Spin-polarized electron scattering from ferromagnetic Fe(110) films on W(110)

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Exchange scattering of spin-polarized electrons from a Fe(110) surface was observed using epitaxial Fe(110) films of less than 80 atomic layers, prepared on a W(110) ribbon. The Fe films could be magnetized along the easy axis [001] by current pulses, using the W ribbon as a strip line. Because stray fields can be neglected for these extremely thin films, they remained in a saturated remanent state in which they were analyzed by electron scattering. As the direction of magnetization coincided with the primary beam polarization, and with the normal of the scattering plane, exchange and spin-orbit-coupling contributions to the scattering asymmetry, respectively, A_{ex} and A_{so}, could be determined separately, by separate reversal of primary beam polarization and magnetization. A maximum value of $A_{ex}=(34\pm10)\%$ was measured for specular reflection in the (100) plane with an angle of incidence of 31°, for electron energies of 46 eV.

A fundamental problem both of magnetism and surface physics is given by the modification of magnetic order near the surface of a ferromagnetic crystal. The problem has attracted considerable attention for many years (Ref. 1 and references given there). In particular, the discussion was stimulated very much by the challenging idea of magnetic "dead layers," introduced by Liebermann.[2] However, although several modern and valuable experimental methods are available in the field, such as spin-polarized electron photoemission,[3] electron capture spectroscopy,[4] Mössbauer spectroscopy,[5] ferromagnetic resonance,[6] anomalous Hall effect,[7] and magnetometry with oligatomic films,[1] there persists considerable lack of reliable quantitative knowledge in surface magnetism. In particular, the local variation of the spontaneous magnetization near clean surfaces of three-dimensional (3D) ferromagnetic persists as a controversial subject. Whereas there is agreement that literally dead layers[2] do not exist at the clean surface of Ni, Co, and Fe,[1] different band calculations for the Ni(100) surface result in an increase[8] or a decrease[9] of the magnetization in the topmost layer; an experimental decision is not yet possible.

One of the most promising probes of surface magnetism is provided by exchange scattering of spin-polarized electrons from ferromagnetic surfaces, which has been discussed theoretically be Feder[10–12] for many years and has been realized for the first time by Celotta *et al.*[13] for the case of Ni(110). In addition, extended studies of surface magnetism in Ni(100) have recently been given by Alvarado and co-workers[14,15]; in particular, the dependence of surface magnetization on temperature could be measured in the critical range near the Curie temperature.[14] The problem of the ground-state surface magnetization, however, which can be solved in principle by spin-polarized electron diffraction in combination with spin-dependent dynamical low-energy electron diffraction (LEED) calculations,[16] remains to be solved.

Fe surfaces are of special interest, in particular because there are predictions of strong, Friedel-type oscillations of the magnetization near the Fe surface,[9] and because one expects strong polarization effects[10–12] as a result of the high spontaneous magnetization of Fe. However, spin-polarized electron scattering experiments are not yet available for Fe surfaces. The first experiments of this type are reported in the present paper, for the case of clean Fe(110) surfaces.

One characteristic problem in electron scattering from ferromagnetic surfaces is to avoid magnetic stray fields near the sample, which at the same time must be in a magnetically saturated state, of course; note that strong exchange polarization is expected only for electron energies below about 100 eV, where the electron paths react very sensitively on magnetic fields. This stray field problem was solved for the case of Ni (Refs. 13–15) by including the single-crystal target in a closed ferromagnetic circuit. We used another approach by preparing the Fe crystal as a thin film consisting of less than 80 atomic layers, prepared by epitaxial growth on W(110). Because magnetic stray fields can be neglected for these extremely thin films, they remain in a magnetically saturated remanent state after switching off the magnetizing field, if they have been magnetized before along the easy axis [100].

An interesting aspect of this experimental approach is the connection with modern band calculations,[8,9] which were done for single-crystal films consisting of only a few atomic layers.

