Magnetic properties of Mo/Ni superlattices (invited)

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We have studied the magnetic properties of Mo/Ni nonlattice matched superlattices. The dc magnetization was measured in the temperature range 5–300 °K and in magnetic fields up to 10 kG. The saturation magnetization and the Curie temperature behavior are consistent with expectations based on thin film effects. However, there are indications of ferromagnetic coupling across the nonmagnetic metal. Light scattering measurements were performed for the first time to study the magnon spectrum in superlattices. The Brillouin magnon spectra obtained from Mo/Ni superlattices show characteristic features associated with the collective behavior of the superlattice and are in good agreement with earlier theoretical predictions.

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The fabrication of magnetic superlattices has received renewed attention in recent years since it is hoped that these new magnetic materials will exhibit, novel interesting as well as useful properties.[1] Magnetization,[2] neutron scattering,[3] and ferromagnetic resonance[4] studies performed to date can be explained as due to simple thin film effects. An exception to the rule is the study of the Curie temperature of Cu/Ni (Ref. 5) compositionally modulated alloy where RKKY coupling is observed across the normal Cu layers. In the present paper we describe our studies of the Mo/Ni superlattice. This is a nonlattice matched superlattice whose constituents do not form solid solutions. Although the dc magnetization studies can be explained as due to simple thin film effects, the magnon spectrum shows a behavior characteristic of the collective nature of the stack.

That Mo/Ni grows as a superlattice was found[6] only after a search was conducted among approximately forty different combinations of elemental materials and a large variety (12) of different substrates. Two well separated beams of particles are prepared using magnetron sputtering. The substrates are held on a temperature controlled rotating table and, by properly controlling the sputtering rate and the rotation speed of the platform, samples with layers in the thickness range 5–5000 Å are prepared. The samples investigated consisted of three series in which the relative thickness of Mo and Ni are in the ratio 3:1, 1:3, and 1:1.

X-ray scattering studies show well separated layer growth as well as a transition from a crystalline to a disordered structure at around a Ni thickness of 8 Å. Correlated with this structural transition we have found a transition from metallic to nonmetallic behavior in the electrical resistivity as well as an anomalous softening of the acoustic phonons. The relationship between the structural and elastic properties have been explained using molecular dynamics calculations.[7]

The dc magnetization of these samples has been measured in the temperature range 5–300 °K and in fields up to 10 kG using SQUID magnetometry.[8] The samples were removed from the mica substrate, rolled into cylinders and measured in a parallel magnetic field. Corrections were applied to take into account the finite magnetization of the Al-3% Si holder. Typical hysteresis curves for an equal layer sample with $\Lambda/2 = 14.3$ Å, where Λ is the superlattice periodicity, are shown in Fig. 1. The saturation magnetization M_s at 5 °K decreases smoothly to zero with decreasing nickel thickness, as shown in Fig. 2, for the three series. The series with the Mo/Ni ratio equal to 1/3 (triangles) consistently shows a higher magnetization indicating some magnetic coupling across the Mo layer. This is also observed in the behavior of the Curie temperature, T_C as extracted from Arrot plots and shown in Fig. 3. However, the major trend in both M_s and T_C is a decrease with decreasing nickel thickness as expected for a thin film. In our case, each Ni layer possibly has a nonmagnetic surface layer due to the proximity of the Mo atoms.

The light scattering studies[9] however indicate a more complex behavior of the superlattice. Brillouin scattering measurements were performed on a five pass Fabry–Perot interferometer, using 100 mW of 5145-Å radiation. The scattering geometry was such that the component of the magnon wave vector parallel to the surface ($Q_{\parallel}$) was $1.31\times10^{5}\,\mathrm{cm}^{-1}$. The sample could also be placed in magnetic fields up to 5 kG. Two recent theoretical predictions[10,11] show that for magnons propagating perpendicular to the applied field a band of magnons is expected at frequencies

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

where γ is the gyromagnetic ratio, M the magnetization of the magnetic layers, and

