

Magnetic Probing Depth in Spin-Polarized Secondary-Electron Spectroscopy

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We have studied the temperature dependence and the sensitivity to oxygen adsorption of the spin polarization of low-energy secondary electrons from Ni(110). Both types of measurements show a strong surface sensitivity, suggesting a mean magnetic probing depth of only three to four atomic layers, contrary to estimates based on the universal escape-depth curve.

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Since the first demonstration that secondary electrons from a ferromagnet are indeed spin polarized,¹ several detailed studies have revealed unexpected interesting features in the spin-polarization spectrum of low-energy secondary electrons from ferromagnetic materials. For instance, a strong enhancement of the spin polarization with respect to the average conduction-band magnetization seems to be common to all 3d ferromagnets (crystalline or amorphous) at very low secondary-electron energy ($\lesssim 10$ eV).²⁻⁶ The spin polarization above ~ 10 eV closely resembles the bulk spin polarization of the material.^{2,4,6} Crystalline materials show structures in the spin-polarization spectrum due to band-structure (LEED)⁷ effects which are absent for amorphous materials.^{3,5}

From a practical point of view the combination of secondary-electron spin-polarization analysis with primary excitation sources with high-spatial resolution (≈ 100 Å) has led to the important development of the "secondary-electron microscope with polarization analysis," which enables us to measure, e.g., the domain structure at a surface with unprecedented resolution.⁸

In this paper we address the question of the magnetic information depth of secondary electrons. According to the so-called universal curve⁹ a rather large escape depth of ~ 30 Å is expected for secondary electrons at zero kinetic energy so that the surface sensitivity would not be very high. No systematic studies have been performed so far. We investigate the surface sensitivity by measuring the temperature dependence of the secondary spin polarization from the clean Ni(110) surface and the influence of oxygen adsorption, and find a mean magnetic probing depth of only a few layers.

The experiments were performed in a new UHV system (base pressure 10^{-10} Torr) which allows the combination of various spin-polarized electron spectroscopies. The primary electron beam for the present measurement is derived from a commercial LEED system. The primary energy used was 800 eV. The electrons impinge upon the surface at grazing angles, while the secondary electrons were collected for close to normal emission (5° – 10°). A bias of -30 V was applied to the sample in order to suppress any stray electrons not origi-

nating from the sample. After passing through a hemispherical energy analyzer ($\Delta E = 300$ meV), the spin polarization is measured in a high-energy (100-kV) Mott detector.

Although this is not of primary concern for the present paper, we mention that attached to the main UHV chamber is a GaAs spin-polarized electron source, so that we can also use spin-polarized primary electron beams (see Fig. 1 for a schematic of the setup).

The sample is a Ni "picture frame" single crystal exposing the (110) surface, as shown in Fig. 1. The sample could be magnetized in the usual way by a current pulse through a coil wrapped around one of its legs. The sample could be heated by radiation from a W filament (up to above the Curie temperature) or by electron bombardment for high-temperature flashes. The temperature was measured by a NiCr/Ni thermocouple spot welded to the sample. The sample was cleaned by extended ion bombardment and heating cycles. Surface structure and cleanliness were monitored by LEED.

The spin polarization as a function of secondary-electron energy at low temperature shows the same features as previously published.¹⁰ Normalized $P(T)$ data, i.e., $P(T)/P_{\max}$, are shown in Fig. 2 for secondary-electron energies of 0 and 10 eV. For comparison we show the experimental bulk magnetization (curve labeled g). There are obviously quite strong deviations in the

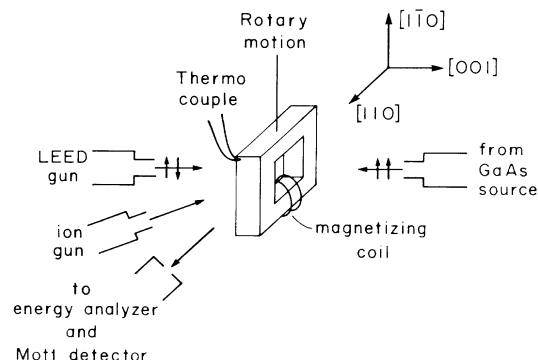


FIG. 1. Schematic of the experimental setup.

