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ELECTRON CAPTURE AND EMISSION SPECTROSCOPY TO STUDY SURFACE AND INTERFACE MAGNETISM

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Abstract

Electron capture spectroscopy (ECS) and spin-polarized electron emission spectroscopy (SPEES) are extremely sensitive techniques to probe surface magnetic properties. Ultra-thin bct Fe(100)(1x1)/Pd(100) films exhibit 2D Ising critical behavior. The surface electron spin polarization (ESP) follows precisely the exact solution of the 2D Ising model as given by Yang. The average magnetization of the topmost surface layer is enhanced by 32% compared to that of bulk layers. Pd Auger electrons emitted from the Fe/Pd interface are spin-polarized, and the ESP is oriented parallel to that of emitted Fe Auger electrons . At surfaces of 5nm thick hcp Tb(0001)/W(110) films, strong surface magnetic surface anisotropies are found. The onset of ferromagnetism occurs ≈30 K above the bulk Curie temperature (220K) of Tb. For clean Fe and Fe/Pd surfaces, the ESP of low-energy (≈2 eV) emitted electrons is substantially enhanced by Stoner excitations. The existence of a nonzero ESP at O/Fe surfaces demonstrates the absence of a magnetically dead surface layer.

1. Introduction

At present, magnetic phenomena at surfaces, interfaces and in thin films receive great attention. This arises from the fact that magnetic materials serve as nearly ideal systems to explore basic concepts in theoretical physics such as phase transitions and critical behavior of thermodynamic quantities in two or three dimensions. Phase transitions at magnetic surfaces are much more diverse than those that occur in the bulk which is mainly due to various anisotropies associated to the material, its lattice structure, and to the presence of the surface itself. It is well known

that surface anisotropies are of paramount importance in determining the magnetic properties of surfaces (Selzer and Majlis, 1983) and thin films (Gay and Richter, 1986; Jonker et al., 1986).

This intense and broad scientific interest also stems from the fact that the development of new electronic and magnetic devices of dimensions in the submicron region requires a fundamental understanding of topmost surface and interface layer electronic properties of magnetic materials and systems to be used in these new devices.

Particle (atoms, ions)-surface scattering experiments provide a powerful means to study the topmost surface-layer electronic and magnetic properties of magnetic materials. In first electron capture spectroscopy (ECS) experiments, it was shown that fast ions can be grazing-angle surface reflected (surface channeled) such that the ions do not penetrate the topmost surface layer (Rau and Sizmann, 1973). This can be achieved by keeping the energy component $E_{\perp}$ of the incident particles (atoms, ions) normal to the probed surface below 10- 20 eV which prevents the penetration of the particles into the surface and, therefore, causes the particles to probe solely the topmost surface layer. This simple fact reveals the extreme surface sensitivity of experimental methods where particle-surface interaction is used to retrieve data on the physical properties of surfaces.

Contrary to spectroscopies such as UV- or X-ray-photoelectron spectroscopy which provide an excellent k-space sensitivity, particle-based techniques provide an extreme real-space sensitivity (Dunning et al.,1985). Photo-electrons or electron-induced secondary electrons emitted from the topmost surface layer are often difficult to distinguish from those that originate in subsurface and deeper layers. Often the emitted electrons originate up to 5 or more layers beneath the surface. Although this probing depth is relatively small, mainly bulk properties will be detected because the electronic structure becomes that characteristic of the bulk within a few atomic layers of the surface (Dunning et al., 1985, Fu et al., 1985, Rau and Eckl, 1980a, Rau, 1980b, Rau, 1982).

Among several extremely surface-sensitive spectroscopies, electron capture spectroscopy (ECS) and spin-polarized electron emission spectroscopy (SPEES), which utilize capture and emission of spin-polarized electrons during grazing-angle surface reflection of fast ions at magnetic surfaces, have shown to provide a powerful means to study the two-dimensional (2D) magnetic properties (critical behavior, element-specific ferromagnetic order, magnetic anisotropies, etc.) of surfaces of ultra-thin films and of bulk materials with unprecedented surface sensitivity (Rau, 1989, Rau et al., 1990).

