Light scattering study on surface magnons in permalloy films

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Brillouin light scattering has been used to study the critical angle behavior for magnetostatic surface waves (MSSW) in thin permalloy films on silicon substrates. The measured magnon frequency versus wave number for various MSSW propagation angles with respect to the applied in-plane static field show that (i) for propagation perpendicular to the applied field, there is good agreement between the experimental and theoretical dispersion; (ii) for propagation away from perpendicular, the experimental frequencies are smaller than the theoretical values; and (iii) the surface mode merges with the zero-order bulk spin wave mode at a propagation angle well above the theoretical critical angle. These results demonstrate a significant departure from existing theories.

INTRODUCTION

Damon and Eshbach (DE) theory for magnetostatic surface waves (MSSW) in in-plane magnetized films predicts the merger of surface waves with the top of the bulk spin wave branch at some critical propagation angle.[1] The Brillouin light scattering technique can be used to detect the thermal surface waves[2–5] and to study directly their critical angle behavior. Such studies on thin iron films have shown substantial departures from the DE theory.[6] The theoretical analysis for the iron films was complicated by the presence of large anisotropy. In this paper, results from similar measurements on an isotropic system, a thin permalloy film on a silicon substrate, are presented. The same anomalous propagation angle effects are found for the permalloy as in the epitaxial iron.

The critical angle characteristics can be understood from the propagation angle dependence of the surface magnon dispersion shown in Fig. 1. The angle between the surface magnon wave vector $\bar{k}_m$ and the applied in-plane static magnetic field $\bar{H}$ is denoted by ϕ_m. The parameters f_S and f_B represent the upper and lower frequency limits for MSSW propagation; the frequency f_B also corresponds to the top of the bulk spin wave band. The surface wave dispersion, i.e., frequency versus wave number, for perpendicular propagation is denoted by the curve $\phi_m = 90°$ in Fig. 1. The magnon frequency decreases from f_S for large k_m values to f_B for $k_m = 0$. For propagation directions other than perpendicular, the surface magnon frequency decreases with decrease in ϕ_m and at a critical angle $\phi_c = \tan^{-1}(H/4\pi M_s)^{1/2}$, it merges with the bulk spin wave band at f_B. Here $4\pi M_s$ is the saturation induction for the film.

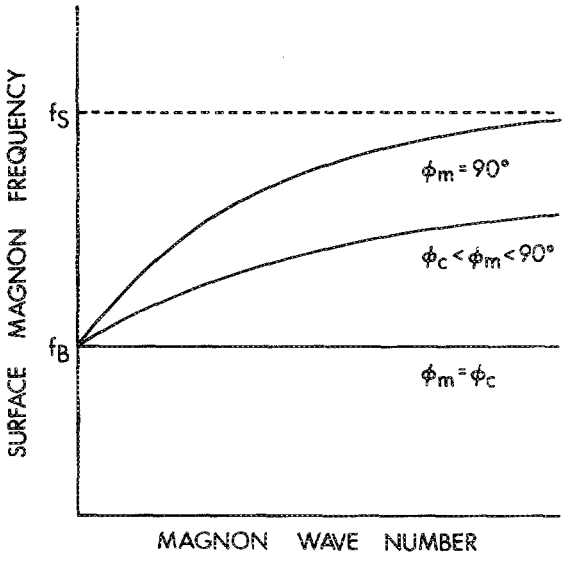

FIG. 1. Typical magnon dispersion for the surface waves in isotropic thin films. The angle between the surface-wave wave vector and the applied static field is ϕ_m and ϕ_c is the critical propagation angle. The frequencies f_S and f_B are defined in the text.

With the Brillouin light scattering technique, it is possible to measure the MSSW dispersion as a function of propagation angle, and one can make a direct comparison between the experimental results and the theoretical predictions. The data for epitaxial iron revealed a collapse of the MSSW dispersion at a propagation angle well above the theoretical ϕ_c. The results of similar measurements on thin permalloy films reveal the same anomaly. These results are described below.

