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Collective Behavior of Magnons in Superlattices

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The magnon spectrum characteristic of collective behavior in magnetic/nonmagnetic superlattices has been observed, and is in good agreement with theoretical predictions.

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The study of the magnetic properties of artificially layered materials and superlattices has not received as much attention as the superconducting, transport, and elastic properties.[1] The magnetic studies have been mostly limited to magnetization,[2] neutron scattering,[3] and ferromagnetic resonance[4] measurements. All magnetic measurements to date can be explained as due to simple thin-film effects. In the present paper we present our observations of magnons in superlattices, which are in good agreement with earlier theoretical calculations and show the existence of modes which are due to the collective behavior of the layers.

Two recent articles[5,6] have dealt with the problem of the magnon spectrum in a system of layered magnetic and nonmagnetic materials. They treat the problem by considering only dipolar coupling and ignore any effects due to exchange. In this approximation it is found that surface magnons in each individual layer are coupled and give rise to a characteristic spectrum associated with the superlattice. The calculations show that for magnons propagating perpendicularly to the applied magnetic field (H) a band of magnon modes is expected at frequencies[6] given by

$$\nu^2 = \gamma^2 [H(H+4\pi M) + (2\pi M)^2 w], \qquad (1)$$

where γ is the gyromagnetic ratio, M is the magnetization of the magnetic layers, and w is a number that can take on a range of values, thus giving rise to a band of modes. The quantity w is given by[6]

$$w = \frac{2\sinh(d_1 Q_\parallel)\sinh(d_2 Q_\parallel)}{\cosh[(d_1+d_2)Q_\parallel] - \cos[Q_\perp(d_1+d_2)]}, \qquad (2)$$

where d_1 and d_2 are the thicknesses of the magnetic and nonmagnetic layers, respectively, and $Q_\parallel$ and $Q_\perp$ are the components of the magnon wave vector parallel and perpendicular to the layers. $Q_\perp$ also satisfies the inequalities

$$0 \leq Q_\perp(d_1+d_2) \leq \pi. \qquad (3)$$

The most striking feature of the calculations, however, is that when $d_1 > d_2$ (magnetic layers

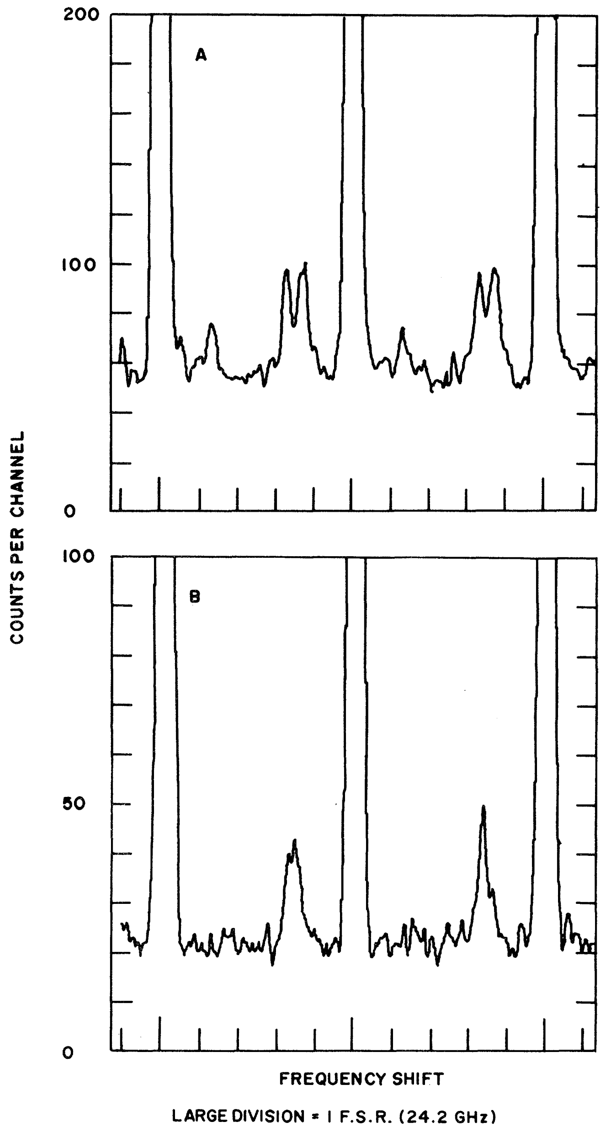

FIG. 1. Brillouin spectra showing magnon modes in Mo/Ni superlattices [(a) $d_1 = 249$ Å and $d_2 = 83$ Å; (b) $d_1 = 100$ Å and $d_2 = 300$ Å] in an applied field of 0.93 kG. The truncated peaks are unshifted laser radiation, visible in three interferometric orders; shifted to the left of each laser peak are its associated Stokes magnon peaks. Anti-Stokes lines from one of the modes are also visible to the right of the unshifted lines in (a).

thicker than the nonmagnetic layers) an additional mode appears at a frequency

$$\nu = \gamma (H + 2\pi M). \tag{4}$$

This frequency is the same as that of the surface magnon in a semi-infinite medium of magnetization M.