Despite many breakthroughs in the interpretation of surface-related experimental data obtained using various surface-sensitive spectroscopies (ECS) (Rau,

1982), (SPEES) (Rau et al., 1990), spin-polarized metastable-He de-excitation spectroscopy (SPMDS) (Hammond et al., 1992) and ion neutralization spectroscopy (INS) (Hagstrum, 1966, Zeijlmans Van Emmichoven et al., 1988) at surfaces of magnetic and nonmagnetic materials, there is still no complete and fundamental understanding of how these data are linked to the local surface electronic band structure of these materials. The unraveling of the physical processes involved in the above mentioned spectroscopies is not only of broad theoretical interest, it can also greatly enhance the power and applicability of these techniques.

In this paper, we report, using ECS, on the surface magnetic properties of 2 monolayer (ML) thin bct Fe(100)p(1x1) films which are epitaxially deposited on atomically clean and flat Pd(100) substrates (Rau et al., 1993). The films order ferromagnetically at low temperatures, a fact which already indicates the presence of magnetic anisotropies (Malyshev, 1975, Bander and Mills, 1988). Next, it is found, that for reduced temperatures $t = (T_{Cs} - T)/T_{Cs}$ being within a few percent close to 1, the magnetization of the topmost surface layer behaves like $(T_{Cs} - T)^{\beta}$, with $\beta = 0.125 \pm 0.01$ in excellent agreement with the exact result for the 2D Ising model for T very close to T_{Cs} . Most important, we find that the temperature dependence of the surface electron spin polarization (ESP) for t ranging from 0.5 to 1.0 follows precisely the exact solution of the 2D Ising model as given by Yang (1952). We note that, above T_{Cs}, there are no rounding-off effects of the surface ESP, a fact which points towards the high quality of the deposited films.

Using ECS, we report on the surface magnetic properties of thin (5 nm) films of hcp Tb(0001) epitaxially deposited on atomically clean and flat bcc W(110) substrates Rau et al., 1989). It is found that the topmost Tb-layer orders ferromagnetically at a surface Curie temperature T_{Cs} =249.96 K, which lies above both the bulk Curie and Néel temperatures T_{Cb} =220 K and T_{Nb} = 228 K, respectively. In striking contrast to all earlier studies on other systems, the magnetization of the topmost Tb layer is found to vary in a strongly non-monotonic fashion close to 240K. Near T_{Cs}, novel critical behavior is observed suggesting strong surface anisotropies, in accord with a recently predicted anisotropic special surface phase transition.

Using SPEES, we have studied the angle-resolved energy distribution of spin-polarized electrons emitted during ion-surface scattering at Fe surfaces. At clean Fe surfaces, ESP values of up to 48% are found (Rau et al., 1993). Varying, for 25 keV Ne^+ ions, the scattering angle from 1^o to 45^o, and thereby varying the probing depth of SPEES, we find that the layer-dependent, average ESP at the topmost surface layer is enhanced by 32% compared to that of the bulk and that the mean free path of electrons with energy 4-10 eV is about 3 atomic distances. The absence of a magnetically dead layer at Fe surfaces covered with one monolayer of O is revealed by the existence of a nonzero surface ESP.

We report on SPEES studies performed at surfaces and interfaces of 1 - 4 ML Fe(100)p(1x1)/Pd(100) thin films. Changing the scattering angle of the ions, or the probing depth from the topmost surface layer to deeper layers, we find that the average electron spin polarization (ESP) at the topmost surface layer amounts to 37%, an enhancement of 32% as compared to that of the bulk (28%) (Lu et al., 1993). We observe that Pd(MVV) Auger electrons emitted from interfaces are spin polarized and the ESP is oriented parallel to that of Fe(MVV) Auger electrons.

