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Ferromagnetic resonance measurements on epitaxial grown Fe/ZnSe and Co/ZnSe films on GaAs substrates

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Ferromagnetic resonance (FMR) measurements have been performed over a broad frequency range on epitaxial films of Co and bcc α-Fe grown onto epilayers of ZnSe by molecular-beam-epitaxy techniques on (001) and (110) GaAs substrates. In-plane and perpendicular FMR results were used in deducing the magnetic parameters and spin-wave resonance (SWR) dispersion of the films. The magnetic parameters deduced for Fe films agree with previous results obtained on the (001) Fe/ZnSe film. Well-resolved SWR modes were observed in the Fe/ZnSe films, allowing extraction of the exchange stiffness constant. Few spin-wave excitations were observed for the Co/ZnSe films. Both (110) Fe/ZnSe and (110) Co/ZnSe show evidence for surface spin-wave excitations. These excitations are attributed to variations in the internal field near the interface.

INTRODUCTION

In the continuing efforts to produce idealized magnetic/semiconductor layered systems, ferromagnetic resonance (FMR) techniques have proven to be of great value in characterizing the film magnetic parameters.[1–5] In particular, resolution of the spin-wave dispersion has been useful in inferring the effects of strain, which have proven to be a significant factor in iron films grown previously on gallium arsenide substrates.[2] Much of the strain in an epitaxial film can be attributed to the intrinsic mismatch in the lattice spacing between the film and substrate. Recently, effort has been directed into growing epitaxial iron films onto semiconductor substrates other than GaAs. In particular, the semiconductor ZnSe can be epitaxially grown onto GaAs by molecular-beam-epitaxy techniques, and hence can serve as a spacer layer between the magnetic film and GaAs substrate.[6,7] Using a ZnSe layer greatly improves the surface morphology (flatness) and modifies the Fe(Co)/semiconductor interface chemistry. Previous work has reported FMR measurements on these Fe/ZnSe films.[5] In this paper we complement and extend those results with additional FMR results upon both Fe/ZnSe and Co/ZnSe films on GaAs substrates.

EXPERIMENT

The Fe and Co thin films were grown by molecular-beam-epitaxy (MBE) techniques upon epilayers of ZnSe previously grown on (001) or (110) GaAs substrates. The growth conditions, along with results from *in situ* characterization by reflection high-energy electron diffraction (RHEED) and Auger electron spectroscopy (AES) were recently published for the Fe/ZnSe films.[6,7] Co/ZnSe films were grown under conditions similar to the Fe/ZnSe films, except the Fe/ZnSe films were capped by a 30-nm-thick overlayer of polycrystalline ZnSe to preclude oxidation. The MBE-grown Fe/ZnSe films were found to be single crystals with a bcc structure.[6] RHEED photos taken during growth of the Co/ZnSe films suggest they are also single crystal. Thin-film x-ray diffraction measurements support a fcc structure for the Co/ZnSe film on (001) GaAs, and indicate a hcp structure for the Co/ZnSe film on (110) GaAs.

The magnetic parameters of the Fe/ZnSe films were previously deduced from a series of ferromagnetic resonance (FMR) and vibrating sample magnetometer (VSM) measurements.[5] To complement this earlier work, we report the results obtained from additional broad frequency FMR and X-band perpendicular FMR measurements. FMR spectra were obtained on the (001) Fe/ZnSe and Co/ZnSe films over the frequency range 0.4 GHz $< \nu <$ 20.2 GHz using a slot line device,[8] with the external magnetic field (H) in the film plane and collinear to the crystallographic $\langle 100\rangle$ (easy) or $\langle 1\bar{1}0\rangle$ (hard) axis. Variation of the resonant field as a function of angle of H relative to the crystallographic axis in the plane of the film was also determined at fixed frequency. Perpendicular FMR measurements, where H lies normal to the film plane, were performed using an X-band cavity and standard techniques in order to resolve the spin-wave resonance (SWR) dispersion of the films.