EXPERIMENT

The measurements were carried out on a 50-Å-thick permalloy film ($Ni_{80}Fe_{20}$) on a silicon substrate. For such thin films the bulk exchange modes are shifted well above the surface modes, and the use of such thin films is essential in order to avoid magnetoexchange interaction between branches. The Brillouin light scattering measurements were done using a multipass tandem Fabry–Perot interferometer. Laser light from an argon ion source ($\lambda = 5145$ Å) was directed towards the sample at an angle θ with respect to the film normal. Magnetic excitations within the material interact with the incident light and result in frequency-shifted scattered light. Backscattered light from the sample, collected about the incident light direction, was analyzed using the interferometer to determine the magnon frequency. The surface magnon wave number k_m was controlled by the angle θ (see Kabos *et al.*[3]).

Data were obtained for k_m values over the range 0.4×10^5–2.3×10^5 cm^{-1}. The static magnetic field was ap-

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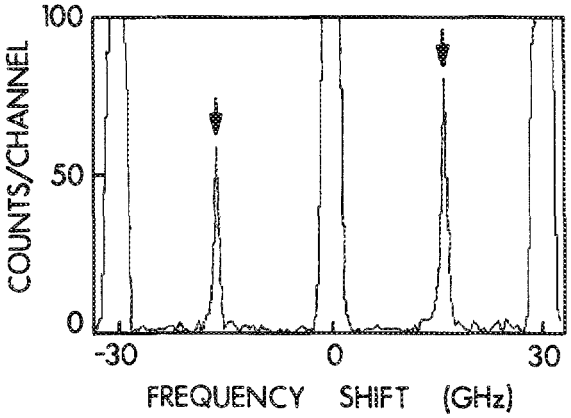

FIG. 2. Brillouin light scattering spectrum for surface waves in a 50-Å-thick permalloy film with applied field $H = 2.73$ kOe, wave number $k_m = 0.42 \times 10^5$ cm^{-1}, and for perpendicular propagation. The arrows indicate the surface magnon peaks.

plied parallel to the film plane. Variation in the MSSW propagation direction relative to the applied field H was achieved by rotating the in-plane field.

A representative permalloy spectrum is shown in Fig. 2 for $H = 2.73$ kOe. The peaks at $\pm$ 16.5 GHz, on *both* sides of the central Rayleigh peak, are due to thermal surface magnons propagating in a direction perpendicular to the applied field with $k_m = 0.42 \times 10^5$ cm^{-1}. The scattered intensity due to surface waves was quite strong in this film. The propagation for the MSSW is nonreciprocal, i.e., the propagation is unidirectional on a given film surface, and the magnon peak is expected to appear on only one side of the Rayleigh peak. However, in thin films the MSSW amplitude for the mode associated with the one surface is large at both surfaces, and magnon peaks associated with both surfaces of the film are observed. According to DE theory,[1] the strong-peak–weak-peak intensity ratio is $\exp(-2k_m s)$, where s is the film thickness. The intensity ratio for the magnon peaks shown in Fig. 2 is about 1.2 and is in good agreement with the theoretical predictions.

The main objective of this work, the measurement of the surface magnon frequency versus propagation angle and the comparison of such data with magnetostatic theory, requires that the effect of various anisotropies on the MSSW frequencies be negligible. The samples were confirmed to be magnetically isotropic by measuring the MSSW frequency as a function of field orientation at $\phi_m = 90°$. Ferromagnetic resonance (FMR) spectra yielded no evidence for pinned surface spins or surface anisotropy.

