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## ADVERTISEMENT



## Magnetic resonance experiments on ion beam sputtered {100} Fe films

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Ferromagnetic resonance (FMR) measurements have been performed on single-crystal Fe films, produced by ion beam sputtering techniques on GaAs substrates. In-plane FMR results over the frequency range 0.1–20.0 GHz were obtained by a slot line technique. The magnetic parameters deduced from these measurements are comparable to bulk Fe. In-plane angular variation reveals a negligible uniaxial anisotropy contribution to the magnetic anisotropy energy. Spin-wave excitations were observed in 9.5-GHz cavity measurements, and are found to obey the  $n^2$  law. The exchange stiffness constant is found to be somewhat larger than seen in other epitaxial Fe films. These results show that epitaxial Fe/GaAs films possessing good magnetic properties may be produced by ion beam sputtering techniques.

### INTRODUCTION

In the past few years, magnetic resonance techniques have been heavily used in studying the magnetic properties of single-crystal Fe films grown on semiconductor substrates.<sup>1–5</sup> These measurements have shown that high-quality magnetic films can be produced by means of molecular-beam epitaxy (MBE). Recently, a new technique for producing epitaxial iron films has been developed, that of ion beam sputtering (IBS).<sup>6</sup> We present results for the magnetic properties of a pair of IBS produced iron films on gallium arsenide substrates, measured by ferromagnetic resonance techniques. We find these films to be of high quality, comparable to those produced by the MBE technique.

### EXPERIMENT

The Fe films were epitaxially grown on (100) GaAs substrates by ion beam sputtering. The growth conditions, structural characterization, and results from vibrating-sample magnetometer (VSM) measurements on these films have recently been reported by Tustison *et al.*<sup>6</sup> The two films measured had differing thickness calibrations. Thickness of the thinner film was determined by scanning electron microscopy (SEM) photographs. The thicker film, produced at a later date, was measured repeatedly by a “Dec-Tac” thickness profilometer. The nominal thickness of the two films were found to be 700 and 2440 Å, with thickness accuracy of 10% and 5%, respectively.

Ferromagnetic resonance (FMR) measurements were performed using two different experimental techniques. Spin-wave resonance (SWR) measurements were obtained using the traditional magnetic field swept cavity technique. The sample is mounted in a Varian 9.5-GHz cavity, with the film plane oriented perpendicular to the external magnetic field  $H$ . Further FMR results were obtained using a termin-

ated slot line technique.<sup>7</sup> This experimental technique is analogous to traditional FMR, except a planar device is used instead of a microwave cavity. The slot line is mounted between the poles of a bearing mounted 5-kOe magnet, which can be rotated 360°. Microwave energy is transmitted to the slot line through coaxial lines from a Hewlett-Packard 0.01–20.0-GHz sweeper source. Resonance results were obtained with  $H$  angularly varying in the plane of the film, and also with  $H$  parallel to the (100) or (110) crystallographic axis of the films.

### RESULTS AND DISCUSSION

In-plane FMR measurements, using the slot line technique, were used in obtaining values for the effective magnetization and anisotropy fields in the films. Resonant field data taken on the thicker film as a function of angle at fixed frequency (17.1 GHz) is displayed in Fig. 1. Figure 2 shows

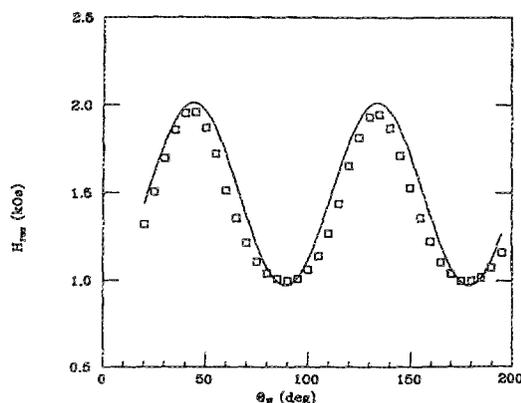


FIG. 1. Resonant field as a function of in plane angular variation for the 2440-Å Fe/GaAs film using the slot line technique. Solid line is the calculated fit using the parameters from Table I.

