Anomalous Angle Dependence of the Surface-Magnon Frequency in Thin Films

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Brillouin light scattering has been used to observe the wave-number dependence of the surface-magnon frequency in thin iron films for different in-plane propagation directions relative to the applied in-plane dc magnetic field. The data show that, for propagation directions other than perpendicular, the falloff in magnon frequency with wave number is much faster than predicted by the generally accepted theory. Furthermore, it is found that the surface mode merges into the bulk band at propagation directions much closer to perpendicular than expected from the theory.

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With the development of high-contrast, multipass Fabry-Perot inteferometry, a number of workers[1-3] have used Brillouin light-scattering techniques to study the properties of surface magnons, and to probe directly the nonreciprocal propagation and critical-angle characteristics predicted many years ago by Damon and Eshbach (DE).[4] For the most part, the data served to confirm, rather quantitatively, the DE predictions. We have recently completed a series of measurements of the wave-number and propagation-angle dependence of the surface-magnon frequency in thin iron films and have found several anomalous results which depart substantially from the DE predictions. The purpose of this Letter is to describe briefly these new results.

The data were obtained on epitaxial (100) thin iron films evaporated on sapphire substrates, kindly provided by Dr. P. Grünberg. The data presented below are for a 232-Å-thick sample. The use of such thin films allows one to avoid the unwanted (for this study) interaction of the surface branch with the bulk exchange modes which are shifted well above the surface-magnon frequency. The light-scattering data were obtained with a multipassed-tandem Fabry-Perot interferometer and a backscattering geometry as in Ref. 1. The angle of incidence of the 5145-Å laser light on the film was used to control the magnitude of the in-plane wave-vector component or surface-magnon wave number k_m from 0.4×10^5 to 2.3×10^5 cm^{-1}. This component was along a [100] direction in the film plane. The in-plane magnetic field was rotated from [001] to achieve different propagation directions relative to perpendicular, denoted by ϕ_m. For propagation angles above 50° the upper limit on k_m was 0.83×10^5 cm^{-1}, due to constraints on the optical access in the limited gap of the magnet.

The variation of the surface-magnon frequency (f_m) with wave number (k_m) and propagation angle (ϕ_m) is indicated schematically in Fig. 1, where we follow the Damon-Eshbach results[4] and ignore (for the moment) shifts and variations due to anisotropy. The y-z plane corresponds to the thin film. The applied dc magnetic field $\bar{H}$ is along the z direction. The angle between the surface-magnon wave vector $\bar{k}_m$ and the y direction is denoted by ϕ_m. For $\phi_m=0°$, propagation is *perpendicular* to the dc field. In the high-k_m limit, $k_mS>>1$, the surface-magnon frequency for $\phi_m=0°$ is constant at $f_s=\gamma(H+2\pi M)$. The magnon frequency decreases to $f_B=\gamma[H(H+4\pi M)]^{1/2}$ at $k_m=0$, coincident with the usual uniform-mode ferromagnetic-resonance frequency for in-plane magnetized thin

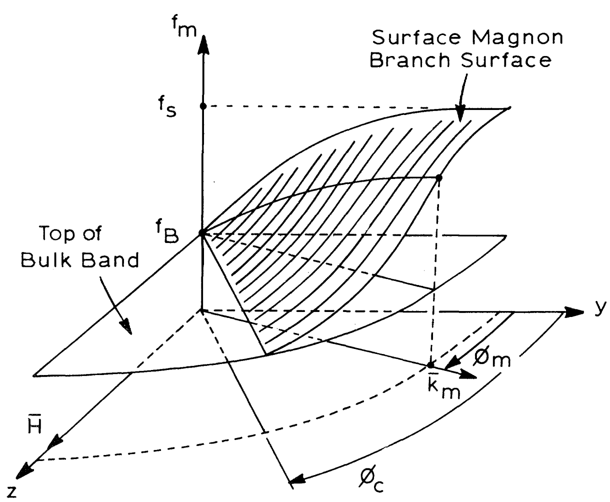

FIG. 1. Schematic variation of the surface-magnon frequency f_m with in-plane wave vector $\bar{k}_m$. The y-z plane is the film plane in the dc magnetic field in the z direction. The in-plane propagation angle is ϕ_m. The critical propagation angle for surface magnons is ϕ_c.

films. In the above, γ is the gyromagnetic ratio and $4\pi M$ is the saturation induction (centimeter-gram-second units). Figure 1 shows that as the propagation angle ϕ_m increases to a critical angle ϕ_c, the surface-magnon dispersion curve, ω_m vs k_m, approaches and merges with the top of the "bulk band" at f_B. (Note, however, that for such thin films the bulk band in the Damon-Eshbach sense is severely modified because of exchange shifts, as discussed by Wolfram and DeWames.[5] These modifications will be considered shortly.)