Single-crystal films of Fe(100) were prepared by epitaxial growth on W(100) in UHV at $T=470$ K. Details of growth and structure of these epitaxial

films were studied in a previous paper.[17] The base pressure of the system was given by 1.2×10^{-8} Pa; it increased to 1.0×10^{-7} Pa during preparation of the Fe films. The films were tested by LEED and Auger electron spectroscopy (AES) in the usual way. Frank van der Merwe (layer by layer) growth could be established by AES. The parallel orientation of Fe(110) and W(110) was shown by LEED. In addition, periodic lattice distortions could be detected by LEED in the thickness range below 10 atomic layers. Their amplitude decreased exponentially with the film thickness. Therefore, they can be neglected on top of the films used for the exchange scattering experiments, which consisted of about 35 atomic layers.

The W(110) substrate was provided by a W ribbon, about 0.17 mm thick, which could be heated to 2200 K by direct current transition along $[1\bar{1}0]$ in order to clean the crystal. In addition, the W ribbon could be used as a strip line for magnetizing the epitaxial Fe film on top of it. Current pulses of up to 180 A provided magnetizing fields of up to 20 000 A/m (251 Oe) along the easy Fe [001] axis. The squareness of the hysteresis loop (remanent magnetization equals saturation) was confirmed both by magnetometry in a high sensitivity torsion magnetometer[18] and by spin-polarized electron scattering *in situ* as described elsewhere.

Spin-polarized electrons were taken from a $GaAs_{0.62}P_{0.38}$ source,[19] irradiated by circularly polarized light from a 5-mW He-Ne laser. The polarization could be modulated using a Pockels cell. The electrons were electrostatically deflected by 90° in the electron optical system, resulting in a transversally polarized electron beam of about 0.5 μA at the target.

Electron energies E were measured with respect to the Fermi level of the target; to get the kinetic energy in vacuum near the surface, they must be reduced by the work function of the target.

The direction of electron polarization $\vec{P}_0$ (defined as direction of majority electron angular momentum) was parallel to the normal of the scattering plane (SP), $\vec{n}=(\vec{k}_0\times\vec{k})/|(\vec{k}_0\times\vec{k})|$; $\vec{k}_0$ and $\vec{k}$ are wave vectors of incident and of scattered electrons. The electrons were detected by a movable Faraday cup. The difference (I_+-I_-) of reflected intensities, I_+ for $\vec{P}_0\cdot\vec{n}>0$ and I_- for $\vec{P}_0\cdot\vec{n}<0$, was measured using standard lock-in techniques. The mean reflected intensity $I=\frac{1}{2}(I_++I_-)$ was measured by an electrometer.

A Mott detector was not available in the present work. Therefore, the polarization P_0 of the source had to be determined by SP LEED from a clean W surface, as has been done previously, for example, by Pierce *et al.*[20] using W(100) as a standard surface. In our case, a W(110) surface was available. On principle, W(110) seems to be superior to W(100) as a standard surface, because W(100) tends to reconstruct, whereas W(110) is stable. However, to our knowledge all SP LEED measurements on W have been done for W(100); we could not find any SP LEED data on W(110). Therefore, we could only estimate P_0, by including the first SP LEED measurements on W(100) in our work. This was done in the following way: From direct intensity measurements in the reflected beam, we get $(I_+-I_-)/(I_++I_-)$, which is connected with P_0 and the scattering asymmetry A of the target by[21]

$$P_0A=(I_+-I_-)/(I_++I_-)\ . \tag{1}$$

Both $(I_+-I_-)/(I_++I_-)$ and I are shown in Fig. 1 for specular reflection from W(110) in a (001) scattering plane, with an angle of incidence of $\theta=15°$, for electron energies between 30 and 130 eV. The maximum value of $(I_+-I_-)/(I_++I_-)$ at 86 eV is given by 15.5%. For the case of W(100), the maximum scattering asymmetry was reported as $A_{\max}=80\%$.[22] As we hardly can expect higher asymmetries for W(110), we assumed $A<80\%$ for our case, resulting in $P_0>19.4\%$. On the other side, typical values of P_0 measured for the GaAsP-He-Ne source, at room temperature, were published as $(35\pm3)\%$.[19] Lower values were found, however, by several groups.[23] With the use of all these data we could estimate the polarization of our primary beam