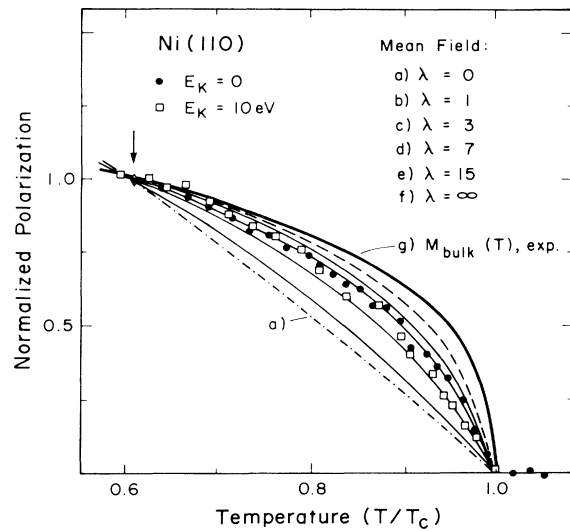


FIG. 2. Temperature dependence of secondary electrons at 0- and 10-eV kinetic energy (circles and squares, respectively). Also shown are calculations based on a layer-dependent mean-field calculation with different escape depths from $\lambda=0$ to $\lambda=\infty$ (see text for details). Curve g represents the experimental bulk magnetization curve. All curves are normalized to the same point at $T=0.6T_c$.

measured data from the bulk magnetization, indicative of the surface sensitivity. In order to get more quantitative information we performed model calculations within a layer-dependent mean-field (MF) theory. We calculated the layer-dependent magnetization $M_n(T)$ ($n=0$ is surface layer) for a 30-layer slab with no change in the surface coupling constants. The assumption that each layer emits polarized electrons according to its magnetization, and that the intensity originating from layer n is attenuated by the overlaying layers with an exponential factor $\exp(-n/\lambda)$, leads to

$$P_{MF}(T) = \alpha [\sum_n M_n(T) e^{-n/\lambda} / \sum_n e^{-n/\lambda}]$$

for the polarization. The constant α is needed in order to normalize the polarization to the experimental data. In Fig. 2 we show $P_{MF}(T)$ for several values of λ from $\lambda=0$, i.e., only the surface layer is contributing, to $\lambda=\infty$, which corresponds to the bulk magnetization in MF theory. The curve with $\lambda=7$ gives a perfect fit to the experimental data for zero energy. Within the accuracy of the measurements the 10-eV data are not significantly different. These findings are in contrast to expectations based on the universal curve. First, much lower surface sensitivity is expected for zero-energy secondaries ($\lambda \approx 30 \text{ \AA}$); second, the 10-eV secondaries should show significantly higher surface sensitivity ($\lambda \approx 10 \text{ \AA}$) than the zero-energy secondaries.

The good agreement between the calculation for $\lambda=7$ and the data only gives an upper limit for the escape depth, since the mean-field calculations underestimate