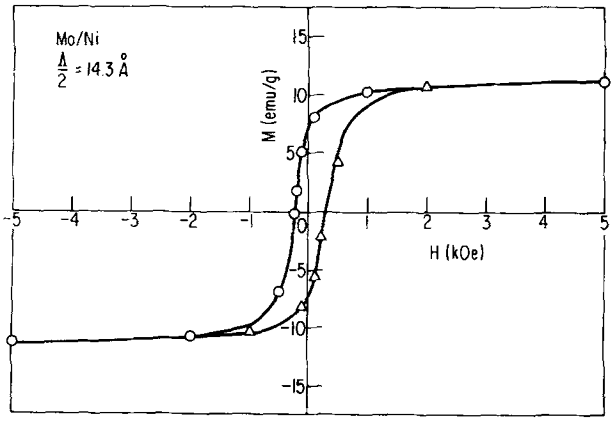

FIG. 1. Typical hysteresis curve for an equal layer sample with $\Lambda/2 = 14.3$ Å.

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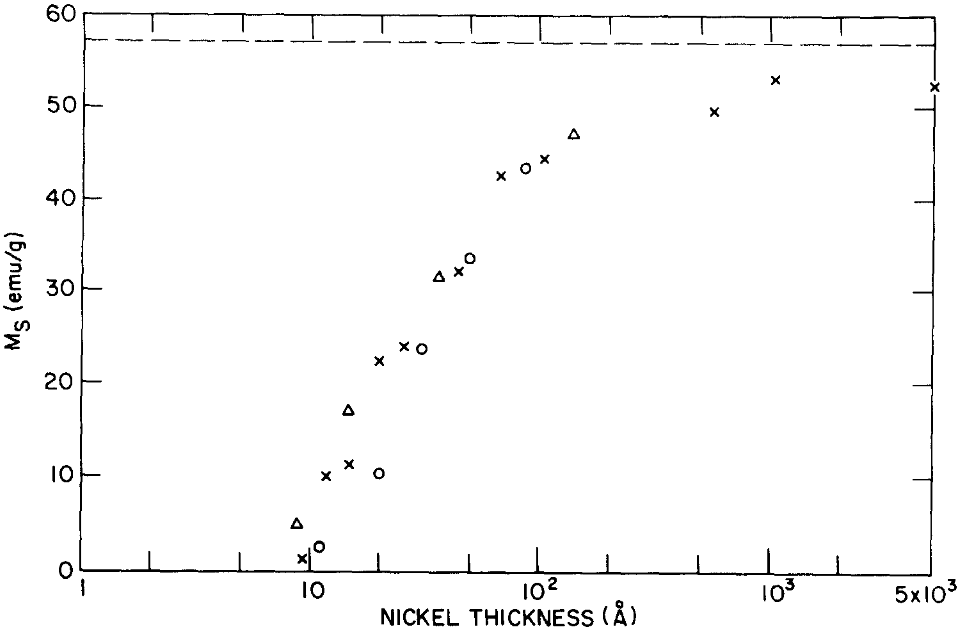

FIG. 2. Dependence of the saturation magnetization on the nickel thickness.

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

with d_1 and d_2 the thicknesses of the magnetic and nonmagnetic layers and $Q_\parallel$ and $Q_\perp$ the components of the magnon wave vector parallel and perpendicular to the layers. In addition, quite surprisingly, for $d_1 > d_2$ an additional mode appears at a frequency

$$\nu = \gamma(H + 2\pi M). \tag{3}$$

The modes described by Eqs. (1) and (3) arise from the interaction of surface like modes in each individual layer. Although modes arising from the interaction of bulk-like modes in each layer also exist these will not be discussed here.

