the behavior expected from the shape anisotropy theory.

This report presents the initial stages of a systematic program in progress. Conductivity measurements will be desirable. If very small skin depths can be achieved under suitable conditions, exchange effects will be a consideration. Thinner films may show that the resonance disappears entirely since it is already very weak at 760 A.

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