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[7] We define the resistivity ratio here as the ratio of the resistance at room temperature to that at 12 K.

[8] By this we mean a thin-film sample whose width (typically 1 mm) is sufficiently large that it should not be affected by localization.

[9] The resistance rise we observe is slightly larger than that reported by previous workers [L. R. Edwards, C. W. Chen, and S. Legvold, Solid State Commun. 8, 1403 (1970)]; however, our films have much higher resistivities than those studied by Edwards, Chen, and Legrold and this may affect the mechanism proposed by those workers. It is also possible that our films are exhibiting "two-dimensional" localization. However, the resistance increase does not appear to scale inversely with the sheet resistance as would be expected for this mechanism (Ref. 5).

[10] This result also indicates that the effect is independent of the length of the wire. Although the theory (Ref. 2) predicts that at low temperatures the resistance will vary exponentially with the length of the wire, this is expected to be observable only when the inelastic mean free path is longer than the wire, and this is not the case in our samples.

[11] Recent theoretical work by Abrahams *et al.* [E. Abrahams, P. W. Anderson, D. C. Licciardello, and T. V. Ramakrishnan, Phys. Rev. Lett. 42, 673 (1979)] predicts a logarithmic variation in the case of localization in two dimensions. However, in one dimension this theory appears to predict a temperature dependence which is identical to that given by Thouless (Ref. 2).

[12] The current-voltage characteristics of our samples were linear to within the experimental error at currents down to 5×10^{-10} A corresponding to an electric field strength of approximately 3×10^{-3} V/cm. These limits were set by our electronics.

[13] After this work was completed we have learned that P. Chaudhari and H.-U. Habermeier (to be published) have studied continuous wires made using a different method and have obtained results somewhat similar to ours.

Surface Magnetization of Ferromagnetic Ni(110): A Polarized Low-Energy Electron Diffraction Experiment

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The magnetic field dependence (hysteresis curve) and the temperature dependence of the magnetization at a Ni(110) surface was measured by polarized low-energy electron diffraction. The diffracted intensities are spin dependent by a few percent. The temperature dependence of the surface magnetization measured in the range $0.5<T/T_c<0.8$, is significantly different from that of the bulk.

The magnetic moments, and even the magnetic order at the surface of a ferromagnet, may be different from that of the bulk.[1-6] This is a result of the lack of translational invariance perpendicular to the surface and the reduced number of neighbors of surface atoms compared to the bulk. The surface magnetization, its temperature dependence, and the transition temperature at the surface have been described by a number of theoretical models using mean-field theory,[1,2] scaling theories,[3] and numerical techniques.[4] However, experimental determination of surface magnetization is difficult and there have been few tests of the models by measurements on well-characterized surfaces.[7,8]

In this work, we present the first measurements of polarized low-energy electron diffraction (PLEED) from a magnetic surface. We observe the average magnetization of the outer few layers of a Ni(110) single crystal, the hysteresis of this surface magnetization, and its temperature dependence, which is significantly different from that of the bulk in the range of our measurement, $0.5 < T/T_c < 0.8$. The sensitivity of the surface magnetization to surface contamination suggests that the surface layers are ferromagnetically active.

The important terms in the interaction Hamiltonian for polarized electrons incident on a ferromagnetic crystal are

$$H_{\text{int}} = \sum_i V(\vec{r} - \vec{r}_i) + \sum_i J(\vec{r} - \vec{r}_i)\vec{s} \cdot \vec{S}_i + H_{\text{s-o}}. \quad (1)$$

$V(\vec{r} - \vec{r}_i)$ is the Coulomb potential between an electron at $\vec{r}$ and an atom at $\vec{r}_i$. The exchange interaction is given by the second term, where $J(\vec{r} - \vec{r}_i)$ is the exchange potential, $\vec{s}$ is the spin of the incident electron, and $\vec{S}_i$ is the spin at the ith atom. The spin-orbit interaction, $H_{\text{s-o}}$, can be minimized by choosing the incident spin polarization to lie in the scattering plane.

