cause of discrepancy. Moreover, the Fermi energies of the samples used here correspond to temperatures greater than 500°K.

Also, similar to the case of n-type antimonide, the intrinsic edge for impure n-type indium arsenide samples is shifted to higher energy. Figure 14 shows the room temperature intrinsic edge as a function of photon energy for a p-type sample of low carrier concentration and an n-type sample with a carrier concentration of 2.20×10^{18} cm^{-3}. By using (24) with $E_g=0.33$ ev[17] $h\nu(\alpha)=0.470$ ev, and $m_e^*/m_h^*\sim0.1$, ζ may be determined for the impure sample. From ζ and N, m^* is calculated to be $0.035m$. The value of $E_g=0.33$ ev obtained from either photovoltaic effect or optical absorption is subject to uncertainty, depending on what level of the effect is taken to be the threshold. As can be seen in Fig. 14, the value of E_g can be taken to be 0.31 ev, in which case we would obtain $m^*=0.031m$ in substantial agreement with the values given by the susceptibility.

Table I summarizes the results obtained for the various semiconductors investigated. Available data on effective mass given by other experiments are given for comparison. The relaxation times, τ_H, are determined from the room temperature electrical measurements and Eq. (22).

Measurements of the optical constants provides a simple method of determining the effective mass of carriers. However, in cases where there is more than one band of spherical constant energy surfaces or a band in which the constant energy surfaces are not spherical, the value m_s obtained is an average and the individual mass parameters cannot be determined. Another limitation is the necessity of using rather large carrier concentrations and, therefore, large impurity concentrations, which may affect the effective mass to some extent. For samples of smaller carrier concentrations, measurements have to be made at longer wavelengths.

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Stress in Evaporated Ferromagnetic Films

J. Ross Macdonald
Texas Instruments Incorporated, Dallas, Texas
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Ferromagnetic resonance and oscillation magnetometer measurements on a thin evaporated nickel film annealed in a magnetic field are described. Observations of the dependence of the resonant field magnitude on the angle in the plane of the film between the direction of the magnetic field during annealing and the static resonance field direction show that magnetic annealing produced a preferred magnetic axis in the plane of the film. The good agreement between theory and experiment allows one to establish that the film had bulk-nickel g and saturation magnetization values, a large isotropic tension in the plane, and a lesser uniaxial compression in the plane in the direction of the preferred magnetic axis. In the light of these results, it is suggested that part of the discrepancy between theory and ferromagnetic resonance experiments found recently by Conger and Essig for the dependence of saturation magnetization on evaporated film thickness may have arisen from their omission of stress corrections to the resonance condition. Further, part of the difference between film switching times derived from resonance line widths and those directly measured on the same films by these authors may have been caused by the narrowing of ferromagnetic line widths for thin films, as compared with bulk material, produced by the strong dependence on resonant absorption of power transmission entirely through sufficiently thin films.

FERROMAGNETIC resonance and oscillation magnetometer[1–3] measurements on films or disks afford a powerful means of determining accurate g values[1,3,4] and of investigating the dependence of saturation magnetization,[1,3] magnetocrystalline anisotropy,[5,6] and stress[1,3,4,6] on film parameters.

It has recently been shown that thin alloy films evaporated and annealed in a magnetic field lying in the plane of the film show rectangular hysteresis loops[7] and are useful for very fast switching and storage applications.[7–9] The magnetic field causes the films to develop a preferred magnetic axis or uniaxial anisotropy in the film plane. An applied magnetic field can then switch the film magnetization from a parallel to antiparallel orientation along the magnetic axis and vice versa.

This current interest in evaporated films has suggested that the use of the above measuring techniques be illustrated for data[3] obtained in the spring of 1950 on

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[8] R. L. Conger and F. C. Essig, Phys. Rev. **104**, 915 (1956).
[9] D. O. Smith, Phys. Rev. **104**, 1280 (1956).

an evaporated nickel film annealed at about 300°C in a magnetic field of several hundred oersteds. Similar results were obtained on films both evaporated and annealed in a magnetic field. The film was evaporated on a mica substrate, and a disk 1.47-cm in diameter punched out after magnetic annealing and slow cooling. Its thickness determined by weighing was 2.3μ. The results of K-band resonance measurements on this film are illustrated in Fig. 1, where H_0^r is the resonant field corrected for shape demagnetization effects,[6] γ is the angle between the applied static field H_0 (taken in the Z direction) and the direction in the film corresponding to the direction of the magnetic field during annealing, and side 1 is that attached to the mica. For a polycrystalline film having random crystallite orientation and lying in the $X-Z$ plane, the resonance condition may be written[6]

$$\hbar\omega_0=g\mu_B\left[\left(B_0^r+\frac{3\lambda_0 T_0}{M_0}+\frac{3\lambda_0 T}{M_0}\cos^2\theta\right)\times\left(H_0^r+\frac{3\lambda_0 T}{M_0}\cos 2\theta\right)\right]^{\frac{1}{2}}, \quad (1)$$

where λ_0 is the isotropic magnetostriction constant, -34×10^{-6} for nickel, M_0 is the saturation magnetization, T_0 is a planar stress isotropic in the $X-Z$ plane, and T is a unidirectional stress lying in the $X-Z$ plane at an angle θ with the applied static field. The stresses are positive for tension, negative for compression.