RESULTS

Figure 3 shows the measured wave-number dependence of the surface magnon frequency in permalloy for $H = 2.73$ kOe and various ϕ_m values. Because of mechanical limitations on the light scattering geometry, dispersion data could not be obtained for ϕ_m values below 30°. Theoretical dispersion curves from the DE theory are shown by the solid lines. These curves were obtained with values of 10.5 kG and 2.69 GHz/kOe for the saturation induction $4\pi M_s$ and the gyromagnetic ratio γ, respectively. These parameters, which are

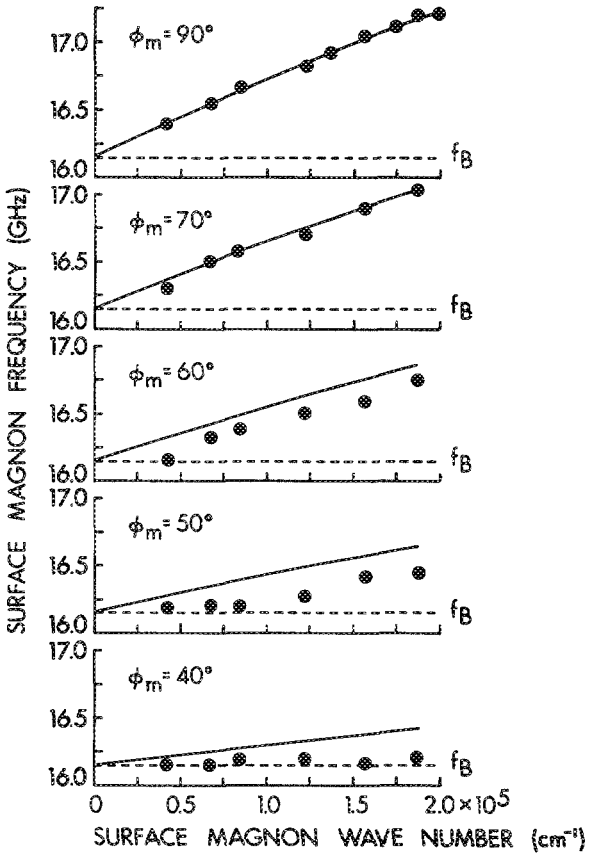

FIG. 3. Propagation angle ϕ_m dependence of the surface wave dispersion in permalloy film for $H = 2.73$ kOe. The solid lines represent the theoretical dispersion based on the Damon–Eshbach theory. The dotted line denotes the frequency corresponding to the top of the zero-order bulk spin-wave mode.

in agreement with the values obtained from FMR measurements, were deduced from fits to frequency versus wave number data for various H values at $\phi_m = 90°$.

The data in Fig. 3 reveal the same basic anomaly for permalloy as for epitaxial iron. The data and theory agree closely for propagation angles close to perpendicular but not for smaller ϕ_m values. Even though the critical angle ϕ_c for permalloy with an in-plane field of 2.73 kOe is about 27°, the MSSW dispersion collapse to f_B at $\phi_m = 40°$ or so.

As in the iron experiments, several possible sources of an apparent anomaly were examined. A spread in k_m or ϕ_m due to the large aperture for the lens used to collect the back scattered light from the sample is expected to broaden the magnon peaks and may give rise to anomalies in f-vs-k_m data. Such possibilities can be eliminated by placing a slit-type aperture behind the collection optics in the spectrometer. With such an arrangement scattered light from the sample with specific ϕ_m values is analyzed with the interferometer. Experiments performed with the slit-type aperture in place did not show any change in the magnon peak position.

The anomaly here and for the iron films originates in observed dispersion behavior that differs from that predicted from a *magnetostatic* theory. While exchange effects could be important, they should not affect the MSSW dispersion in

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any significant way for these *thin* films. Detailed comments on this point have been given in Ref. 6.

This anomaly is quite real but so far unexplained. A full comparison of dispersion data with magnetoexchange theory for a range of film thickness, propagation conditions, and possibly out-of-plane fields is needed. Such results will be important, not only for single layer magnetic films, but also for multilayer film structures as well.

ACKNOWLEDGMENT

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