If the thermal average elastic PLEED intensity is expressed in the first Born approximation,[9,10] we can write $S(\vec{K})$, the scattered intensity for $\vec{s}$ parallel to $\vec{S}_i$ minus that for $\vec{s}$ antiparallel to $\vec{S}_i$, normalized to the sum of the two intensities, as

$$S(\vec{K}) = \frac{\sum_{ij}[V_i(\vec{K})J_j^*(\vec{K})\langle S_j^z\rangle + V_j^*(\vec{K})J_i(\vec{K})\langle S_i^z\rangle]\exp B_{ij}}{\sum_{ij}[2V_i(\vec{K})V_j^*(\vec{K}) + (\frac{1}{2})J_i(\vec{K})J_j^*(\vec{K})\langle S_j^z S_j^z\rangle]\exp B_{ij}}, \quad (2)$$

where $B_{ij} = -i\vec{K} \cdot (\vec{r}_i - \vec{r}_j) - \frac{1}{2}\langle \vec{K} \cdot (\vec{u}_i - \vec{u}_j)\rangle^2$, $V(\vec{K})$ and $J(\vec{K})$ are Fourier transforms of the Coulomb and exchange potentials, $\vec{K}$ is the momentum transfer $\vec{k}' - \vec{k}$, $\vec{u}_i$ is the instantaneous displacement of the ith atom from its equilibrium position $\vec{r}_i$, $\langle S_i^z S_j^z\rangle$ is the spin-spin correlation function between atoms i and j, and $\hat{z}$ is in the direction of the magnetization $\vec{M}$. The exponential factor contains the familiar interference function due to the phase difference for scattering from different atoms and the Debye-Waller factor. The numerator, which is the interference between the Coulomb and exchange scattering, contains the magnetization per atom, $M_i^z = -g\mu_B\langle S_i^z\rangle$. The magnetization is averaged over the top few layers in our experiment since the electron mean free path[11] is 5 Å at 125 eV; the electron has a $1/e$ chance of scattering without energy loss as it penetrates and returns through two atomic layers. (S remains proportional to an average magnetization in the presence of multiple scattering although the weighting of the average may be different. A dynamical LEED calculation can in principle yield the layer-by-layer magnetization.)

Under the approximation that V_i, J_i, and S_i are the same for each atom, the exponential factor in Eq. (2) cancels exactly in the kinematic approximation. Then $S(\vec{K})$ can be expressed in the appealingly simple form derived by Saldaña and Helman,[12]

$$S(\vec{K}) = -J(\vec{K})M^z(T)/g\mu_B V(\vec{K}), \quad (3)$$

where the small term in the denominator of Eq. (2) which is of order $|J|^2 \ll |V|^2$ has been omitted in Eq. (3). It is interesting to note, however, that it is this small $|J|^2$ term proportional to the spin-spin correlation function that caused the fractional-order exchange scattering observed in the spin-averaged LEED measurements on antiferromagnetic NiO by Palmberg, DeWames, and Vredevoe.[13]

The PLEED measurements were performed on a thin Ni(110) crystal ($0.3 \times 5 \times 10$ mm^3) suspended by Ta rods so that it closed the magnetic circuit of a small c-shaped electromagnet, as shown in Fig. 1. The $[1\bar{1}1]$ direction of the surface, which is an easy magnetization direction, was chosen to be the magnetization axis and was oriented to lie in the scattering plane determined by the electron beam. The magneto-optic Kerr effect was used to determine the domain structure of the Ni crystal. Hysteresis curves indicated that the central region of the crystal consisted of a single magnetic domain (along the $[1\bar{1}1]$ direction) that could be reversed by reversing the applied field (~± 20 Oe). After repeated Ar$^+$-ion bombardment and annealing cycles, the crystal was well ordered and clean as determined by LEED and Auger analyses using a cylindrical mirror analyzer.

