Ferromagnetic resonance in a Ni-Mo superlattice[a)]

M. J. Pechan
Department of Physics, Miami University, Oxford, Ohio 45056

M. B. Salamon
Department of Physics, University of Illinois at Urbana-Champaign, Urbana, Illinois 61801

Ivan K. Schuller
Materials Science and Technology Division, Argonne National Laboratory, Argonne, Illinois 60439

Ferromagnetic resonance (FMR) measurements, at room temperature and at 4.2 K, have been made on a layered Ni (249 Å)-Mo(83 Å) superlattice. We have examined the resonance position as a function of the angle between the film normal and the applied field. The measured g value agrees with that of bulk Ni, but the magnetization is lower than that obtained for bulk Ni and also for this sample using both light scattering and direct measurement techniques. This low magnetization contrasts with FMR measurements on compositionally modulated Ni-Cu samples, where the magnetization was reported to be greater than that of bulk Ni. We show that a reduced value of the magnetization is consistent with perpendicular uniaxial anisotropy. When the applied field is less than 20° from the surface normal, additional lines appear that move to *higher* fields than the main resonance. These lines are consistent with the existence of nonuniform regions of distinct magnetization. An observed resonance, which is suggestive of a spin-wave mode, is discussed.

The potential for precise control of their electromagnetic properties has generated considerable interest in a class of compositionally layered materials known as superlattices. Magnon spectra and dc magnetization studies on Ni-Mo superlattices have been previously measured and reported,[1,2] indicating magnetizations comparable to bulk Ni values and the existence of spin-wave modes. FMR measurements were performed to check for evidences of spin-wave modes and to obtain an independent measure of the magnetization.

The sample was prepared by alternately sputtering layers of Ni (249 Å) and Mo(83 Å) onto a mica substrate. The sample has been characterized extensively as reported elsewhere.[3] A 5 mm × 10 mm rectangle of the thin film was mounted in a fused quartz envelope for secure, accurate positioning during low-temperatures FMR measurements. Room-temperature and 4.2 K measurements were made in a TE102 mode multipurpose cavity at 9.289 GHz. At both temperatures, FMR spectra were recorded with the plane of the sample set at various angles with respect to the applied field.

Figure 1 shows the resonance spectra at $\phi = 0$ and $\phi = 85°$, where ϕ is the angle between the applied field and the normal to the sample plane. The asymmetry of the low-field scan indicates the distortion of a single Lorentzian, which becomes obvious in the high-field spectrum. Since the structure apparent in the $\phi = 0$ scan indicate the presence of several resonances, a computer routine was designed to fit the spectrum to multiple Lorentzians. The results of fitting are shown in Table I, where one observes that the high-field spectrum can be explained in terms of five Lorentzian shaped signals, and the low-field spectrum in terms of three. It should be pointed out that, although there are many adjustable parameters in such fitting procedures, neither four nor six Lorentzians produced a satisfactory fit to the high-field spectrum. It is logical to assume the multiple resonances arise from nonuniform regions of distinct magnetization within the sample. Although at $\phi = 0$, the spectrum is best fit to five Lorentzians, only three are necessary for each peak above $\phi = 15°$, and at $\phi = 25°$ the spectrum collapses to a single Lorentzian. For $25° < \phi \leqslant 90°$ three Lorentzians again give the best fit to each spectrum. Since it is not possible to follow the five resonances observed at $\phi = 0$ from $\phi = 0$ to 90°, the angular dependence is presented for three values of magnetization. These values are obtained from the central and extremal resonances at $\phi = 0$ and from the three observed resonances at $\phi = 90°$. Table II shows the magnetizations and g factors obtained from the standard demagnetization equations

$$H_r = H_\perp - 4\pi \text{ and}$$
$$H_r = [H_\parallel (H_\parallel + 4\pi M)]^{1/2} \quad (1)$$

where $H_\perp$ and $H_\parallel$ correspond to resonance when $\phi = 0°$ and 90° respectively, H_r is the internal resonance field and M is the magnetization. The validity of assuming these peaks arise from distinct magnetizations, can be tested by comparing the angular dependence of resonance positions extracted from the spectra with calculations predicting such depen-