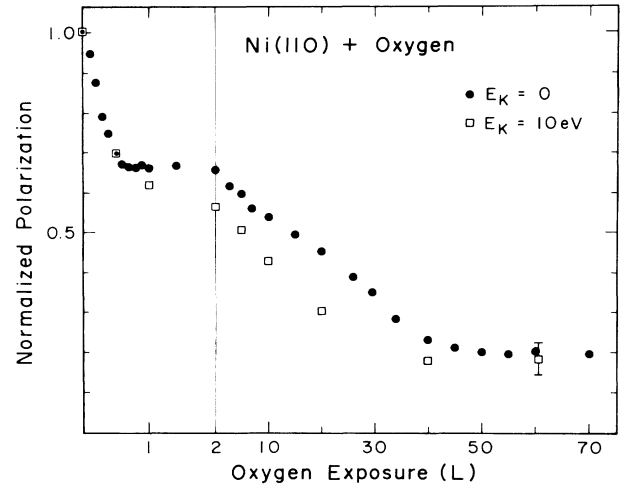


FIG. 3. Measured spin polarization of secondary electrons at 0- (dots) and 10-eV (squares) kinetic energy as a function of oxygen exposure ($1 \text{ L} \equiv 10^{-6} \text{ Torr sec}$). Note the change in exposure scale at 2 L.

the magnetization in the critical regime (see Fig. 2, curves f and g for the bulk deviations). If we assume that the relative errors of MF theory at the surface are of the same order as in the bulk ($\sim 10\%$ at $0.9T_c$, for instance), then all curves for the different λ 's in Fig. 2 have to be increased by this amount. We stress that this correction is not simply a uniform enhancement, but that it changes the shape of the curves, significantly enhancing the magnetizations only above $\approx 0.85T_c$. Taking this into account we arrive at the conclusion that a λ of only three to four layers is a more realistic value.¹¹

As another independent test of the surface sensitivity, we studied the effects of oxygen adsorption on the spin polarization. In Fig. 3 we show normalized-polarization curves as a function of oxygen exposure for 0- and 10-eV secondary-electron energy (these experiments were performed at $T \sim 0.6T_c$). We see that the decrease in polarization resembles the well-known oxygen adsorption kinetics: (1) A rapid decrease within the first langmuir of exposure corresponds to rapid adsorption leading to formation of a (2×1) structure (and surface reconstruction); (2) a plateau followed by a slower decrease, corresponding to NiO nucleation and growth phase, until the completion of two to three layers of NiO.¹² [Here 1 langmuir (L) $\equiv 10^{-6} \text{ Torr sec}$.] Again we try to extract some more quantitative information by employing a simple model: We assume that oxygen adsorption kills the ferromagnetism in a number of layers N (dead layers) and that the underlying Ni is unaffected. The measured spin polarization is then given by

$$P = P_0 e^{-N/\lambda},$$

where P_0 is the polarization of the clean surface. By our taking P/P_0 values from Fig. 3 for the (2×1) stage (be-

tween 1 and 2 L) and the final NiO stage (> 50 L), and assuming a λ of three to four layers then gives estimates on the number of dead layers. We arrive at $N \approx 2$ and $N \approx 5-6$, respectively. The value for the (2×1) phase, $N \approx 2$, is quite consistent with previous estimates based on the apparent reduction of exchange splitting in photoemission results.¹³ The number of five to six dead layers for the NiO phase certainly seems large, considering it is well established that only two to three layers of NiO exist. But we would not discard this possibility since there might well be small amounts of oxygen diffused into deeper layers, thus reducing the magnetization there.

Another cause for a decrease in spin polarization might be depolarization (exchange) scattering in the dead layers.¹⁴ Experiments by Meier, Pescia, and Baumberger and Hüner *et al.* on the spin polarization of optically oriented electrons in Ge, transmitted through thin overlayers of Ni, Gd, and Ce, show very strong depolarization.¹⁵ We checked this possibility by scattering a spin-polarized electron beam (from the GaAs source) off an oxidized Ni surface, and measuring the spin polarization of the elastically scattered electrons. Even at very low primary kinetic energy (as low as 2 eV) preliminary results did not show any significant depolarization (within 1% of the primary polarization).¹⁶ Therefore, we believe that depolarization in the NiO layer is not of great importance in reducing the polarization of secondaries in our data.

Finally, we mention one rather curious effect in our data. Ni changes its axis of easy magnetization from (111) to (110) at about 100°C. For our sample geometry at low temperature the spin polarization should be reduced by 20% if the magnetization breaks up into (111) oriented domains. There is no indication of this in the $P(T)$ data.