Figure 4 shows the spectra obtained from samples with $d_1 = 249$ Å $= 3d_2$ and $d_2 = 300$ Å $= 3d_1$. The observation of two peaks in Fig. 4(a) and only one peak in Fig. 4(b) is in good

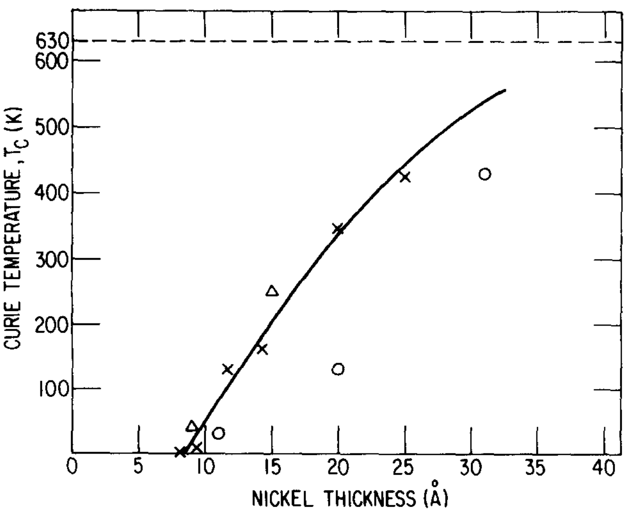

FIG. 3. Dependence of the Curie temperature, extracted from Arrot plots, as a function of nickel thickness.

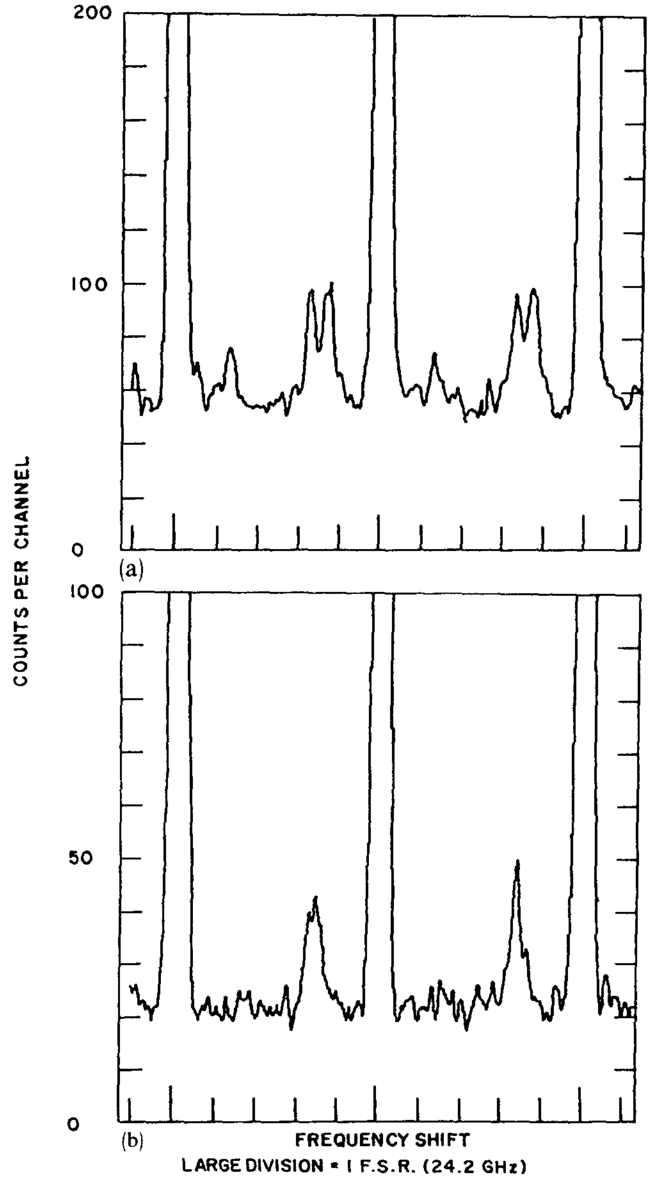

FIG. 4. Typical light scattering spectra showing the effect of having the magnetic layer thicker (a) or thinner (b) than the nonmagnetic layer.

