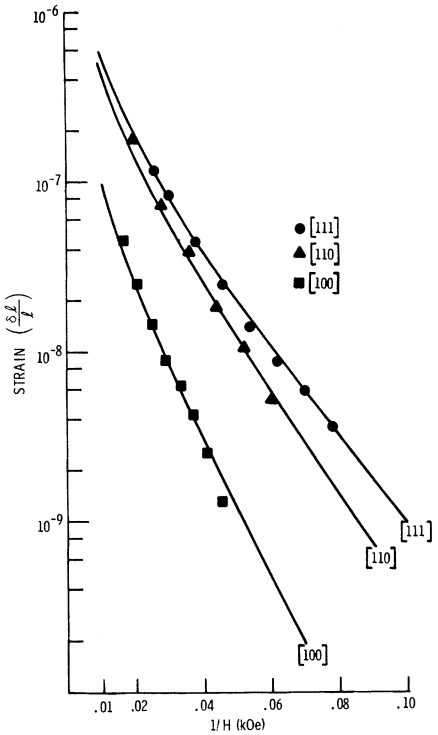

FIG. 3. Oscillatory strain amplitudes in three crystallographic directions as a function of reciprocal field strength. The solid curves represent theoretical and the points experimental amplitudes. m_t and K $(=m_l/m_t)$ were deduced from observed frequencies and the work of Cuff et al. The multiplicative amplitude factors ($a_{[ijk]}$), which only translate the curves vertically, were deduced by fitting at one point.

edge the help of Miss Claudia Evans in the early stages of this work.

[1]During the course of this work, the observation of oscillatory magnetostriction in PbTe was reported in a post-deadline paper by P. R. Aron, B. S. Chandrasekhar, and T. E. Thompson at the meeting of The American Physical Society, Chicago, Illinois, 27-30 March 1967.

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STANDING SPIN-WAVE RESONANCE IN "FLASH-EVAPORATED" PERMALLOY FILMS*

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After Penn and West[1] examined the Fe enrichment in boat-evaporated Permalloy films and suggested that many of the anomalous spin-wave results may be due to composition gradients, it was decided to prepare compositionally homogeneous films by the "flash evaporation" method[2] and to compare these films with those deposited from a tungsten filament under identical conditions.

It should be recalled that in Kittel's original work,[3] the films are considered to be magnetically homogeneous with surface conditions which give rise to the spin-pinning mechanism, and that this model predicts quadratic dependence of the mode spacing on mode number. Other theories[4,5] assume a variation of magnetization and, depending on this variation, the mode spacing ranges from linear to quadratic. With the latter models one cannot determine the exchange interaction, which is one of the most significant features of spin-wave resonance measurements. Depending on the surface spin-pinning, the intensities of the modes in Kittel's model vary, but in general, the even-ordered modes are less intense or even absent, while in the other models one observes both types. This numbering of the modes in the perpendicular configura-

tion (i.e., the static magnetic field is perpendicular to the plane of the film) has always been a controversial subject, and in certain instances[6] agreement with either model can be obtained by selective numbering of the modes. Of course, this is easily done when only a few modes are observed, but when many modes are present, the low-order modes are ignored.[7]

With magnetically homogeneous films one should be able to determine exactly the spin-pinning mechanism by controlled surface effects, and can study the temperature dependence of the exchange constant, the exchange coupling between multilayered films, and the magnon-phonon interaction.[8] The significance of these experiments is strongly dependent upon the model one chooses.

It has been found in this experiment that "flash-evaporated" films confirm Kittel's model beyond any reasonable doubt, while other films made under identical conditions are anomalous.

A conventional oil-diffusion-pumped vacuum system equipped with liquid-nitrogen trapping and having an ultimate pressure of 3×10^{-8} Torr was employed for deposition. The pressure before deposition was normally 2×10^{-7} Torr, and during the initial stages of deposition the pressure normally rose into the 10^{-4} Torr range. "Flash evaporation" was accomplished by allowing short lengths (normally from 3 to 4 mm) of 20-mil ultrahigh-purity Permalloy (Ni/18.10% Fe) to fall sequentially onto a 62.5-mil, spirally wound, tungsten filament. The evaporation charge was baked at 300°C for an extended period but was cooled to 200°C before deposition. The complete evaporation process lasted up to 105 sec depending upon the amount of charge. Up to 20 cm of wire were evaporated during this time. Nine bits were produced each time; however, in some of the runs, six were initially "masked off" but later exposed to the vapor beam during the course of the evaporation in order to produce films of essentially the same properties but differing thicknesses. The ordinary films were produced by evaporation of 20-mil Permalloy from a 62.5-mil circular tungsten filament.