2. Experimental

Here, we give a brief discussion of ECS and SPEES. For further details, we refer to Rau (1982) and Rau et al (1990). ECS allows us to study long-ranged and short-ranged ferromagnetic order at surfaces of magnetic materials (Rau, 1982, Rau and Eichner, 1981). The physical process in ECS is the capture of one or two spin-polarized electrons during small-angle surface reflection of fast ions. For 150 keV deuterons and for an angle of incidence of 0.2^0 of the ions, the distance of closest approach of the ions to the reflecting surface amounts to about .1nm (see Fig.1. full line). Therefore, the ions solely probe spin-polarized local electron densities of state at the topmost surface layer.

For the measurement of long-ranged surface ferromagnetic order, we exploit one electron capture processes ($D^+ + e^- = D^0$) and determine the spin polarization of the captured electrons. Details about the detection of long-ranged ferromagnetic order are discussed by Rau (1982).

For the measurement of short-ranged ferromagnetic order, we use 25 keV or 100-150 keV protons or deuterons and study two-electron capture processes ($H^+ + 2e^- = H^-$ or $D^+ + 2e^- = D^-$)(10). The only stable bound state of H^- or D^- is the $1s^2\ ^1S$ state. Therefore, stable H^- or D^- ions can only be formed by capture of two electrons possessing oppositely oriented spins. For the ion energy range noted above, the length within which 2 electrons are captured by a single ion, amounts to about .5-2 nm. Thus, two electron capture processes are sensitive to short-ranged ferromagnetic order existing within a range of a few atomic neighbors. It is obvious that two electron capture will be strongly suppressed by the presence of short-ranged ferromagnetic order where predominantly electrons with parallel oriented spins are available for capture by a single ion. The reduction in the H^-/H^+ or D^-/D^+ ratio measured after beam reflection at the surface of a magnetic sample, relative to that for a nonmagnetic target, such as Cu, provides a direct measure of the short-ranged ESP at a magnetic surface.

In angle- and energy-resolved, spin-polarized electron emission spectroscopy (SPEES), we use small angle surface scattering of energetic (5 - 150 keV ions (H^+, He^+ or Ne^+) to study the emission of spin-polarized electrons as a measure of long-

ranged, surface ferromagnetic order. Fig.1 illustrates ion trajectories for various scattering angles, the emission of ion-induced electrons and the surface potential plotted on a plane perpendicular to the reflecting surface. Varying the scattering angle $\propto$ from 0.2^{o} up to 45^{0} allows us to vary the *probing depth* of the incident ions from the topmost surface layer to interface and deeper layers. The distance d_{min} of closest approach of the ions towards a surface is well characterized by the energy component $E_{\perp}$ of the ions normal to the surface, $E_{\perp} = E_{o}\sin^{2}\propto \approx E_{0}\propto^{2}$. For E_{o}=25 keV and $\propto = 1^{o}$, $E_{\perp}$ amounts to 7.6 eV. Using appropriate planar surface potentials (see Fig.9 in Rau, 1982), d_{min} amounts to approximately 0.1 nm for $\propto = 1^{o}$ which reveals that under these experimental conditions ions cannot penetrate surfaces such as Ni, Fe or Tb and

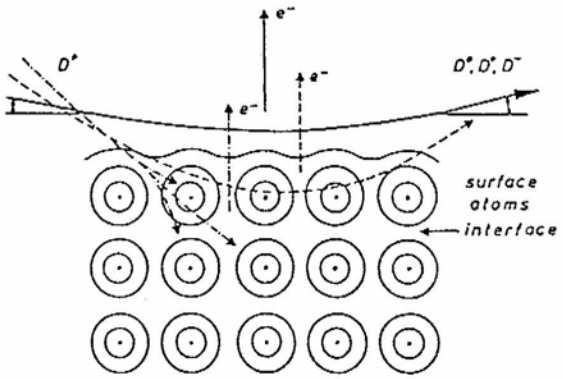

Fig. 1. Scheme illustrating ion trajectories for various scattering angles, the emission of ion-induced electrons and the surface potential plotted on a plane perpendicular to the reflecting surface.

are specularly reflected thereby causing the excitation of electrons solely to occur at the surface layer. We note, however, that, for $E_{\perp} \geq$ 10-20 eV - the exact value for $E_{\perp}$ depending on the specific (hkl) surface orientation and on the material - the ions are able to penetrate the surfaces and induce the emission of electrons from interface and deeper layers.