The solid lines in Fig. 1 are calculated for the best fit of the data to Eq. (1) using $\theta\equiv\gamma$, and $g=2.21$, the bulk value for nickel. The equivalence of θ and γ makes it clear that the uniaxial anisotropy shown by Fig. 1 was caused by the magnetic field during annealing. A similar angular defendence would have been obtained for uniaxial magnetocrystalline anisotropy; since the film is polycrystalline and nickel does not have uniaxial magnetocrystalline anisotropy, it is preferable, however, to assign the observed dependence to uniaxial stress rather than to magnetocrystalline anisotropy.* The table shows the values of T_0 and T in dynes/cm^2 obtained for the two sides by curve fitting. In a more exact treatment, account would have to be taken of the dependence of the magnetostriction constant on stress and single domain structure. In the present film, which is likely to be approximately a single domain and for which λ_0 is negative, such correction could result in a maximum reduction of the values of T_0 and T given in the table by a factor of as much as 33%. Since the sample was about 10 skin depths thick at resonance, the two sides are effectively isolated from each other for resonance measurements.

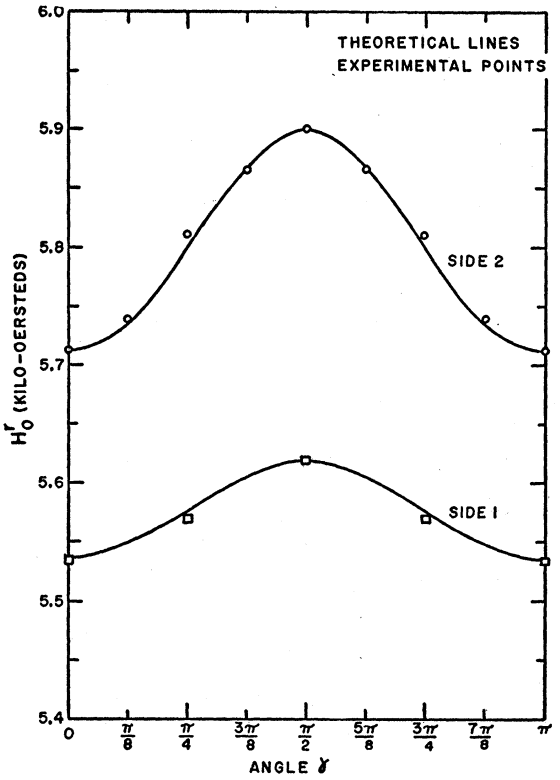

FIG. 1. Dependence of the resonant field strength of a magnetically annealed nickel film upon planar angle between film magnetic annealing direction and resonance static field direction. Side 1 is that attached to the substrate.

	T_0	T
Side 1	5.2×10^9	-2.5×10^8
Side 2	8.4×10^9	-5.1×10^8

These results show that for side 1, for example, there is a tension of 4.9×10^9 dynes/cm^2 along the easy axis in the film and a tension of 5.2×10^9 dynes/cm^2 perpendicular to this axis. The reduction in tension, or alternatively, the compression caused by magnetic annealing may be tentatively explained as follows. Because of the negative value of λ for nickel, it is easier to magnetize it in the direction of a compression than a tension. It is possible that the uniaxial compression inferred from the measurements on the above basis is associated with the inverse effect: magnetic annealing produces an easy direction of magnetization which, in turn, produces compression. The planar stress T_0 probably arises from several processes such as (a) intrinsic compression $T_0\cong\lambda E$ (where E is Young's modulus) equal to about -7×10^7 dynes/cm^2 for nickel arising from magnetostriction on cooling from the Curie point to room temperature,[10] (b) tension produced by loss of

* *Note added in proof.*—Although a partial atomic ordering could yield uniaxial anisotropy even for a cubic element, Bozorth [Proceedings of the Conference on Magnetism and Magnetic Materials, Boston (October 16–18), 1956, p. 69] has recently preferred to interpret thin-film uniaxial anisotropy in terms of possible ordered imperfections caused by small strains. Relating the observed uniaxial anisotropy to stress seems more consistent with this explanation than does relating it to magnetocrystalline anisotropy; the matter is by no means closed however.