Figure 1 shows the derivative of the perpendicular-configuration resonance absorption spectrum for a film deposited by the "flash-evaporation" method. Notice that there are no missing modes and that the even numbered modes are less intense than the odd ones; this is what is expected for asymmetric spin pinning and/or an inhomogeneous microwave field. Figure 2 illustrates the quadratic dependence of the resonance absorption fields on the mode number for the spectrum shown in Fig. 1 and for a film of much smaller thickness which was deposited in the same vacuum as the former. Notice that for the thicker film the quadratic dependence deviates slightly for the first

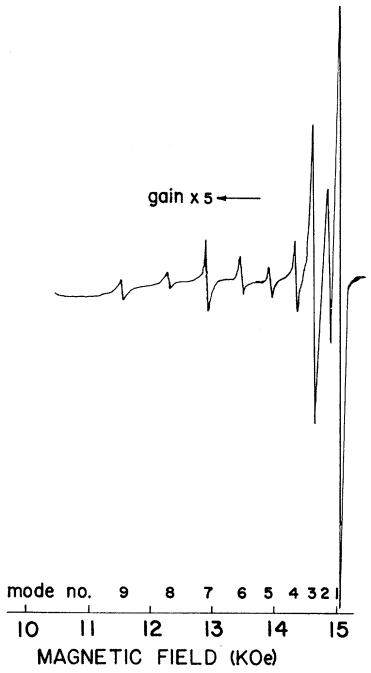

FIG. 1. Perpendicular-configuration standing spin-wave resonance absorption spectrum for a 2200-Å "flash-evaporated" Permalloy thin film. The rf frequency was 12.33 GHz.

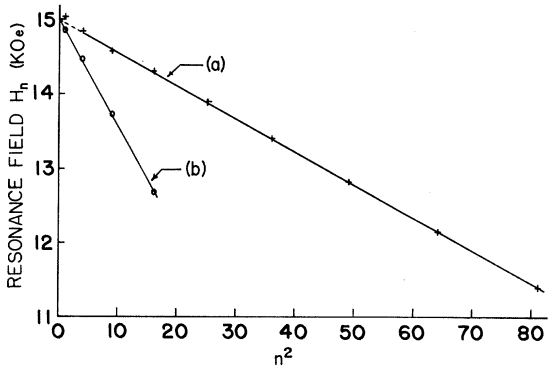

FIG. 2. A plot of the resonance field H_n as a function of the mode number squared for two films made in the same vacuum. Curve a is for 2200-Å film, whose resonance absorption spectrum is shown in Fig. 1. Curve b is for an 1100-Å film. For each film $g \simeq 2.01$, $4\pi M \simeq 10\,600$ Oe, and $A/M \simeq 1\times10^{-9}$ G cm^2.

mode. As discussed above, this effect is usually present and is more pronounced in thicker films. Nisenoff and Terhune[9] illustrate this effect for a 1800-Å film. For film thicknesses greater than 2000 Å, the low-order modes are very close (≃200 Oe); so the Gaussian absorption peaks are nearly superimposed, which makes it very difficult to determine exactly the resonant field for each mode. The effect of this is to raise the high-field mode to a higher field and to decrease the spacing between the first two modes. (See Fig. 1.) The films of different thicknesses deposited together exhibit marked dependence of the position of the high-field spin-wave mode on film thickness, but the $n=0$ mode for each film obtained by quadratic extrapolation is essentially the same; this is illustrated in Fig. 2 and is predicted by the dispersion relation[10]

$$(\omega/\gamma)=H_n-4\pi M+(2A/M)(n\pi/d)^2, \qquad (1)$$

where ω, γ, M, and A, have their usual meanings and $n\pi/d$ is the wave vector associated with the nth standing spin-wave mode. n is the order number assigned to each mode and d is the film thickness. Because of the large variation of the position of the high-field resonance mode with time[11] and deposition conditions, this effect has been previously unobserved. However, it is very evident for "flash" films of large thickness differences. Thus, the mode numbering ambiguity which arises so often is not present for these films.

Spin waves were also observed in the parallel configuration. The results confirm those of Nisenoff and Terhune[9] and Lykken, Harman, and Mitchell[11] and the calculations Wolf[12] insomuch as the surface spins are not strongly pinned in the parallel configuration and there is an effective thickness difference between the two configurations.

Typical film parameters for a series of 14 depositions are the following

$$g\simeq 2.01,$$

$$4\pi M\simeq 10\,600 \text{ Oe},$$

$$A/M\simeq 0.95\times 10^{-9} \text{ G cm}^2,$$

Thickness from 300 to 2200 Å.

