Investigation of the dependence of BLS frequencies on angle of incidence for thin iron films

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Brillouin light-scattering experiments have been done at various angles of incidence, θ, for four specimens prepared by molecular-beam epitaxy. The specimens were single ultrathin films of Fe deposited on single-crystal Ag substrates. Dependence of magnon frequency on θ is easily resolvable in all specimens. We find that the magnitude of this dependence is in good agreement with a theoretical calculation that takes into account magnetic anisotropies, dipole-dipole, and exchange interactions. Our results imply that magnetic excitations in these specimens are correlated over distances of at least 5000 Å.

INTRODUCTION

In the theory of Brillouin light scattering (BLS) from ultrathin magnetic films it is usually assumed that the ferromagnetic spin waves which couple to the incident optical wave field are characterized by an infinite coherence length in the plane of the specimen, i.e., it is assumed that the spin-wave spatial variation in the plane can be described by e^{iqy} where y lies in the plane of incidence of the light.[1] Ultrathin magnetic films are composed of terraces over which the films are characterized by a relatively uniform thickness. It is estimated[2] from reflection high-energy electron-diffraction studies (RHEED) that thickness variations for Fe(001) grown on suitably prepared Ag(001) substrates amount to approximately ±1 atomic layer over terraces whose lateral dimensions are of the order of 300 Å. The question which we wish to address is whether the coherence length of spin waves in iron films a few monolayers (ML) thick grown on an Ag(001) substrate is comparable to the dimensions of a terrace ($\approx$300 Å), or whether the coherence length is comparable to the wavelength of the light used to carry out the BLS studies ($\lambda = 5145$ Å). It can be shown that the *intensity* of the back-scattered light in BLS studies should be relatively insensitive to the coherence length of the spin waves in the film plane.[3] If the spin-wave coherence length in the film plane is much smaller than λ then the *frequency shift* observed for the scattered light should be insensitive to the magnitude of the optical wave-vector component in the plane of the incident light. That is, the frequency of the scattered light should be independent of the angle of incidence of the light used for the BLS measurement. However, if the spin-wave variation in the plane can be described by e^{iqy}, where $q=2(\omega/c)\sin\theta$ and where θ is the angle of incidence of the light beam, then the frequency shift $\Delta F/F$ of the back-scattered light should be related to the angle of incidence by the relation[4]

$$\Delta F/F \approx [2\pi M_s/(\omega/\gamma)]^2 |q| d, \tag{1}$$

where F is the shift in scattered light frequency for normal incidence $\theta=0$ and $\Delta F = F(\theta) - F$, where $F(\theta)$ is the frequency shift observed for an angle of incidence θ. Thus the degree to which spin-wave frequencies are observed to vary with the angle of incidence of the light used for the BLS measurement can be used to probe the in-plane magnetic coherence length.

EXPERIMENTAL DETAILS

The specimens were grown in a Φ-400 molecular-beam epitaxy (MBE) system equipped with a reflection high-energy electron-diffraction (RHEED) apparatus. The four specimens consisted of single epitaxial Fe films grown on single-crystal Ag substrates and capped by a protective overlayer. Their compositions are given in Table I. Details of the substrate preparation and growth conditions have been described elsewhere.[2] For all four specimens strong RHEED oscillations persisted throughout the entire growth. Specimens *B* and *C* were grown on a single substrate at room temperature. Specimens *A* and *D* were grown on a separate substrate each and after the first 5 layers of Fe were deposited the temperature of the substrate was raised to 150 °C for deposition of the subsequent layers. It is known that growth at elevated temperature produces larger terraces than room-temperature growth and it was of interest to see whether the effect of larger terraces was apparent in our BLS studies.