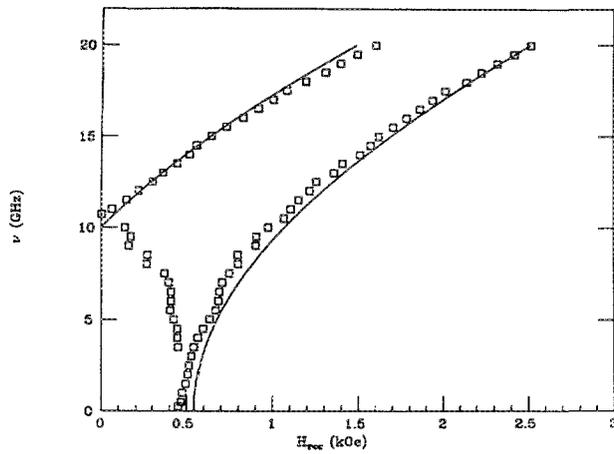


FIG. 2. Resonant field as a function of frequency for the 2440-Å Fe/GaAs film using the slot line technique with  $H$  parallel to the  $\langle 100 \rangle$  or  $\langle 110 \rangle$  axis. Solid line is the calculated fit to the data using the parameters from Table I.

resonance results, taken on the same film, where  $H$  is parallel to either the crystallographic  $\langle 100 \rangle$  or  $\langle 110 \rangle$  axis, performed at a series of frequencies between 0.2 and 20.0 GHz. It should be noted that the error bars for the resonant field in both of these figures are large, being of the order of the plotted block width ( $\Delta H_{\text{res}} = 80$  Oe). This is due to uncertainty in determination of the resonance position, as the resonance curves obtained by this technique do not necessarily possess the classical Lorentzian lineshape.

We deduce values for the magnetic parameters of these films by means of a least squares fitting routines to the resonance equations. The general resonance equation is obtained by the method of Suhl,<sup>8</sup> starting with the expression for the energy density of a  $(100)$  film with magnetization  $\mathbf{M}$  in an external field  $\mathbf{H}$  given by

$$E = -\mathbf{M} \cdot \mathbf{H} + (2\pi M^2 + K_u^\perp) \cos^2 \theta + K_1(\alpha_1^2 \alpha_2^2 + \alpha_1^2 \alpha_3^2 + \alpha_2^2 \alpha_3^2) + K_u \sin^2 \theta \cos^2(\phi - \phi_u).$$

In addition to terms for the demagnetizing field ( $4\pi M$ ) and the normal first-order cubic anisotropy field ( $K_1$ ), a pair of uniaxial fields are also present in the free energy. Coefficients  $K_u^\perp$  and  $K_u$  are included for uniaxial fields both normal to and in the plane of the film.<sup>4</sup> The directional cosines  $\alpha_i$  are the angles between the magnetization and the cubic axes, and  $\phi_u$  is the angle corresponding to the in-plane uniaxial field. The resonance equation is given by<sup>4</sup>

$$\begin{aligned} (\omega/\gamma)^2 &= (H + \alpha)(H + \beta), \\ \alpha &= 4\pi M_{\text{eff}} + (K_1/M)(2 - \sin^2 2\phi) \\ &\quad - (2K_u/M) \cos^2(\phi - \phi_u), \\ \beta &= (2K_1/M) \cos 4\phi - (2K_u/M) \cos 2(\phi - \phi_u), \end{aligned}$$

TABLE I. Summary of magnetic parameters on IBS iron films.

$t$ (Å)	$4\pi M_{\text{eff}}$ (kOe)	$2K_1/M$ (kOe)	$H_0$ (kOe)	$\Delta H$ (Oe)
700	20.6	0.50	23.367	20
2440	21.0	0.55	23.705	91

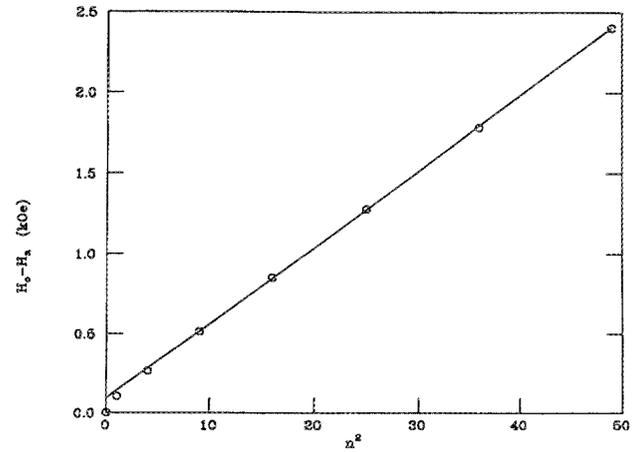


FIG. 3. Spin-wave resonance data for the 2440-Å Fe/GaAs film from perpendicular FMR measurements taken at 9.53 GHz.