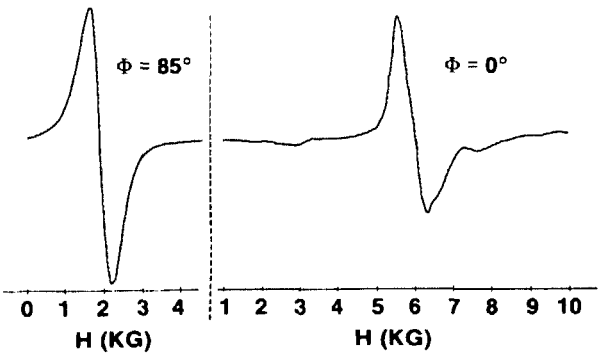

FIG. 1. Room-temperature FMR spectra for $\phi = 85°$ (nearly $H_\parallel$ and $\phi = 0°$ ($H_\perp$), showing noticeable asymmetry at $\phi = 85°$ and multiple resonances at $\phi = 0°$.

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TABLE I. Results of fitting $\phi = 0$ and $\phi = 85°$ spectra to multiple Lorentzians. H_0 is the resonance position, A is the amplitude normalized to the largest peak extracted and ΔH_{pp} is the peak to peak line width.

			$\phi = 0$		
H_0(kG)	5.566	5.745	5.978	6.328	7.265
A	0.461	0.722	1.000	0.366	0.098
H_{pp}(kG)	0.225	0.277	0.373	0.558	0.690
			$\phi = 85°$		
H_0(kG)	2.047		1.851		1.564
A	0.969		1.000		0.172
H_{pp}(kG)	0.452		0.432		0.535

dence for a unique magnetization.[4] The equations used in the calculations take into account that the magnetization does not, in general, lie along the applied field and are given by

$$H = 2\pi M [- \sin\phi \sin\theta + 2 \cos\phi \cos\theta + (\sin\phi \sin\theta - 2 \cos\phi \cos\theta)^2 - 4 \cos^2\theta + 4H_r^2/(4\pi M)^2], \quad (3)$$

and

$$H \cos\phi \tan\theta = H \sin\phi + 4\pi M \sin\theta, \quad (4)$$

where θ is the angle the magnetization makes with the film normal. The transcendental Eq. (4) determines the relationship between ϕ and θ for given H and M values. The results of this comparison, shown in Fig. 2, indicate that the sample does contain nonuniform regions of distinct magnetization. At the point where all the magnetizations collapse into one peak ($\phi \simeq 25°$) the line shape fits very well to a single Lorentzian, indicating that the measurements do not suffer from appreciable skin depth problems.

While the g value is in agreement, the magnetization is lower than that for bulk Ni and except for the highest M peak, also lower than that obtained for this sample using light scattering[1] (300 Oe) or dc magnetization[2] techniques (360 Oe). The dc magnetization measurements show that the film magnetization approaches that of bulk Ni as the Ni layers increase in thickness. This low magnetization contrasts with FMR measurements on Ni-Cu superlattices where the magnetization was reported to be greater than that of bulk Ni.[5] Our reduced value of magnetization is consistent with a perpendicular uniaxial anisotropy field which modifies the magnetization in Eq. (1) as follows:

$$4\pi M_A = 4\pi M - H_A \quad (5)$$

TABLE II. Magnetizations (M) and spectroscopic splitting factors (g) obtained from combining the extremal resonances of $H_\parallel$ and $H_\perp$ as well as the central resonances of both orientations. Note: $H_\parallel$ values are obtained by taking the averages of the $\phi = 85°$ and $\phi = 95°$ results.