In summary, we have shown that the spin polarization of low-energy secondary electrons is very surface sensitive, in contrast to the prediction based on the universal escape-depth curve. The information depth is only about three to four layers (4–5 Å) and does not depend strongly on secondary energy. We believe that the increase in escape depth at low energies, according to the universal curve, is valid only for simple metals (e.g., Au, Ag, Al), but not for transition metals like Ni. For oxygen on Ni(110) we conclude that there are about two dead layers for the (2×1) structure ($\theta \approx 0.35$), and five to six dead layers for the completed NiO layer (two to three layers of NiO). We suggest that some oxygen is diffused deeper into the Ni reducing the magnetization in several more layers. A comparison to oxygen on Ni(100) would be very interesting since Ni(100) does not reconstruct upon oxygen adsorption. We believe that varying the secondary electron energy does not greatly influence the probing depth, but taking angle-dependent data will allow for at least a crude type of "magnetic depth profiling." The great surface sensitivity of the spin po-

larization of secondary electrons is a very welcome effect, allowing the application of this relatively simple technique to the study of novel thin-film systems or to the study of possible surface magnetism of paramagnetic materials.

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¹G. Chrobok and M. Hoffmann, Phys. Lett. **57A**, 257 (1976).

²E. Kisker, W. Gudat, and K. Schröder, Solid State Commun. **44**, 623 (1982).

³J. Unguris, D. T. Pierce, A. Galejs, and R. J. Celotta, Phys. Rev. Lett. **49**, 72 (1982).

⁴H. Hopster, R. Raue, E. Kisker, G. Güntherodt, and M. Campagna, Phys. Rev. Lett. **50**, 71 (1983).

⁵M. Landolt, in *Polarized Electrons in Surface Physics*, edited by R. Feder (World Scientific, Singapore, 1985).

⁶R. Allenspach, M. Taborrelli, and M. Landolt, Phys. Rev. Lett. **55**, 2599 (1985).

⁷E. Tamura and R. Feder, Phys. Rev. Lett. **57**, 759 (1986).

⁸K. Koike and K. Hayakawa, Appl. Phys. Lett. **45**, 585 (1984); J. Unguris, G. Hambree, R. J. Celotta, and D. T. Pierce, J. Magn. Magn. Mater. **54-57**, 1629 (1986); J. Kirschner, Appl. Phys. A **36**, 121 (1985).

⁹See, e.g., G. Ertl and J. Küpers, *Low Energy Electrons and Surface Chemistry* (Verlag Chemie, Weinheim, 1974).

¹⁰See Ref. 4. The measured maximum polarization is 24%, somewhat larger than previously reported. This may be due to better surface conditions or due to the fact that it is a different surface orientation.

¹¹An indication that the errors of MF for the surface magnetization are indeed comparable to the deviation in the bulk might be derived from the errors in critical exponents: 0.38 vs 0.5 in MF for the bulk, 0.8 vs 1 at the surface.

¹²See, e.g., P. H. Holloway, J. Vac. Sci. Technol. **18**, 653 (1981).

¹³W. Schmitt, H. Hopster, and G. Güntherodt, Phys. Rev. B **31**, 4035 (1985); R. Feder and H. Hopster, Solid State Commun. **55**, 1043 (1985).

¹⁴In a study of oxygen adsorption on Fe(100) (Ref. 6) the strong decrease in secondary-electron spin polarization was actually attributed to this effect.

¹⁵F. Meier, D. Pescia, and M. Baumberger, Phys. Rev. Lett. **49**, 747 (1982); S. Hüfner, G. L. Bona, F. Meier, and D. Pescia, Solid State Commun. **51**, 163 (1984).

¹⁶This surprising result will be the subject of a future detailed study. D. L. Abraham and H. Hopster, to be published.