RESULTS AND DISCUSSION

The main advantage of the slot-line FMR technique over cavity techniques is the capability of measuring the resonant field over a broad frequency range. Figure 1 illustrates this by showing the microwave frequency (ν) versus resonant FMR field (H_{res}) dispersion for the (001) Co/ZnSe film from both slot-line and 9.5-GHz measurements, where H is collinear to the $\langle 100\rangle$ or $\langle 1\bar{1}0\rangle$ axis. Of most interest in this figure is the low-frequency data, where the cusp traced by H_{res} when H lies along the hard axis is clearly evident. Error bars for the resonant field are of order 80 Oe at lower frequencies, as the experimental absorption derivative versus field curves do not necessarily correspond to a Lorentzian absorption shape for frequencies below 12 GHz. The

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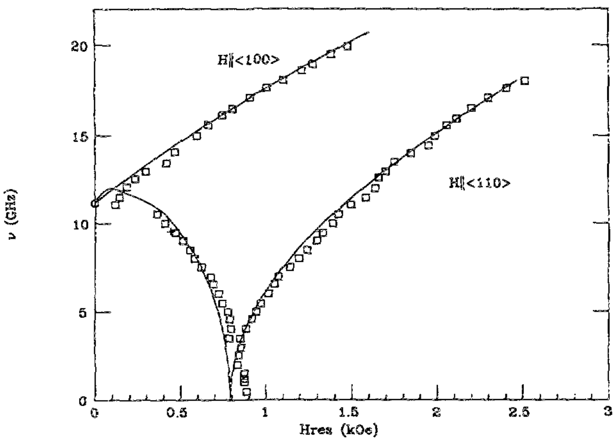

FIG. 1. Frequency vs resonant field dispersion is shown for H collinear to the ⟨100⟩ and ⟨110⟩ axis of the (001) Co/ZnSe film. (□) Slot-line FMR; (+) 9.5 GHz cavity FMR; and (O) zero-field resonance results.

value of H_{res} is chosen to be the approximate center of the absorption derivative under these conditions.

Analysis of the slot-line FMR results on the cubic (001) films follows the method of Artman,[9] beginning with an expression for the free energy per unit volume of a film having magnetization **M** in an external field **H**. The free energy includes terms for the demagnetizing energy and the intrinsic cubic anisotropy, given by the fourth-order magnetocrystalline anisotropy term having coefficient K_1. Additional energy terms corresponding to uniaxial fields both in (K_u) and normal ($K_u^{\perp}$) to the film plane are included, yielding a free energy of the form

$$F = -\mathbf{M}\cdot\mathbf{H} + (2\pi M^2 + K_u^{\perp})\alpha_2^2 + K_1(\alpha_1^2\alpha_2^2 + \alpha_2^2\alpha_3^2 + \alpha_3^2\alpha_1^2) + K_u\cos^2(\theta - \theta_u), \qquad (1)$$

where the α_i's are the direction cosines of the magnetization relative to the crystallographic axis and $\theta - \theta_u$ is the angle between **M** and the in-plane uniaxial hard axis. The resonance condition for the precession of the magnetization in the external field is then found from the equations of motion.[9] The experimental ν vs H_{res} data was fit to the resulting resonance expressions by a least-squares-fitting routine. The g value was chosen to be $g = 2.09$ for Fe (Ref. 10) and $g = 2.16$ for Co (Ref. 11) films for all fits. Deduced fit parameters for (001) Fe/ZnSe were $(4\pi M_{eff} = 4\pi M + 2K_u^{\perp}/M) = 21.4$ kOe, $2K_1/M = 0.74$ kOe, with $2K_u/M$ being negligible. Fit results for (001) Co/ZnSe were $4\pi M_{eff} = 18.5$ kOe, $2K_1/M = 0.74$ kOe, and $2K_u/M = 0.03$ kOe. Calculated values for the ν vs H_{res} dispersion are displayed in Fig. 1 as solid lines, using the parameters for (001) Co/ZnSe listed above. Good agreement is seen between data and fit, especially at higher frequencies. The parameters deduced from the slot-line FMR are also in reasonable agreement with those found previously on the (001) Fe/ZnSe film.[5]

Spin-wave resonance (SWR) dispersions were obtained from the perpendicular FMR measurements. The resonance condition for the uniform resonant mode (H_0) and SWR mode of order n are given as[3]

$$\left(\frac{\omega}{\gamma}\right)^2 = \left(H_n - 4\pi M_{eff} + \frac{2K_1}{M} + \Delta_1\right) \times \left(H_n - 4\pi M_{eff} + \frac{2K_1}{M} + \Delta_2\right), \qquad (2)$$

$$H_n = H_0 - \frac{2A}{M}\frac{\pi^2}{t^2}n^2, \qquad (3)$$

where Δ_1, Δ_2 are contributions from the in-plane uniaxial anisotropy field of order $\Delta_1, \Delta_2 \sim K_u/M \ll 4\pi M_{eff}$. Parameters A and t are the exchange stiffness constant and magnetic film thickness. We note that the spin-wave dispersion is adequately fit by (3) for higher-order modes, without having to recourse to the general resonance condition (2).