$H_\parallel$ (kG)	$H_\perp$ (kG)	H_r (kG)	g	M (Oe)
1.66	7.26	3.11	2.14	331
1.90	5.98	3.03	2.19	234
2.10	5.57	3.10	2.14	196

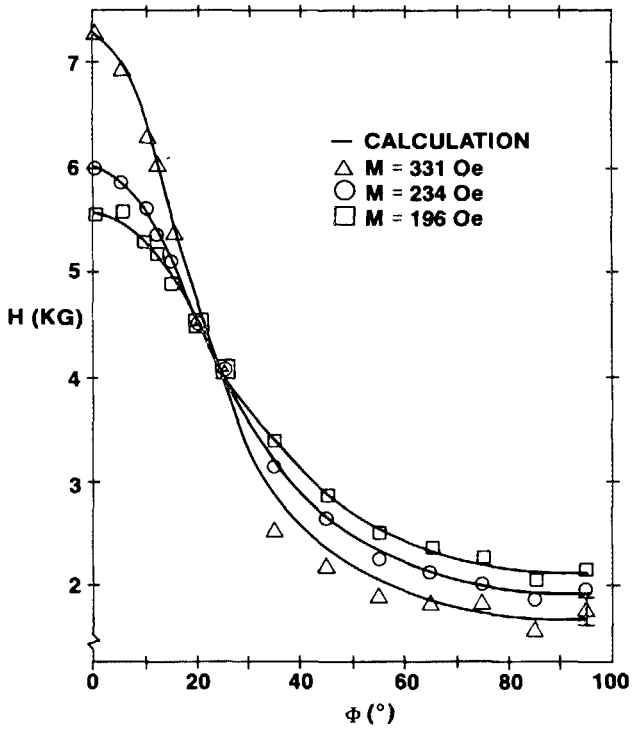

FIG. 2. Comparison between measured and calculate values of resonance position vs ϕ, for three distinct observed magnetization values. Note the convergence to a single resonance at approximately 25°.

where M_A is obtained from FMR and M is obtained from dc magnetization or light scattering techniques. Using the main resonance peak ($M_A = 234$ Oe) and $M = 360$ Oe from magnetization measurements or $M = 300$ Oe from optical data we find $H_A = 1.58$ or 0.83 kOe, respectively.

The source of this anisotropy field can be explained using Macdonald's[6] approach, in which H_A in Eq. (5) is replaced by $-3\lambda\sigma/M$ where λ is the Ni magnetostriction coefficient (negative) and σ is the isotropic stress (positive for tension). X-ray measurements[3] show a positive strain of approximately 0.4% at larger $d_{Ni} = 3d_{Mo}$ layer thicknesses in these samples. Using $\lambda_{111} = -23 \times 10^{-6}$, $M = 360$ Oe and the bulk modulus of Ni one obtains $H_A = 1.4$ kOe, which is consistent with H_A extracted from the present FMR data. This is strong evidence that the planar stress is producing a uniaxial anisotropy which is perpendicular to the sample plane. Further evidence that this stress is giving rise to the anisotropy is obtained from the low-temperature (4.2 K) measurements, where the magnetization decreased by approximately 20% from the room-temperature measurements. This decrease can be explained by noticing that Ni contracts, as temperature is lowered below room temperature, at about 2.5 times the contraction rate of Mo.[7] Therefore the isotropic stress increases, resulting in a further reduction in the magnetization. This decrease in effective magnetization was not observed for the high magnetization resonance, indicating a region of magnetization which experiences negligible anisotropy.

Concerning the existence of spin waves in this superlattice, a low amplitude signal can be observed in Fig. 1 ($\phi = 0$) at approximately 3 kG. This signal persisted in recognizable

form for $\Delta\phi = \pm 5°$ around $\phi = 0$. If this peak is due to spin-wave resonance, the spin-wave stiffness constant would have to be reduced by a factor of 3 from the bulk Ni value.

In summary we have demonstrated that the Ni (249 Å) Mo (83 Å) superlattice contains nonuniform regions of distinct magnetization, and that the low value of magnetization, measured by FMR is consistent with uniaxial, perpendicular anisotropy arising from isotropic stress between Ni and Mo layers. Also possible evidence for a spin-wave mode has been presented.

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