with effective magnetization  $4\pi M_{\text{eff}} = 4\pi M + 2K_u^\perp/M$  and  $\gamma = ge/2mc$ . Values for  $4\pi M_{\text{eff}}$  and  $K_1/M$  deduced from the fits for both films are listed in Table I. We have taken  $g$  to be equal to 2.09 for all experimental fits. We estimate these results to be accurate within 5%. Both sets of values agree well with bulk Fe.<sup>4</sup> The value of the in plane uniaxial term is found to be very small ( $K_u/M < 10$  Oe), exhibited by the near perfect cubic symmetry shown by the angular variation curve (Fig. 1), and in agreement with vibrating-sample magnetometer results.<sup>6</sup> Calculated behavior for the magnetic resonances using the deduced parameters from Table I, in the case where the magnetization is saturated, is plotted as solid lines in Fig. 1 and 2. These follow the general trend of the experimental data for both the angular and frequency varied results.

Both ion beam sputtered Fe films displayed distinct spin-wave resonances (SWR) for perpendicular FMR measurements. We were able to resolve all SWR modes above saturation ( $H > 4\pi M_{\text{eff}}$ ). The resonance equation in this orientation is given by

$$\begin{aligned} \omega/\gamma &= H' - 4\pi M_{\text{eff}} + 2K_1/M, \\ H' &= H_0 - (2A/M)(\pi^2/t^2)n^2, \end{aligned}$$

with  $t$  the film thickness,  $A$  the exchange stiffness constant,  $H_0$  the main line resonance field at excitation frequency  $f = \omega/2\pi = 9.53$  GHz, and  $n$  the mode number of the spin-wave excitation. High-order  $n$  SWR observed in the thicker film show excellent agreement to this  $n^2$  law (Fig. 3). Deviations from  $n^2$  are seen at low  $n$  for the thicker film. Low- $n$  deviations have been noted for other Fe films and are attributed to variation in either the magnetization or uniaxial anisotropy field  $K_u^\perp/M$  at the film interface.<sup>3</sup> The exchange stiffness constant ( $A = 2.37 \times 10^{-6}$  erg/cm) for the thicker film was found using the measured thickness and  $4\pi M_s = 21\,000$  G.<sup>6</sup> This value for the exchange stiffness constant is somewhat higher than those found in the literature,<sup>3</sup> and may be due to uncertainty in the film thickness. Only the first two SWR modes are observable for the thinner film. As these modes also deviate from  $n^2$ , we are unable to obtain  $A$  for this film.

Table I also lists values for  $H_0$  and the linewidth of the

main line resonance ( $\Delta H$ ) at 9.53 GHz. Line widths of the IBS films are narrow, being comparable to those of films deposited by MBE.<sup>3</sup> This is a strong indicator of the quality of these films. In addition, we find no indication for magnetic resonances above that of the main line. These have been noted in MBE produced films, and described as the result of surface modes.<sup>5</sup> The lack of surface modes indicates that the interfacial structure in IBS produced films is different from that of MBE grown films.

## SUMMARY

The ion beam sputtered epitaxial films are found to have magnetic properties comparable to those grown by molecular beam epitaxial techniques. Deduced parameters for the effective magnetization ( $4\pi M_{\text{eff}}$ ), and cubic anisotropy ( $K_1/M$ ), are close to bulk iron, while the in-plane uniaxial field ( $K_u/M$ ) is found to be negligible. Spin-wave resonance data on the thicker film displays  $n^2$  behavior for higher  $n$  modes, but yields a larger value for the exchange stiffness

constant ( $A$ ) than found in other epitaxial iron films. The resonance linewidths are seen to be small, with no indication of surface modes in the FMR results.

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