Journal of Magnetism and Magnetic Materials 126 (1993) 498–500
North-Holland

Magnetotransport in Mo/Ni superlattices

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We have measured the electrical resistivity, magnetoresistance (MR), and Hall resistivity of Mo/Ni superlattices with modulation wavelengths Λ between 13.8 Å and 5000 Å in the temperature range 1–300 K and in magnetic fields up to 50 kG. The samples with Λ less than 680 Å exhibit a resistance minimum below 15 K and a logarithmic temperature dependence below this minimum. The perpendicular $\mathrm{MR}_\perp$ is negative and the parallel $\mathrm{MR}_\parallel$ is positive for large layer thickness. The Hall voltage saturates at high fields and the saturation value exhibits a maximum as a function of superlattice period.

Introduction

Magnetic superlattices have many interesting properties which are of importance both in application and in basic research studies [1,2]. Mo/Ni superlattices in particular exhibit localization effects in their transport properties and competition between magnetism and superconductivity [3].

Scaling theory for transport in solids shows that the dimensional behavior is determined by comparing a physical size t with the characteristic Thouless length defined as $L = (l_e l_i)^{1/2}$ where l_e is the elastic mean free path, l_i is the inelastic scattering length, and t for multilayers is the layer thickness d. Here l_e is temperature independent and l_i is temperature dependent as $l_i \propto T^{-P}$ [4]. As a consequence the dimension changes from three to two and the temperature coefficient of resistance (TCR) changes from positive to negative below T_d. In two dimensions the resistance change is given by

$$(R(T) - R(T_0))/R(T_0) = \Delta R/R_0 = R_0(\alpha e^2/2h\pi^2) P \ln(T/T_0). \qquad (1)$$

The same parameter also controls the magnetic field dependence of the conductance in the form of $f(l_H{}^2/L^2)$, $f(x) = \psi(x + 1/2) - \ln(x)$, where ψ is the digamma function and $l_H = (hc/eH)^{1/2}$. Localization theory predicts a negative MR ($f(x) > 0$) and no correction to the Hall effect in two dimensions [5].

In this paper we present the results of a combined study of the electrical transport, MR and Hall effects of Mo/Ni superlattices grown by sputtering [6,7].

Experiments

The Mo/Ni multilayered samples were prepared from two high rate magnetron sputtering guns shielded from each other to avoid overlap of the particle beams [6]. The 90° sapphire substrates were held to a rotating table which moved them from one beam of particles to the other. The modulation wavelength Λ given by the sum of both layers of equal thickness, was in the range of 13.8 Å to 5000 Å. X-ray characterization was carried out at room temperature on a θ–2θ diffractometer. For modulation wavelengths $\Lambda \geqslant 16.6$ Å, the X-ray peaks are reasonably sharp indicating good crystallization perpendicular to the layers, whereas below this value, only one broad line appears indicating loss of long-range crystalline order [7].

The resistance and Hall voltage were determined by four-probe measurements on well-defined geometric shapes. A six-point bridge structure with two of the points in the middle was formed by standard photolithographic techniques. The resistances and Hall voltage were measured using a standard ac lock-in method with 10 μA current at 25 Hz. The samples held in good thermal contact with a holder could be cooled in this fashion to 1.1 K in a 50 kG superconducting Helmholtz magnet. The MR and the Hall voltage were measured in different fields while the temperature remained constant.

Results

The temperature coefficient of resistivity (TCR) is positive above 20 K for $\Lambda \geqslant 16.6$ Å. Fig. 1 shows the low temperature ($T < 20$ K) dependence of resistivity for different layer thicknesses. For $d > 11.7$ Å a logarithmic temperature dependence of the resistivity fits well the data. For resistivities below 80 μΩ cm, which

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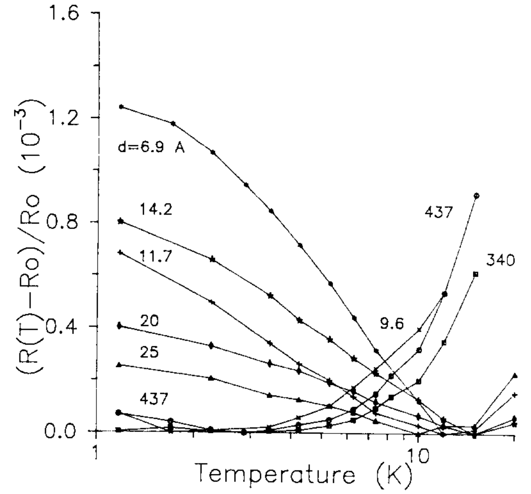

Fig. 1. Temperature dependence of relative change of the resistance for the Mo/Ni superlattice.

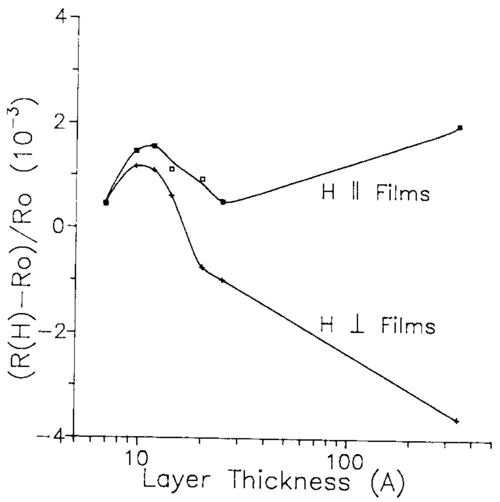

Fig. 2. Magnetoresistance of Mo/Ni superlattices as a function of layer thickness for both perpendicular (cross) and parallel (square) direction of the applied magnetic fields.

correspond to layer thicknesses larger than 11.7 Å, the slope $\partial(\Delta R/R_0)/\partial(\ln T/T_0)$ is roughly proportional to the resistivity as expected for a two-dimensional system (eq. (1)).