It was possible to resolve the full SWR dispersion of the Fe/ZnSe films for $H > 4\pi M$ (saturated). Figure 2 shows the line positions of the spin-wave excitation spectrum of the 3100-Å-thick (001) Fe/ZnSe film, along with the extrapolated fit obtained from (3) for high-order modes. Deviations from n^2 for low-order modes are clearly evident. A portion of this offset is due to the overlap of the main line absorption with those of the low-order modes, such that they appear as shoulders on the main line. However, such deviations of low-order modes from n^2 behavior have also been described as indicative of gradients in the magnetization or anisotropy fields.[12] The deduced exchange stiffness constant (A) for the (001) film is listed in Table I. An estimate of A is also given for the thinner (110) Fe/ZnSe film, although the four spin-wave excitations available are insufficient to assure convergence to the behavior described by (3). Perpendicular FMR measurements on the cobalt films show the (001) Co/ZnSe film to have three resonances [Fig. 3(a)], including a shoulder on the main line, while the (110) Co/ZnSe film shows only a pair of broad resonances [see Fig. 3(b)]. We were unable to resolve any additional spin-wave excitations from our 9.5-GHz cavity measurements, despite using large gain and modulation drive values. However, the resonant field required to resolve higher-order SWR may be lower than the field at which the sample saturates, making these modes accessible only to higher-frequency measurements.

The effects of interfacial strain at the metal/semicon-

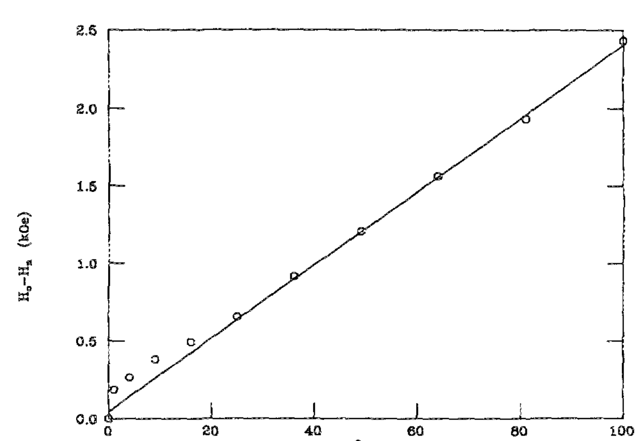

FIG. 2. Field separation of the nth spin-wave resonance (H_n) relative to the main line resonance (H_0) is plotted vs n^2 for the 3130-Å-thick (001) Fe/ZnSe film.

TABLE I. Film parameters deduced from VSM and cavity FMR measurements are shown for all films. ΔH is the linewidth of the main line resonance from perpendicular FMR measurements.

Sample	t (Å)	$4\pi M$ (kOe)	ΔH (Oe)	H_0 (kOe)	$H_0 - H_1$ (kOe)	$H_0 - H_1$ (kOe) (expt.)	A (10^{-6} erg/cm) [Eq. (3)]
ZnSe/Fe/ZnSe							
(100)	3130	20.7[a]	65	24.08	0.19	0.02	1.93
(110)	1230	20.9[a]	50	23.76	0.53	0.17	2.18
Co/ZnSe							
(100)	840	15.7	65	23.68	0.11	0.29	1.3[b]
(110)	1070	15.6	230	22.16	1.14	0.18	1.3[b]

[a] Ref. 5.
[b] Ref. 13.

ductor interface can be observed in the magnetic properties.[2] Earlier FMR results from Fe films on GaAs substrates have been interpreted by allowing variations in the magnetization and anisotropy fields near the interfacial region, which will be observable as surface spin-wave modes.[6] One useful parameter in deducing the presence of surface spin-wave modes is the field separation between the main mode (H_0) and first excited mode (H_1). For ideal, nonconducting films, this separation is given by Eq. (3) where $n = 1$. Table I lists both experimental results and the value of $H_0 - H_1$ calculated from (3). Since a value for the exchange constant is not available for the Co/ZnSe films, we have chosen $A = 1.3 \times 10^{-6}$ erg/cm from Ref. 13 as a rough estimate for the cobalt films.