Experimental determinations of f_m vs k_m for $H = 2.73$ kOe and various ϕ_m values are presented in Fig. 2, along with theoretical curves based on DE theory, suitably modified to include the effects of anisotropy. Data on f_m versus field orientation for $\phi_m = 0°$ magnons indicated cubic anisotropy with an anisotropy field of 560 Oe, a reasonable value for epitaxial iron. Values of $4\pi M$ and γ were taken as 19.2 kG and 2.926 GHz/kOe, chosen to optimize agreement at $\phi_m = 0°$.

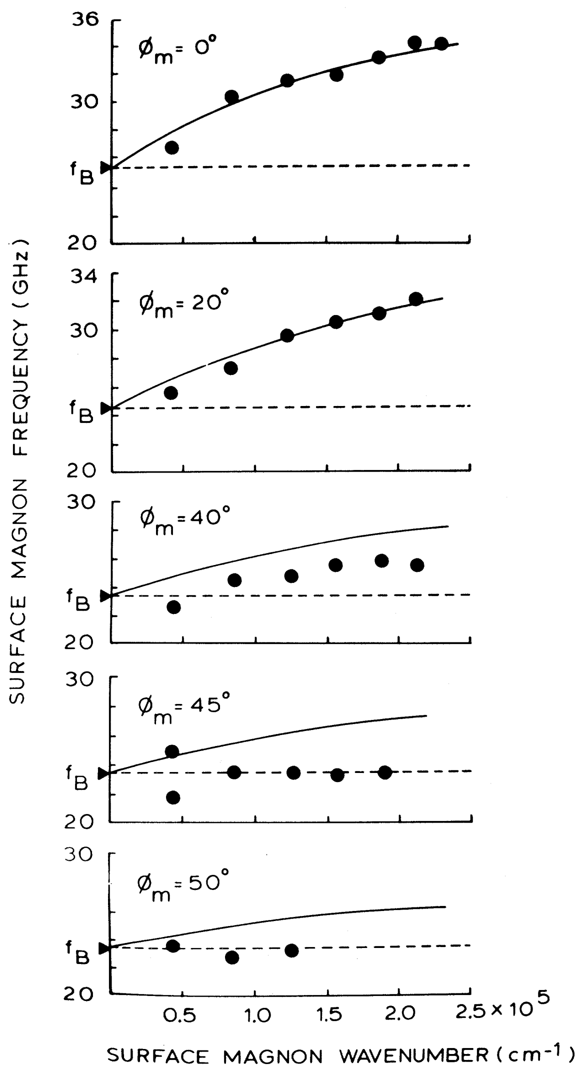

FIG. 2. Surface-magnon frequency vs wave number k_m for various in-plane propagation angles, ϕ_m. The in-plane field (Fig. 1) is 2.73 kOe. The solid lines indicate the k_m dependence of the DE surface mode at the various ϕ_m values. The dashed lines simply denote the frequency position of the top of the bulk band at f_B.

The upper curve and data set for $\phi_m = 0°$ agree rather well. It is evident from the graphs for $\phi_m = 20°$ and 40° that, as ϕ_m increases, the experimental surface-mode frequencies deviate more and more from the theory. For $\phi_m = 45°$ and 50°, there is no distinct surface branch. The modes have essentially collapsed to f_B. This occurs for ϕ_m well below the expected critical angle, $\phi_c = 70.3°$. Figure 3 presents additional data on surface-mode frequency versus propagation angle ϕ_m for two values of k_m. The variation in f_B, the position in frequency of the top of the bulk spin-wave band, with propagation angle, indicated by the lowest solid line in Fig. 3, is related to the changing *field* direction. Recall that the magnon wave vector is kept along [010] and ϕ_m is varied by rotating the in-plane field. Apart from these complications, it is clear that the experimental surface-magnon frequency drops off much more rapidly with angle than expected from the theory.