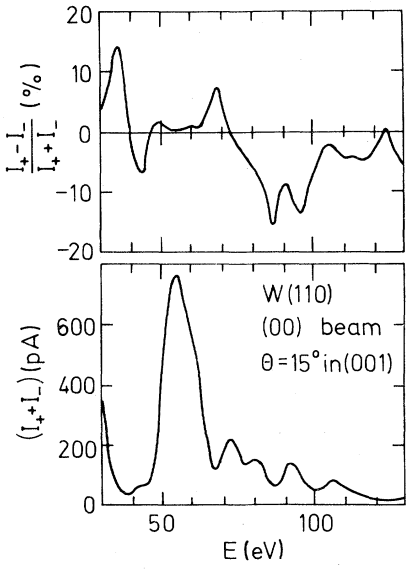

FIG. 1. Spin-dependent specular reflection of a transversally polarized electron beam from W(110), with $\theta=15°$ in the (001) plane, measured at $T=300$ K in $p=1.2\times10^{-8}$ Pa, 5 min after flashing. I_+ and I_- are reflected electron currents for primary beam polarization $\vec{P}_0$ (direction of majority electron angular moment), respectively, parallel and antiparallel to the normal of the scattering plane, $\vec{n}=(\vec{k}_0\times\vec{k})/|(\vec{k}_0\times\vec{k})|$; electron energy E with respect to the Fermi level of the target.

as $P_0 = 28\%$, with a maximum error of $\pm 8\%$ for the absolute value. From the reproducability of our measurements, we conclude that the stability of P_0 is better than $\pm 1\%$.

For the magnetic case of Fe(110), our geometry is characterized by the coincidence of the magnetic easy axis [001] with the normal $\vec{n}$ of the scattering plane, which in turn is parallel (or antiparallel) to the polarization $\vec{P}_0$ of the primary beam. Because the quantization axis of both exchange and spin-orbit coupling coincides with the axis of polarization, the separation of exchange and spin-orbit effects becomes easy in this geometry. This has been shown recently in detail by Alvarado *et al.*,[15] who used the same geometry for magnetic SP LEED on Ni(100).

Following roughly the discussion given there and removing some unclarity in sign of A, we argue in the following way: As the magnetization $\vec{M}$ can be either parallel or antiparallel to the scattering normal $\vec{n}$, we may characterize the state of magnetization by $\mu \equiv -\mathrm{sgn}(\vec{M} \cdot \vec{n})$. In taking the negative sign, we refer to the spin of the majority electrons instead of their magnetic moment, in accordance with common use in nonmagnetic SP LEED. In the real experiment, we measure scattering asymmetries A^{μ} for both positive and negative μ, which are connected with reflected intensities I_{σ}^{μ} ($\sigma = \mathrm{sgn}\,\vec{P}_0 \cdot \vec{n}$) by

$$P_0 A^{\mu} = (I_{+}^{\mu} - I_{-}^{\mu})/(I_{+}^{\mu} + I_{-}^{\mu}) \quad . \tag{2}$$

To separate exchange and spin-orbit effects, let us discuss at first the case of vanishing spin-orbit coupling. The intensity then depends only on the orientation of $\vec{P}_0$ to $\vec{M}$. Therefore, we get $I_{+}^{+} = I_{-}^{-}$ and $I_{+}^{-} = I_{-}^{+}$. As a consequence, $A^{+} = -A^{-}$ and the exchange-only asymmetry A_{ex} is given in this case by

$$A_{\mathrm{ex}} = \tfrac{1}{2}(A^{+} - A^{-}) \quad . \tag{3}$$

Alternatively, for the case of vanishing exchange coupling, the intensity depends only on the orientation of $\vec{P}_0$ to $\vec{n}$. Therefore, we get $I^{+} = I^{-}$ and the spin-orbit-only asymmetry A_{so} is given in this case by

$$A_{\mathrm{so}} = \tfrac{1}{2}(A^{+} + A^{-}) \quad . \tag{4}$$

Evidently, Eqs. (3) and (4) must remain as approximations if the alternative coupling is gradually switched on. It has been shown by Alvarado *et al.*[15] that the theoretical asymmetries A_{ex} and A_{so}, which result from switching off the other interaction, are connected with the experimental asymmetries A^{μ} by

$$A_{\mathrm{ex}} = \tfrac{1}{2}(A^{+} - A^{-}) + \delta\tfrac{1}{2}(A^{+} + A^{-}) \tag{3a}$$

and

$$A_{\mathrm{so}} = \tfrac{1}{2}(A^{+} + A^{-}) + \delta\tfrac{1}{2}(A^{+} - A^{-}) \quad , \tag{4a}$$

where δ is of the order of $A_{\mathrm{ex}} A_{\mathrm{so}}$, which in turn is of the order of 1% or below in our case. We therefore neglect the weak interference correction given by δ and use the approximate Eqs. (3) and (4) in the following discussion.