S is determined experimentally using a beam of spin-polarized electrons,[14,15] in which the polar-

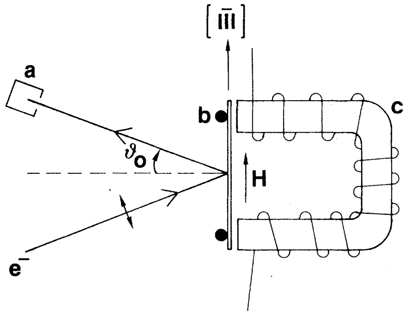

FIG. 1. The electron beam at an angle of incidence ϑ_0 is diffracted from the Ni(110) crystal into the Faraday cup (a). Ta rods (b) support the crystal which closes the magnetic circuit of the miniature electromagnet (c). The incident-electron spin polarization and the crystal magnetization lie in the scattering plane.

ization in the $\vec{z}$ direction can be modulated between $\pm P_0$. We measure the normalized difference S in the scattered intensity I, where

$$S(E,\theta)=\frac{1}{|P_0|}\frac{I(P_0)-I(-P_0)}{I(P_0)+I(-P_0)}. \qquad (4)$$

Positive P_0 corresponds to $\vec{s}$ parallel to $\vec{S}_i$. Measured in this way, S is independent of the magnitude[15] of P_0 and in general depends on the incident electron energy E and scattering angle θ.

Two types of experimental tests were performed to confirm magnetic scattering. One test was to measure a hysteresis curve and the other was to measure the temperature dependence of S. The results of these tests are presented in Figs. 2 and 3. The measurements presented here were made at an intensity maximum of the specularly reflected (00) beam at an angle of incidence $\vartheta_0 = 12°$ and energy of 125 eV.

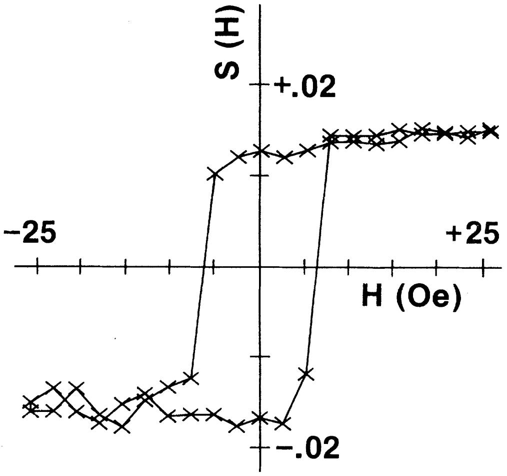

FIG. 2. A hysteresis curve, $S(H)$, at $E = 125$ eV and $\vartheta_0 = 12°$. The raw data points, which are connected by straight lines, were obtained between the $S(T)$ measurements (× and +) of Fig. 3.

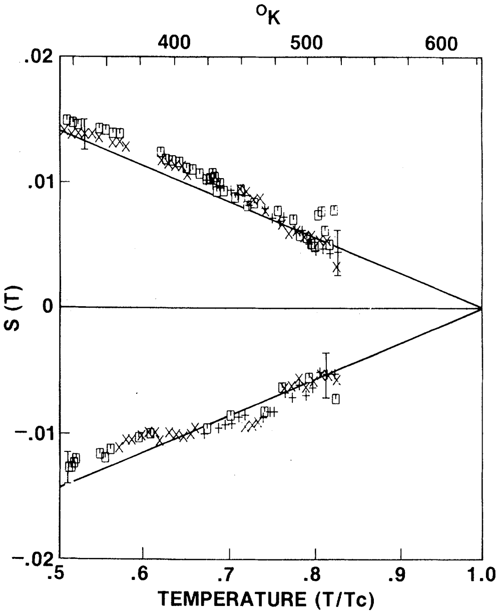

FIG. 3. The temperature dependence, $S(T)$, at $E = 125$ eV and $\vartheta_0 = 12°$ is shown in the range $0.5 < T/T_C < 0.8$. There is less curvature than in the bulk magnetization in this temperature range because of the surface sensitivity. The different points denote three different cooling curves for each applied field direction. The applied fields were (squares) 18 Oe, (pluses) 21 Oe, (crosses) 26 Oe. The estimated uncertainty is indicated by error bars at representative points. The straight lines represent a linear dependence of the magnetization to T_C (see text).