Using an einzellens system, we detect electrons emitted along the surface normal (emission cone angle 8^{o}) of a nonmagnetic or remanently magnetized ferromagnetic target. For energy analysis, an electrostatic energy analyzer (energy resolution: 300 meV) is used. For spin analysis, using a second einzellens system, the energy-analyzed electrons are accelerated into an ESP detector. In this ESP detector, the electron beam is precisely focused on a Au target. The count ratio N_{A}/N_{B} of electrons elastically backscattered in two channeltrons A and B, positioned at $\theta = 135^{o}$ to the

incoming beam direction, provides a direct measure of the ESP whereas the sum of the count rates N_A+N_B provides a measure of the total intensity N(E) of the emitted electrons. We note that N(E) can also be directly measured by replacing the ESP detector by a single channeltron and recording directly the intensity N(E). For zero ESP calibration, the Au target is replaced by an Al target. Further zero ESP calibration can be performed by using non-magnetic samples for the ion-surface reflection or by heating ferromagnetic targets above the Curie temperature where only non-polarized electrons are emitted. The component of the ESP, P, along the direction of magnetization of the ferromagnetic target is given by $P = S(\theta)^{-1}(N_A-N_B)/N_A+N_B)$, where $S(\theta)$ is the Sherman function. We note that the ESP is also defined by $P = (n^+ - n^-)/(n^+ + n^-)$ with n^+ and n^- being the numbers of majority- and minority-spin electrons (Rau, 1982). $P>0$, therefore, is related to a predominance of majority-spin electrons (ESP parallel to the total magnetization), and $P<0$ refers to a predominance of minority-spin electrons (ESP antiparallel to the total magnetization).

The samples are prepared and characterized in a target preparation chamber operating at $1x10^{-10}$ mbar and then transferred to the measuring chamber operating at a base pressure in the 10^{-11} mbar region (Rau, 1982). For the deposition of thin magnetic films, atomically clean and flat substrate crystals are prepared in our target preparation chamber. The surface orientation of the substrate crystals is better than 0.01^o, and is monitored by use of a precision X-ray diffractometer. The flatness of the substrate surfaces on an atomic scale is achieved by thermal surface smoothening (Rau, 1982) and is characterized by using grazing-angle ion reflection (Rau and Sizmann, 1973, Rau, 1982) of highly collimated (angle of divergence $< 0.0^o$) 150 keV deuterons at the substrate surface. The ion reflectivity I (reflected beam intensity per solid angle/ incoming beam intensity per solid angle), which is extremely sensitive to the existence of atomic steps, amounts to 95 %, clearly establishing the atomic flatness of the substrate surfaces. From our work on the atomic flatness of surfaces of single crystalline substrates using a scanning tunneling microscope (STM), which reveals that our surfaces are atomically flat within 150- 200 nm along the surface, there is direct evidence that the ion reflectivity I is strongly correlated to the presence of atomic steps as was already indicated in the past by our computer simulations on the intensity and energy distribution of ions in surface and subsurface channeling (Rau, 1982).

Applying standard cleaning and annealing procedures, developed in our earlier studies, and using Auger-electron spectroscopy with a cylindrical-mirror analyzer, residual C and O contaminations are measured to be less than 1% of a monolayer. The single crystalline state of the substrate and film surfaces is detected by low-energy electron diffraction (LEED) and reflection high-energy electron diffraction (RHEED).

Ultra-thin magnetic films are deposited by electron beam evaporation. The thickness of the films is determined using a calibrated quartz oscillator, calibrated Auger electron signals and RHEED oscillations. The island-free growth of the films is checked by monitoring the ion reflectivity I and the energy distribution of the specularly reflected deuterons. At the surface of all films, I is not reduced from its initial value of 95%, measured at the atomically flat substrate surfaces. Furthermore, the presence of islands would yield an additional energy loss of the deuterons caused by penetration of the ions through islands by planar channeling, which is not observed.