Extended measurements were done of $A^{\mathrm{rem}}(0) \equiv A^{\mu}$ in the remanent state after applications of a high magnetizing field, at room temperature, for several Fe(110) films in the thickness range between 34 and 79 monolayers. No significant dependence on film thickness could be detected in this range. A_{ex} and A_{so} were determined using Eqs. (3) and (4). Results are shown in Fig. 2 for a film consisting of 34.4 atomic layers.

The spin-orbit contribution A_{so} of the stray asymmetry is of the order of 1% with peak values of the order of 3%. This is by a factor of 2 or 3 less than what Alvarado *et al.*[15] found for the case of Ni(100). There is no explanation, at the moment, for this astonishingly low value of A_{so}.

The exchange contribution A_{ex}, however, is strongly enhanced in comparison with Ni. In the present

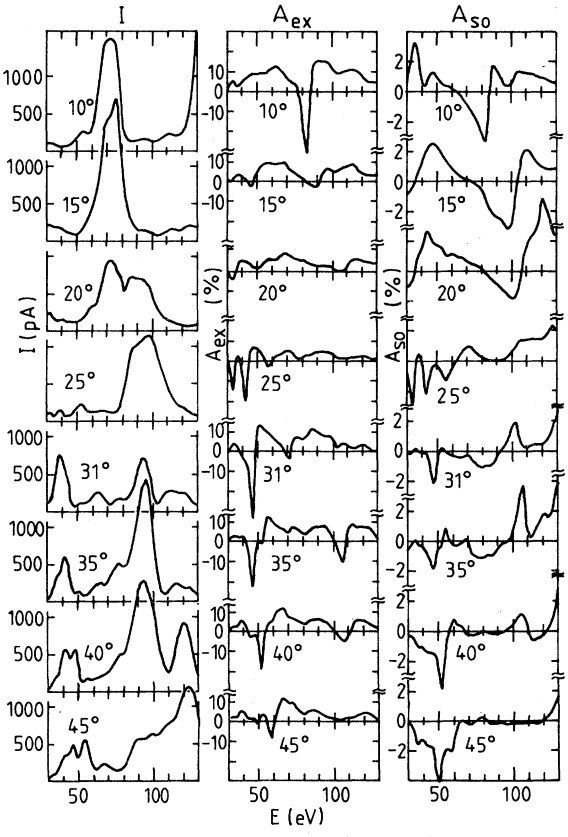

FIG. 2. Spin-polarized electron scattering for specular reflection from a 34.4 atomic layers Fe(110) film on W(110), in the (100) plane. Intensity I and exchange contribution and spin-orbit contribution, respectively, A_{ex} and A_{so} of the scattering asymmetry are given as a function of the electron energy E, for different angles of incidence, θ. Note the different scale of A_{ex} and A_{so}, respectively. Electron energies E with respect to the Fermi level of the target.

energy range between 30 and 130 eV, A_{ex}(Fe(110)) is of the order of 7%, with a maximum value of $(34 \pm 10)\%$ at $\theta = 31°$ and $E = 46$ eV. For comparison, A_{ex}(Ni(100)) is of the order of 1% with a maximum below 2%, in this energy range; however, a sharp maximum of $A_{ex} = 10\%$ was found for Ni(100) for a lower energy of 15 eV, which is not accessible, at the moment, for our measurements. Of course, the enhanced amount of A_{ex} results from the increased spontaneous magnetization $[M(\text{Fe})/M(\text{Ni}) = 3.8]$.

Unfortunately, quantitative comparison with the calculations of Feder[12] for Fe(110) is not possible, because Feder used (110) as scattering plane. However, the order of magnitude of A_{ex} is in accordance with Feder's calculations.

In comparison with corresponding calculations, which can be expected in the near future, the present measurements form a first step for an analysis of surface magnetization structure in iron.

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