BLS measurements were carried out using 150 mW of the 5145 Å line from an argon ion laser. The back-scattering configuration was used, i.e., the angle of incidence θ was the same on average as the collection angle for

TABLE I. Composition and anisotropy constants of the four specimens. K_1 is the in-plane cubic anisotropy constant. K_u is the out-of-plane uniaxial constant corresponding to a surface energy term $E_s = -K_u(M_z/M_s)^2$, where M_z is the magnetization component perpendicular to the specimen surface: K_u includes contributions from both iron film interfaces. The values of K_u and K_1 that are given here were obtained by a least-squares fit of the theory described in the text (Ref. 6) to the data shown in Fig. 2.

		Fit parameters	
Specimen	Composition	K_1 (10^5 ergs/cm^3)	K_u (ergs/cm^2)
A	Ag/5+3Fe/1Fe^{57}/7Ag/10Au	2.215	1.535
B	Ag/20Fe/18Au	3.985	1.036
C	Ag/10Fe/18Au	2.253	1.112
D	Ag/5+5Fe/15Au	2.125	1.314

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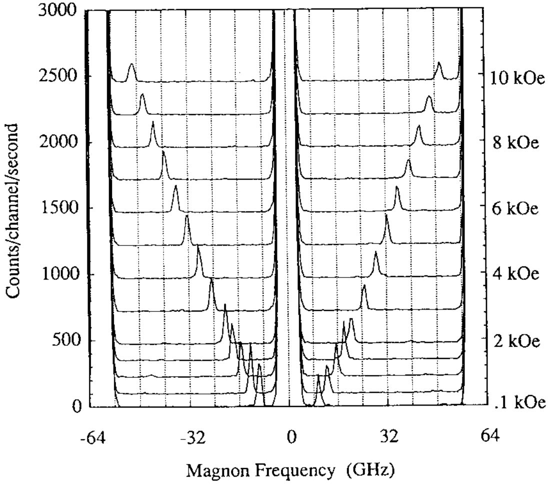

FIG. 1. BLS intensity vs frequency data for specimen *A* at 13 different values of applied magnetic field. The angle of incidence is $\theta=2.5°$ and the power incident on the specimen is 150 mW. The data sets have been offset by an amount proportional to the field strength. The data were collected using 5145 Å incicent radiation in the back-scattering configuration; the free spectral range (FSR) used was 60 GHz; the FSR was divided into ≈ 128 channels with a collecting time of 2 msec/channel. The data shown in the figure have been normalized to 500 scans; 200–300 scans were used for a typical experiment.

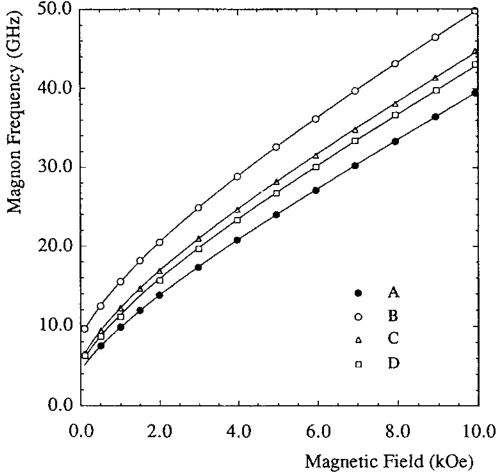

FIG. 2. Summary of magnon frequency vs applied magnetic field data for the four specimens for an angle of incidence of 2.5°. The composition of the specimens is given in Table I. The solid lines represent a two-parameter fit of our theoretical calculation (Ref. 6) to the data. The fitting parameters are the in-plane anisotropy constant K_1 and the out-of-plane uniaxial anisotropy constant K_u. Values obtained for these parameters are given in Table I.

the scattered light. For small angles of incidence a beam stop was required to prevent the specular beam from entering the collection optics. The scattered light was analyzed using a Sandercock[5] tandem interferometer in a 4 pass+2 pass configuration and a free spectral range of 60 GHz. Magnon frequencies were measured both as a function of applied magnetic field and as a function of angle of incidence.