[10] L. F. Bates, *Modern Magnetism* (Cambridge University Press, New York, 1951), third edition, p. 450.

crystal imperfections during deposition and annealing,[11] and (c) differential contraction stress caused by the difference in the coefficients of thermal expansion of nickel and mica.[1,3,6] Since the nickel coefficient is greater than that of mica, one would expect the film to be under tension on cooling from its formation temperature of about 300°C to room temperature. The values of T_0 in the table are in substantial agreement with the value calculated from such differential contraction[3] and with values obtained by another method on somewhat similar samples by Hoffman and Crittenden.[12] The results are somewhat anomalous for this film, however, in that the larger T_0 value is found for the outer side; in the vast majority of films measured, the plane tension relaxed from a large value on the mica side to a smaller value on the outer side.[3] This result suggests that cause (b), above, may have been more important for this magnetically annealed film than cause (c).

Oscillation magnetometer measurements on this film gave independent verification of the value $g=2.21$ used in the resonance calculations. The oscillation magnetometer measures both M_0 and the average demagnetization factor $\langle\alpha\rangle=\langle(N_y-N_z)M_0\rangle$ for the film. Neglecting uniaxial stress T, $\langle\alpha\rangle=4\pi M_0+3\lambda\langle T_0\rangle/M_0$ for this film, where $\langle T_0\rangle$ is an average of the plane stress through the thickness of the film. Experimentally, $\langle\alpha\rangle$ was found to be 4780 gauss. Alternatively, the resonance experiments allow one to determine $\alpha_i=(N_y-N_z)_iM_0$ within a skin depth of the surface, where $i=1, 2$ for the two sides. From curve fitting, we can obtain the portion of α_i arising from shape effects and isotropic stress and find, for the curves of Fig. 1, 5086 and 4420 gauss for sides one and two, respectively. The arithmetic average of these values is 4753, satisfactorily close to 4780 when it is recognized that the plane stress may not vary linearly from one side to the other and when possible experimental error in $\langle\alpha\rangle$ is taken into account. The value of M_0 found with the oscillation magnetometer was equal to the bulk value for nickel within the limits of error. We have elsewhere[13] discussed how a modified oscillation magnetometer can be employed to give an independent measure of the anisotropy factor $(N_x-N_z)M_0$ also appearing in the ferromagnetic resonance equation. Thus, the oscillation magnetometer can measure average values of both demagnetization factors appearing in resonance experiments.

Conger and Essig have recently carried out ferromagnetic resonance measurements on thin evaporated alloy films and have mentioned stress corrections without showing how the corrections are quantitatively related to stress or determining their magnitudes by means of angular measurements such as those of Fig. 1 and/or by the use of magnetometer measurements. They have also presented a curve of the dependence of $4\pi M_0$ on film thickness for an 80-20 nickel-iron alloy. This curve does not agree with theory and other experiments[11] very well, as Conger and Essig point out. The values of $4\pi M_0$ were obtained from the resonance equation assuming no dependence of g on thickness and applying no stress corrections at all. We wish to suggest that a part of the observed decrease in $4\pi M_0$ as the film thickness is decreased could have come from isotropic planar tension arising from the causes discussed above. Earlier measurements by the author on an extensive series of evaporated nickel films down to 870 A thickness showed a strong dependence of apparent $4\pi M_0$ and/or g on film thickness until the resonance equation was corrected for the presence of isotropic tension, separately measured with the oscillation magnetometer. After such correction, both g and $4\pi M_0$ were found to be independent of thickness down to the minimum thickness measured.[1,3] It is possible that stress corrections would, therefore, bring Conger and Essig's results into better agreement with other experimental results and theory.

Finally, it should be mentioned that ferromagnetic resonance measurements on films of the order of a skin depth thick should be interpreted with care since transmission of microwave power through the film and possible reflection of some of the transmitted power back into the film may change the resonant field and cause an apparent change in g or $4\pi M_0$. For nickel films of thickness 0.68μ or less measured by the author at K-band, no appreciable shift was found between the resonant fields determined by absorption and those determined for the same film by power transmission through the film into an adjoining wave guide.[3] However, it was noted that whenever there was appreciable transmission of microwave power through the film, the absorption resonance curve, $\mu_R^{\frac{1}{2}}$, tended to narrow as compared to its thick-sample width. Such narrowing agreed with theoretical predictions.[3] It is associated with the fact that the skin depth increases as H_0 deviates from H_0^r, and therefore much more power is transmitted by the film (and less absorbed) off resonance than at resonance. Conger and Essig[8] have used the width of such curves to calculate damping constants which are then related to experimental film switching times. The values obtained from resonance experiments are much smaller than those determined by switching, and it is possible that a relatively small portion of the difference may be ascribed to the above narrowing.

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[12] R. W. Hoffman and E. C. Crittenden, Jr., Phys. Rev. **78**, 349(A) (1950).
[13] J. R. Macdonald, Rev. Sci. Instr. (to be published).