3. Results and Discussion

We have used ECS to measure the existence of long-range ferrromagnetic magnetic at surfaces of ultra-thin (1-4 ML) bct Fe(100) films which are deposited epitaxially on at atomically flat Pd(100) substrates. For a substrate temperature of 293 K and an evaporation rate of 0.002 nm/s, homogeneous and island-free growth of the Fe films is obtained (Rau et al., 1993). We note that the epitaxial growth of bct Fe(100) on Pd(100) was already extensively studied (Quinn et al., 1991). The samples are magnetized in magnetic fields ranging from 75 Oe to 0 Oe, and the temperature of the samples being kept constant within 0.05^{o}. Such applied fields have a negligible effect on the ESP in the investigated temperature range which shows that, within experimental errors, the remanent magnetization is equal to the saturation magnetization.

In Fig. 2, the temperature (T) dependence of the in-plane, spontaneous, normalized long-ranged ESP P/P_o at the surface of well-annealed ($350^{o}C \geq T_{Cs}$) 2 ML thin Fe(100) films on Pd(100) is given as function of T/T_{Cs}, with T_{Cs} =613.1 K being the surface Curie temperature of the films and P_o =-33% the calculated ESP at T=0. The full line in Fig. 2 represents the T-dependence of the magnetization as predicted by Yang (1952) for the 2D Ising model. The dashed line in Fig. 2 gives the asymptotic power law approximation. It is obvious that the experi-mental data points can be precisely described by the exact solution of the 2D Ising model as given by Yang (1952).

For well annealed 2 ML thin films, T_{Cs} and the critical exponent ß are determined by a linear least-square fit of the ESP data under the assumption of a power law of the form $(T_{Cs} - T)^{\beta}$ for t between 0.97 and 1.0. The value of ß is found to be ß =0.125 ±0.01 giving the slope of a straight line in the log-log representation of the ESP data. The dashed curve in Fig. 2 corresponds to ß=0.125 and fits the experimental ata quite well for t between 0.97 and 1.0. The value we obtain for the critical exponent ß agrees well with the exact value (1/8) of the 2D Ising model of a ferromagnet for $T \rightarrow T_{Cs}$. In addition, we have performed fits of the experimental data points for t values ranging far beyond ($0.75 \leq t \leq 1$) the critical region . Within experimental errors, we

obtain again ß=0.125. We note that more experimental evidence is needed to establish if the critical region for 2D phase transitions extends over a larger range of temperatures compared to that for 3D phase transitions.

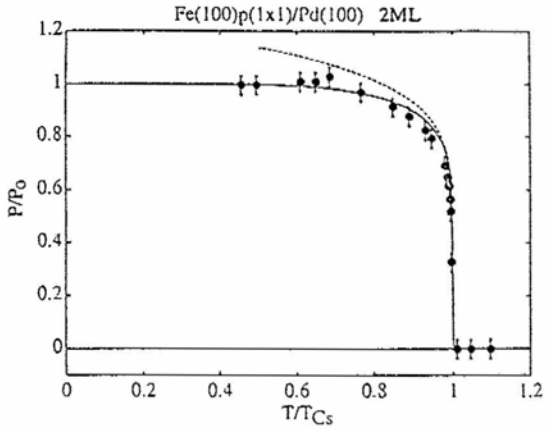

Fig. 2. ESP P/P_0 as function of T/T_{Cs} for the surface of a 2 ML thin bct Fe(100)p(1x1)/Pd(100) film. The solid and dashed lines represent, respectively, the exact solution of the 2D Ising model and the power law approximation for $T \rightarrow T_{Cs}$.

It is interesting to note, that our experimental data are, for $0.45 \leq t \leq 1$, in excellent agreement with the T-dependence of the spontaneous magnetization as predicted by Yang (1952) for a 2D Ising magnet.