RESULTS AND DISCUSSION

Figure 1 shows typical results from an experiment in which BLS spectra were collected at various magnetic fields. A summary of such experiments done at $\theta=2.5°$ for our four specimens is given in Fig. 2. Magnon frequencies were obtained by fitting a Gaussian line profile to the peaks seen in the raw data. We estimate the uncertainty in these frequencies to be roughly ± 0.1 GHz.

The solid lines in Fig. 2 represent the results of a computer calculation which takes into account the dipole-dipole and exchange interactions and magnetic anisotropies.[6] The saturation magnetization of the Fe films was taken to be the bulk value $4\pi M_s=21.5$ kOe; we used a g factor of 2.09. The in-plane anisotropy constant K_1 and the out-of-plane uniaxial anisotropy constant K_u were treated as fitting parameters. The values required to fit the data are given in Table I and are in good agreement with values deduced from FMR measurements on similar films.[2]

We also measured magnon frequencies as a function of field at $\theta=45°$. The difference between the 45° and 2.5° data is shown in Fig. 3. The difference predicted by our computer calculation is also shown. The parameters used in the calculation are taken from Table I. The observed shifts in frequency are somewhat lower than those predicted by theory.

Figure 4 summarizes the results of a series of experiments in which we fixed the applied field at 0.1 kOe and measured the magnon frequency as a function of θ. In all cases the frequency dependence is more or less linear in $q=2(\omega/c)\sin\theta$ [in agreement with Eq. (1) above] and consistent with our detailed computer calculation.

CONCLUSIONS

It has been shown that the observed dependence of magnon frequency on wave vector in four simple MBE grown ultrathin magnetic films is in good agreement with

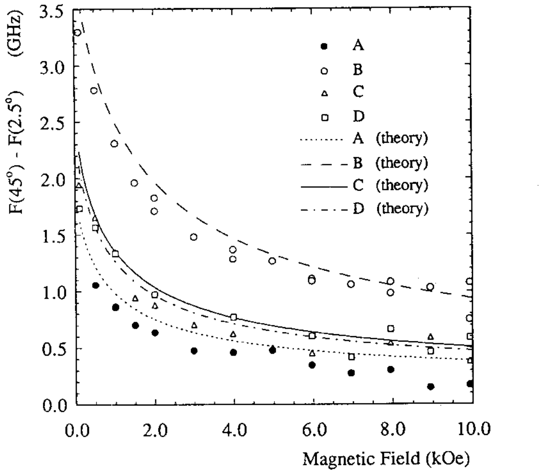

FIG. 3. The difference between $\theta=45°$ magnon frequencies and $\theta=2.5°$ magnon frequencies as a function of applied magnetic field. The theoretical calculations shown were carried out using the parameters obtained from the fits shown in Fig. 2.

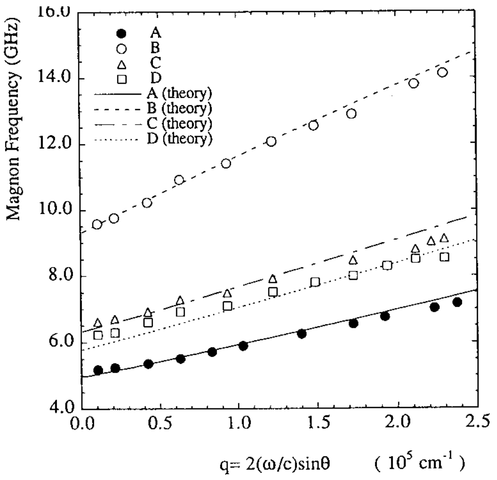

FIG. 4. Magnon frequency as a function of wave vector q for the four specimens. The applied magnetic field is 0.1 kOe. The theoretical calculations shown were carried out using the parameters obtained from the fits shown in Fig. 2.

expectations for a specimen in which the magnetic excitations are correlated over distances of the order of a wavelength of visible light.

Angular dependence BLS measurements have the potential to yield a good deal of information about the range of magnetic correlations. It will be of great interest to see if the conclusions of the present paper hold for more complicated magnetic ultrathin film structures.

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