While interpreting the measured $(H_0 - H_1)$ difference in terms of the existence of surface modes it is also necessary to include exchange conductivity effects.[14] For thicker films, such as the (001) Fe/ZnSe film, the effect of exchange conductivity will be a shift of the main line resonance away from the uniform precession FMR mode. Hence we interpret the relatively small difference between the measured ($H_0 - H_1 = 0.19$ kOe) and calculated (0.02 kOe) mode separations as implying no significant interfacial surface mode excitations in the (001) Fe/ZnSe film. In contrast, we do attribute the larger mode separation observed in the (110) Fe/ZnSe film as due to surface excitations (see Table I). By using the results of Ref. 12, where the magnetization and anisotropy field are assumed to vary exponentially near the interfacial region, estimates for the magnitude of variation in internal field (ΔH_i) can be obtained. In this analysis we have made use of Fig. 3 of Ref. 12, where the (experimentally measurable) separation between lowest-order spin-wave modes (δH) is proportional to internal field variation and the ratio A/M. We note that this dependence of δH upon both ΔH_i and A/M is more explicitly seen for the linearly varying magnetization used in Ref. 15. We calculate $\Delta H_i = 1.8$ kOe for the (110) Fe/ZnSe film, using the experimentally determined parameters from Table I and decay parameter $1/\Gamma = 100$ Å.[12] This is comparable to prior results of $\Delta H_i \sim 2.0$ kOe for Fe films grown directly onto (110) GaAs substrates.[12]

A similar analysis was undertaken for the Co/ZnSe films, although with assumptions regarding the values chosen for A and $1/\Gamma$. Since there is no data on thinner Co films which would permit deduction of the magnitude of the decay parameter, we have chosen $1/\Gamma = 100$ Å analogously to the Fe films.[12] The value of the exchange stiffness constant was chosen from the results of Ref. 13. Using these assumptions and parameters from Table I, the calculated internal field variation for the (110) Co/ZnSe film was of order 3.3 kOe. For the (001) Co/ZnSe film, we find that ΔH_i must be relatively small, as the measured mode separation is in good agreement with that predicted by Eq. (3).

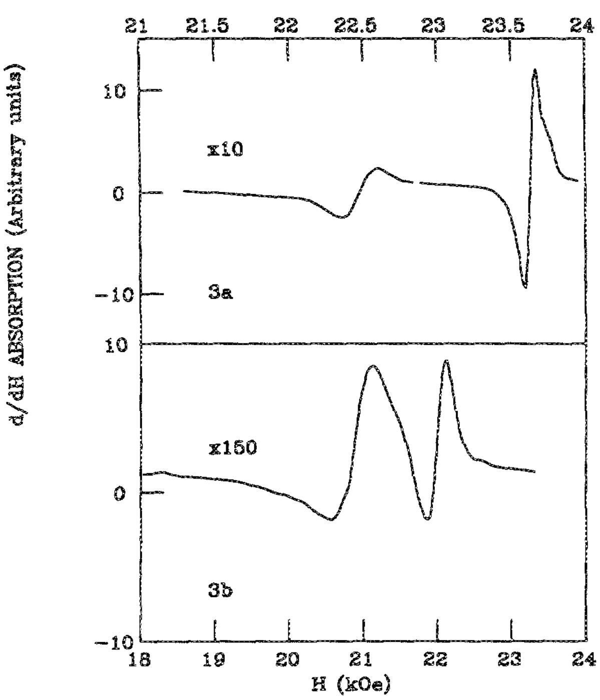

FIG. 3. Absorption derivative vs external applied field data is shown for (a) 840-Å (001) Co/ZnSe and (b) 1070-Å (110) Co/ZnSe films on GaAs substrates.

CONCLUSIONS

We find that the magnetic parameters deduced by slotline FMR techniques agree reasonably well with previous measurements.[5] Similarly, values of the exchange stiffness constant on Fe/ZnSe films, obtained from the SWR dispersion, agree with those obtained on Fe on GaAs substrates.[3] No such value could be obtained for Co/ZnSe films. Strong indications for the existence of interfacial surface modes were observed for both Co/ZnSe and Fe/ZnSe (110) films. There are two possible sources for the variation in the internal field (ΔH_i): variations in (1) demagnetizing field ($4\pi M$) and (2) perpendicular anisotropy field ($H_u^{\perp} = 2K_u^{\perp}/M$). In previous studies[12] variations in $H_u^{\perp}$ were deduced, because variations in $4\pi M$ could be independently measured by VSM experiments upon films of differing thickness. Presently, no data are available for the dependence of $4\pi M$ on thickness for the Co/ZnSe and Fe/ZnSe films and hence, no estimate for the magnitude of $1/\Gamma$. We believe that these data are essential in order to quantify changes in $H_u^{\perp}$ near the interface for the Fe/ZnSe and Co/ZnSe films.

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