The possibility that these "anomalous" results are due to the spread in k_m and/or ϕ_m for the ob-

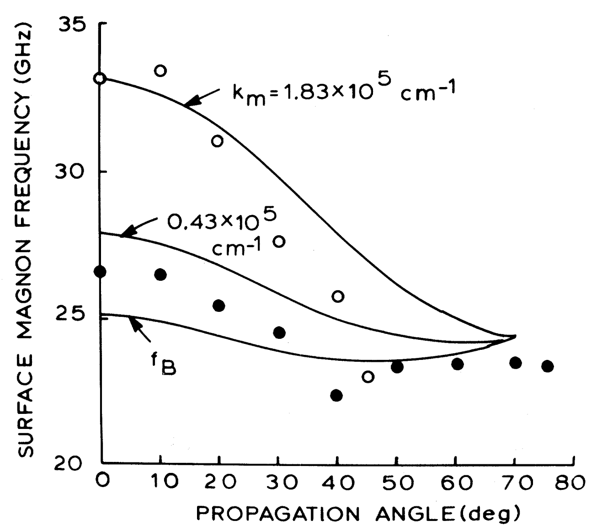

FIG. 3. Surface-magnon frequency as in Fig. 2, but vs propagation angle ϕ_m for the indicated experimental k_m values. The upper two solid lines represent the DE theory for these same k_m values. The lower solid line indicates the frequency f_B, the top of the bulk band, vs ϕ_m.

served backscattered magnons because of the large collection-lens aperture was considered and experimentally eliminated. By the placing of a slit behind the lens, only modes with specific ϕ_m values, unaffected by the collection aperture, were selected. While the peaks were somewhat sharper and less intense, the *positions* of the peaks were unchanged.

Some additional comments are in order concerning the absence of any observed magnons at the top of the bulk band (f_B) for the smaller ϕ_m values, and the collapse of the surface-magnon frequencies to f_B for the larger ϕ_m values in Figs. 2 and 3. The absence of zero-order bulk modes at f_B for $\phi_m = 90°$ is consistent with previous reports,[2,6–9] but the possible reasons for these missing modes need some clarification. While pinning would eliminate such modes,[9] the fundamental reason for their absence is that they do not represent normal modes of the system even in the absence of pinning. This is evident even from the DE paper, on the basis of the odd symmetry of the lowest-order volume mode. The theoretically allowed branches are implicit in Fig. 1 of Ref. 5 and in Fig. 1 in the work of DeWames and Wolfram.[10]

Turn now to the apparent collapse of the surface mode frequency to f_B for large ϕ_m. One might think that such a collapse is indicative of the appearance of a bona fide mode at f_B. We propose, however, that this "collapse" is simply a manifestation of the evolution of the surface mode into the lowest-order volume modes as ϕ_m increases. With exchange, this branch would bottom out (for $\phi_m = 90°$) some 2 GHz below f_B. Restrictions on ϕ_m and k_m becuase of mechanical limitations on the light-scattering geometry presently limit our experimental access to this portion of the dispersion. Some limited data on the frequency of the lowest-order volume mode for $\phi_m = 90°$ (propagation parallel to the dc field) yield a mode frequency which is slightly above f_B for low k_m and falls below f_B at moderate k_m. A complete map of the lowest-order mode frequency versus ϕ_m and k_m should prove very interesting. Such work is now in progress.

The possibility that these "anomalies" are due to the limitations of the magnetostatic theory has also been considered. Computed curves based on the magnetoexchange formalism of Camley, Rahman, and Mills[11] (courtesy of Camley) are quite similar to the theoretical curves in Fig. 3. One might expect such a similarity, in view of the small wave numbers and corresponding small exchange contribution for the surface magnons involved.

The one instance in which the experimental ϕ_m dependence of the mode frequencies was compared with the full magnetoexchange theory predictions was for a moderately thick film and fixed k_m.[2] A good match was obtained. Although not explicitly noted in Ref. 2, the lowest mode had a limiting frequency at $\phi_m = 90°$ which was *below* f_B, in line with the comments presented above.

The above results demonstrate a significant departure of the experimental surface-magnon dispersion properties for thin iron films from those expected from either DE or magnetoexchange theory. These departures are not seen for perpendicular propagation ($\phi_m = 0°$) or for thicker films, in agreement with Ref. 3. In light of these results, further experimental and theoretical work on magnon dispersion as a function of the wave vector and film thickness should prove to be very interesting.

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