In this paper we present the first observation of this mode in a superlattice and we feel that it represents one of the clearest indications of collective behavior in superlattices. Our studies were performed on a superlattice system composed of Mo and Ni layers with the use of Brillouin scattering techniques. The structural and normal-state properties of the samples have been described elsewhere.[7] The reader is referred to Ref. 8 for a review of light scattering from magnetic materials.

In Fig. 1 we present the spectra observed in samples with $d_1 = 249$ Å, $d_2 = 83$ Å and $d_1 = 100$ Å, $d_2 = 300$ Å. These spectra were recorded with ~20 mW of 5145-Å radiation, $Q_{\parallel} = 1.31 \times 10^5\ \mathrm{cm}^{-1}$. A magnetic field of 0.93 kG was applied in the plane of the sample and perpendicular to $Q_{\parallel}$. We should point out that all spectra were recorded on samples that had been freshly peeled off the substrate with Ni as the outermost layer. Spectra recorded from samples whose surfaces had been exposed for more than a few days were of considerably lower quality, possibly because of surface oxidation. Also, in the case of a thick Ni film, data taken from unpeeled samples yielded a magnetization lower than that previously reported for Ni,[9] whereas a freshly peeled sample was in good agreement.

The position and field dependences of the single peak in a representative sample with $d_1 = d_2/3$ [Fig. 1(b)] are shown in Fig. 2. The line represents Eq. (1) with $w = 0.049$ calculated from Eq. (2) [under the assumption $Q_{\perp}(d_1 + d_2) = \pi$ as suggested in Ref. 6] and M chosen to give the best fit. This yields $M = 0.39 \pm 0.02$ kG, which is to be compared with that from independent dc magnetization measurements, $M = 0.30 \pm 0.03$ kG. A complete study of samples with various d_1 and d_2 with their field and wave-vector dependences will be presented elsewhere.

The existence of the doublet in Fig. 1(a) bears out the striking theoretical prediction of an additional mode which appears for cases when $d_1 > d_2$. The position of the two peaks (for this representative sample), as a function of applied field, is shown in Fig. 3. In this figure, the full lines represent Eqs. (1) and (4), with M used as a fitting parameter. The value of w (0.03) was calculated from Eq. (2) under the assumption $Q_{\perp}(d_1 + d_2) = \pi$. The fit can be seen to be excellent and yields $M = 0.29 \pm 0.02$ kG, which is to be compared with the value $M = 0.38 \pm 0.04$ kG determined from independent dc magnetization measurements. We are not yet in a position to attribute any significance to the discrepancies in the values of M since, as we mentioned earlier, the quality of the spectra and the position of the peaks depend on the sample surface, indicating that a certain amount of deterioration occurs as a function of time.

In conclusion, we have verified the rather surprising prediction of an "additional" magnon mode in superlattices in which the magnetic lay-

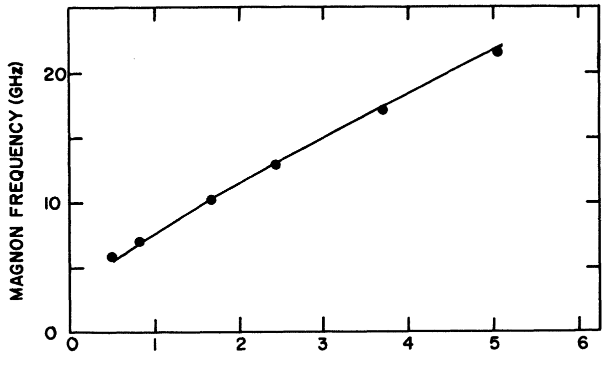

FIG. 2. Magnon frequency vs applied magnetic field in a superlattice system in which $d_1 < d_2$ [Fig. 1(b)]. The line represents Eq. (1) with $w = 0.049$ and $M = 0.39$.

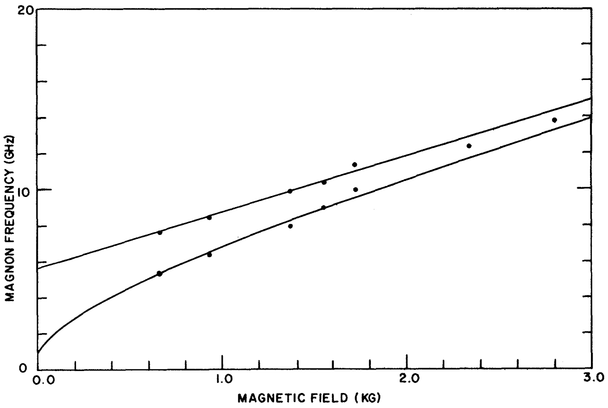

FIG. 3. Magnon frequency vs applied magnetic field in a superlattice system in which $d_1 > d_2$ [Fig. 1(a)]. The lines represent Eqs. (1) and (4), with $w = 0.03$ and $M = 0.29$ kG.

ers are thicker than the nonmagnetic ones.

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