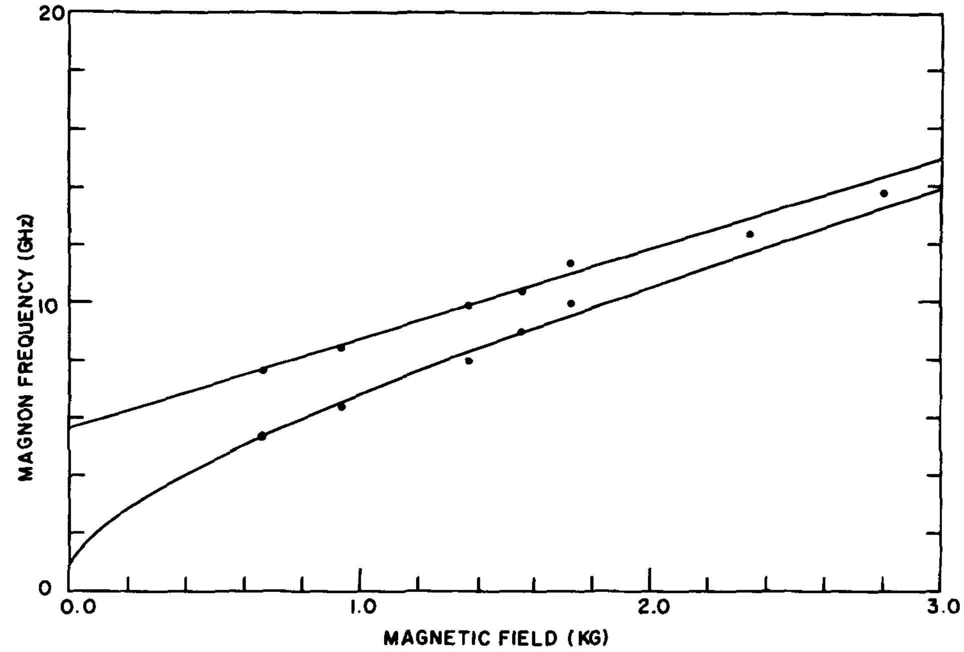

FIG. 5. Magnetic field dependence of the magnon modes. The solid lines are fits according to Eqs. (1) and (3) using only the saturation magnetization as an adjustable parameter.

agreement with theoretical expectations. The magnetic field dependence of both peaks in Fig. 4(a) is shown in Fig. 5. The only adjustable parameter used in fitting the experimental results to theory is the saturation magnetization of the magnetic layer. Comparison of the saturation magnetization extracted from light scattering measurements and from dc magnetization shows good agreement and will be the subject of a future publication.

In summary, we have shown that in Mo/Ni superlattices although dc magnetometry mostly shows results which are consistent with thin film effects, the magnon spectra show a behavior which is characteristic of the collective behavior of the stack.

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[1] C. M. Falco and I. K. Schuller, in *Synthetic Modulated Structure Materials*, edited by L. Chang and B. C. Giessen (Academic, New York, to be published).

[2] E. M. Gyorgy, J. F. Dillon, D. B. McWhan, L. W. Rupp, Jr., L. R. Testardi, and P. J. Flanders, Phys. Rev. Lett. **45**, 57 (1980).

[3] G. P. Felcher, J. W. Cable, J. Q. Zheng, J. B. Ketterson, and J. E. Hilliard, J. Magn. Magn. Mater. **21**, L198 (1980).

[4] B. P. Thaler, J. B. Ketterson, and J. E. Hilliard, Phys. Rev. Lett. **41**, 336 (1978).

[5] W. S. Zhou, H. K. Wong, J. R. Owens-Bradley, and W. P. Halperin, Physica B **108**, 953 (1981).

[6] M. R. Khan, C. S. L. Chun, G. P. Felcher, M. Grimsditch, A. Kueny, C. M. Falco, and I. K. Schuller, Phys. Rev. B **27**, 7186 (1983).

[7] I. K. Schuller and A. Rahman, Phys. Rev. Lett. **50**, 1377 (1983).

[8] G. Felcher, M. R. Khan, P. Roach, and I. K. Schuller (unpublished).

[9] M. Grimsditch, M. R. Khan, A. Kueny, and I. K. Schuller, Phys. Rev. Lett. **51**, 498 (1983); (unpublished).

[10] P. Grünberg and K. Mika, Phys. Rev. B **27**, 2955 (1983).

[11] R. E. Camley, T. S. Rahman, and D. L. Mills, Phys. Rev. B **27**, 261 (1983).