In Fig. 2 we show $S(H)$, the dependence on S on applied magnetic field.[16] As defined in Eqs. (2)–(4), the sign of S depends upon that of $J(\vec{K})/V(\vec{K})$, but is independent of the applied field direction. A positive S means that parallel spins scatter more strongly than antiparallel spins at that diffraction condition. In order to measure a hysteresis curve, we must establish a preferred direction in the laboratory, for example, to distinguish between $+H$ and $-H$; consequently, the negative value of S in Figs. 2 and 3 denotes the reversal of the magnetization in the laboratory frame. [A negative value of S, from Eqs. (2)–(4), gives a hysteresis curve reflected about the vertical axis.]

The coercive force (H at $S=0$) and the residual magnetization (S at $H=0$) depended on the thermal and magnetic history, and the crystal cleanliness. Measurements of $S(H)$ at different angles, energies, and maximum fields show no evidence of a depolarization of the incident beam due to precession of the polarization about a stray magnetic field. The behavior of $S(H)$ was extremely sensitive to sulfur contamination. At a sulfur (152 eV) to nickel (102 eV) Auger peak height ratio[17] $\simeq 0.3$, a hysteresis curve as in Fig. 2 could be obtained on the first cycling of H after cooling from above the Curie temperature, T_C, while at a sulfur level ten times higher the magnetization was greatly reduced. This suggests that the clean surface layer is ferromagnetically active as can be tested by future adsorbate studies.

We also found at $\vartheta_0 = 12°$ and $E = 20$ eV (just above the first Bragg peak) that S becomes negative and increases in magnitude to -0.04. This corresponds to a momentum transfer of 4.2 Å^{-1} for a single scattering event. Saldaña and Helman[14] used band-structure potentials in Eq. (3) to estimate $S(K)$ for Ni and predicted a negative S in this region.

As a second demonstration of magnetic scattering, the temperature dependence of S is shown in Fig. 3. In a typical run, the crystal was Joule heated to 580°C ($\sim 1.35 T_C$). The heater was then turned off and $S(T)$ was measured in an applied field H of 18, 21, of 26 Oe. The procedure was repeated with the applied field in the opposite direction to determine the true zero of S independent of any spurious offset. The temperature was measured indirectly by a thermocouple on a Ta support rod. [In an independent measurement under identical cooling conditions, the temperature at the crystal surface was measured with an infrared pyrometer thereby calibrating the thermocouple to the surface temperature within ± 10°C.]

The observed temperature dependence further demonstrates that the PLEED experiment is sensitive to the surface magnetization. In contrast to the large curvature of the bulk magnetization, S has a temperature dependence that, within experimental uncertainty, is approximately linear over the temperature range $0.5 < T/T_C < 0.8$. Note that the data in Fig. 3 are not inconsistent with a linear extrapolation to zero at T_C (as suggested by the straight lines). Calculations[2,4] indicate that the temperature dependence is expected to be different from that in the bulk and that a linear dependence is possible for the outer layer if J in that layer is less than that of the bulk. Future measurements will extend to T_C and to lower temperatures, where S can be normalized to the saturation magnetization.

In summary, we observe for the first time the surface magnetization of a ferromagnet using PLEED. We have measured surface hysteresis curves and the temperature dependence of the surface magnetization. The implication of these results is that PLEED may be used to probe surface magnetic properties in much the same way as neutron scattering has been used to study bulk magnetic properties.

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