The MR is anisotropic and depends on field direction. The perpendicular MR$_\perp$ (i.e. H perpendicular to the layers and current) is negative and the parallel MR$_\parallel$ (i.e. H parallel to layers and perpendicular to current) is positive for the thicker layers. .The anisotropy becomes smaller as the layer thickness is decreased. Similar observations have been reported earlier for the Al/Ni system [8]. For the films with $d = 6.9$ Å, the MR is isotropic and positive as expected from the structural measurements which indicate the loss of the layered structure and formation of a disordered Mo/Ni mixture. Fig. 2 shows the saturation value of MR$_\perp$ and MR$_\parallel$ as a function of layer thickness. The parallel MR$_\parallel$ is always positive while the perpendicular MR$_\perp$ changes from negative to positive becoming equal to MR$_\perp$ for the thinnest layers.

Fig. 3 shows Hall voltage as a function of field for pure nickel and Mo/Ni superlattices with layer thicknesses between 6.9 Å and 2500 Å at 1.17 K. The Hall voltage increases with the applied magnetic field and saturates at higher fields for the films with layer thickness less than 25 Å. The Hall voltages for these films are all higher than that of pure nickel. The saturation voltage increases with increasing layer thickness and reaches a maximum at $d = 14.3$ Å as shown in Fig. 4. The anomalous part of the Hall resistivity can be written as $\rho_{\mathrm{Ha}} = (a\rho + b\rho^2)M_s$ where the first term represents skew scattering while the second accounts for the side-jump mechanism. Since the saturation magnetization is only weakly dependent on layer thickness for thicker layers [9], the resistivity dominates the thickness dependence of the anomalous Hall effect. Therefore, the anomalous Hall effect increases with decreasing thickness in this region. At low thicknesses the resistivity saturates, and the magnetization decreases strongly. As a consequence, the anomalous Hall voltage decreases below about 14.3 Å. Due to the increased scattering in the multilayers the anomalous

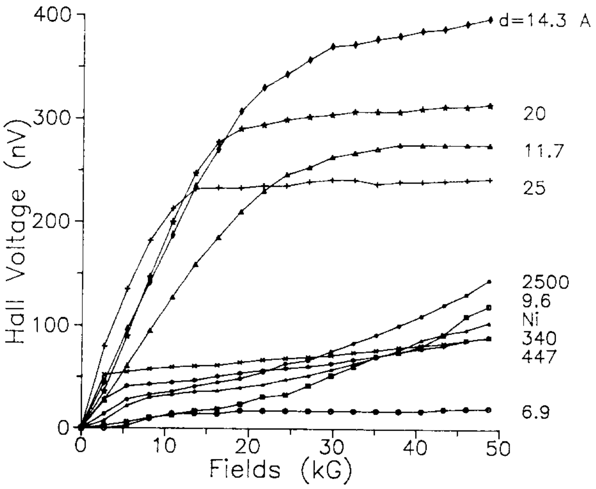

Fig. 3. Hall voltages of Mo/Ni superlattices and pure nickel as a function of applied magnetic fields.

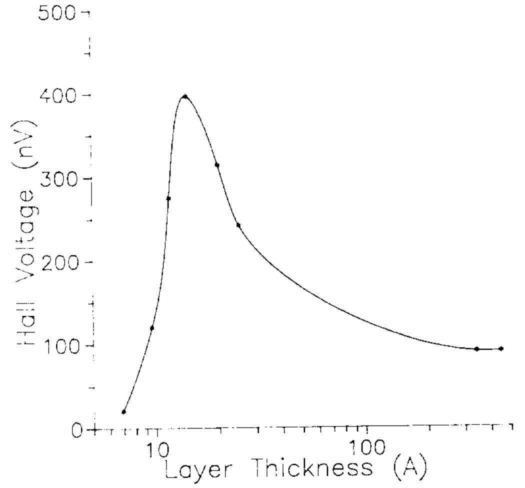

Fig. 4. Hall voltages taken at 50 kG, as a function of layer thickness for Mo/Ni superlattices.

Hall effect in multilayers is above that of single Ni films [10].

Conclusion

We have measured the electric resistivity, magnetoresistance, and Hall resistivity of the Mo/Ni superlattices for layer thicknesses from 6.9 to 2500 Å in the temperature range 1–300 K and magnetic fields up to 50 kG.

The experimental results show:

(1) Two-dimensional behavior including negative TCR, logarithmic temperature dependence, and negative perpendicular magnetoresistance appears in the low temperature range for short modulation wavelength superlattices.

(2) For the thinnest layer films, the two-dimensional behavior disappears (i.e. the temperature dependence of resistivity is no longer logarithmic, the MR becomes isotropic and positive). The system becomes a three-dimensional disorder system as expected from structural measurements. The dimensional crossover happens in the range of layer thickness around 10 Å.

(3) A peak is observed in the anomalous Hall voltage due to the changes of the resistivity and saturation magnetization as a function of layer thickness.

Acknowledgments: Work was supported by the national Science Foundation Grant No. NSF DMR 92-06198. International Travel was provided by NATO.

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