Although it has been shown[9,11] that deposition conditions effect the spin-wave spectra of thin films insofar as fewer anomalies are observed for films deposited in relatively high vacua (from 10^{-7} to 10^{-9} Torr) it would seem that there is an even larger contributing factor, that being the composition gradient across the film. (Recall that both Nisenoff and Terhune[9] and Lykken, Harman, and Mitchell[11] observed anomalies for films with thickness greater than 1800 Å, while here they are very slight even for a 2200-Å film.) It would not be unreasonable to assume that films deposited in ordinary vacua by the "flash" method contain many impurities, since each "flashed layer" is subjected to a very high flux of residual gas atoms before it is covered by the succeeding layer. However, one may also assume that a film consisting of many individual "flashed layers" (here up to 60) will be of uniform composition, although each individual layer may have a gradient. It appears, therefore, that the various spin-wave models are correct depending mainly on the composition gradient present.

As is pointed out above, compositionally invarient films are invaluable in the study of the basic magnetic properties of thin Permalloy films.

In closing, it may be appropriate to speculate that many of the anomalies previously observed in Permalloy thin films can be directly attributed to composition gradients and nonuniform deposition environments.

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NUCLEAR MAGNETIC RESONANCE OF ^{57}Fe IN DILUTE ALLOYS OF Fe†

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The nuclear magnetic resonance spectra of the dilute alloy systems FeCo, FeNi, FePd, FeSn, and FeV have been examined. The hyperfine distributions show satellites which are interpreted as due to ^{57}Fe atoms with an impurity atom as a third, fourth, or fifth nearest neighbor. Satellites due to ^{57}Fe atoms with an impurity atom as a nearest or second-nearest neighbor are not observed. A discussion of these results is presented.

The magnetic environment of an impurity atom in a metallic ferromagnet is of considerable interest. Nuclear magnetic resonance (nmr) provides a sensitive probe of this magnetic structure.[1] In dilute alloys the hyperfine spectra provide information about the magnetic structure of ^{57}Fe sites near an impurity. All the sites with an impurity atom as a particular near neighbor will, in general, produce satellite resonances, the center of gravity of which will be displaced with respect to the resonance of pure iron due to isotropic changes in the hyperfine field. Anisotropic interactions will distort the shape or even split a line into several components. Thus it is difficult to determine the origin of observed satellite lines without precise measurements of intensity.

Many attempts have been made to obtain the distribution of hyperfine fields in dilute Fe alloys using Mössbauer-type experiments[2,3] and high-rf-power spin-echo nmr experiments.[4,5] The Mössbauer experiments have difficulty resolving the satellites of distant neighbors because of the lifetime-limited linewidth of ~1 MHz. Stearns[3] has attempted to extract the unresolved components in the broad Mössbauer lines assuming that each contribution had the line shape of pure Fe. However, these analyses have not always agreed with the results of spin-echo experiments on the same alloys[4] or with other Mössbauer measurements.[2] Spin-echo experiments have been reported identifying the nearest-neighbor satellite and in some cases first-, second-, and third-nearest neighbor satellites.[4-6] However, the spin-echo experiments also have difficulty resolving higher-neighbor satellites because the rf pulse width limits the resolution.

We wish to report here the resolution of third-, fourth-, and in some cases fifth-nearest neighbor satellites in the alloy systems FeCo, FeNi, FePd, FeSn, and FeV.[7] We have obtained a plot of the hyperfine fields in each alloy using low-rf-power nmr on multidomain particles. It has been possible to measure satellite intensities to about 10% and thus to assign each satellite to a particular set of ^{57}Fe sites.

The experimental setup used is similar to that used in the studies of pure Fe and Ni by Cowan and Anderson.[8] They have shown that a direct plot of the hyperfine field distribution can be obtained, using suitable detection techniques, from the nmr signal under conditions of adiabatic fast passage.[8,9] The signal originates from those ^{57}Fe nuclei in the domain walls. If we assume that the hyperfine field distribution in the walls is essentially the same as in the domains, then the information obtained here can complement the data from Mössbauer and other experiments that study the hyperfine fields in the domains themselves.

Figure 1 shows the distribution of hyperfine fields in four FeCo alloys at room temperature. We have obtained a number of these traces and the numbers in Table I are the averages of many measurements. In the FeCo system the satellite at ~45.9 MHz is interpreted as being due to ^{57}Fe sites that are third-nearest neighbors of a Co atom. In Table I, $\Delta H_3^{(1)}/H_{\mathrm{Fe}}$ is the shift of the hyperfine field of this satellite away from the main resonance divided by the hyperfine field of pure Fe. The intensity of