We report on further ECS experiments performed at surfaces of ultra-thin (5nm) hcp Tb(0001) films, which are epitaxially and homogeneously deposited at 300 K on bcc W(110) substrates (Rau et al., 1989). We remark that, for rare-earth metals such as Tb and Gd, the measured ESP P is attributed to the polarization of the 5d-6s surface electrons (Rau, 1982) and is proportional to the surface magnetization of the localized 4f electrons, which are the predominant carriers of the magnetization of Tb. T is kept constant within 0.02° and P is measured in fields ranging between 25 and 600 Oe. Such applied fields have been shown to have a negligible effect on the ESP in the investigated temperature range (Balberg and Helman, 1978).

In Fig. 3, the T-dependence of P at Tb(0001)/W(110) surfaces is given for H= 250 Oe. H was varied between 25 Oe and 600 Oe, and no remarkable influence on the ESP data was detected. Nonzero P values establish that the surfaces of the films are ferromagnetically ordered up to 248 K, which lies above both T_{Cb} and T_{Nb} as indicated in Fig. 3. Similar behavior was recently found in ECS experiments at surfaces of polycrystalline (Rau et al., 1988). In these experiments, using ferromagnetic induction and Kerr effect measurements, T_{Cb} was found to be located at 220 K as shown in Fig. 3. With increasing temperature, P decreases from 22 % at 146 K, until it

reaches a value of 7 % at about 240 K, which lies slightly above T_{Cb} and T_{Nb}. As T increases further, P increases very steeply to 21% at 243 K, at which it drops suddenly to zero at a surface Curie temperature T_{Cs} =249.96 K. From further ECS experiments, it is found the short-ranged ESP extends even up to temperatures of about 300 K.

Using a log-log plot for the T-variation of P near T_{Cs} , we determined ß simultaneously with T_{Cs} by a linear least-square fit of the P data. For $(T_{Cs} - T)/T_{Cs}$ ranging between $2x10^{-2}$ and 10^{-4}, we obtain ß = 0.348 ±0.01.

For several magnetic systems, previous magnetic studies of ß have been restricted to the case $T_{Cs} = T_{Cb}$, for which ß is measured to be 0.75 ±0.05 (Alvarado et al., 1982, Dauth et al., 1987). The only previous experimental determination of ß for the case T_{Cs} larger than T_{Cb} was for ultra-thin films of V(100) on Ag(100) substrates (Rau et al., 1988); but for V, unlike for Tb, T_{Cb} =0, and the exact value ß =1/8 for the two-dimensional (2D) Ising ferromagnet was recently confirmed by ECS. In the

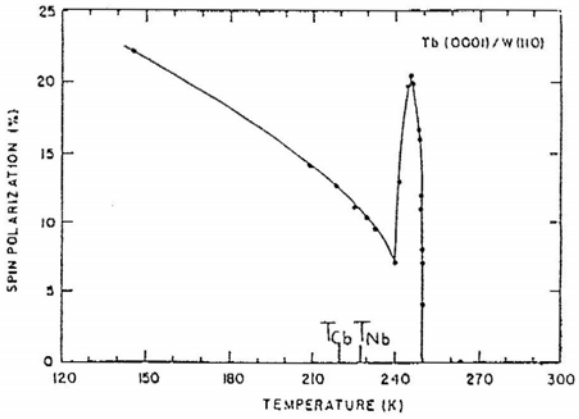

Fig. 3. Electron spin polarization P(%) of the topmost surface layer of 5 nm thin Tb(0001)/W(110) films as function of temperature. T_{Cb} denotes the bulk Curie temperature, and T_{Nb} denotes the bulk Néel temperature of Tb.

present case, T_{Cs} lies close to T_{Cb}, and we can no longer expect, as we did for V, to observe 2D Ising critical behavior. The fact that $T_{Cs} \neq T_{Cb}$ indicates that the magnetic couplings between the surface spins are strongly anisotropic suggesting that spin isotropy, which leads to a large value of =0.75 may not be valid for the present system. Taking surface anisotropies into account, it is recently found (Diehl and Eisenriegler, 1984) that ß can deviate from 0.75 ± 0.05. Along an axis of easy (hard) magnetization ß is 0.35 (0.93). The value ß =0.35 agrees well with our experimental result ß =0.348 measured along an easy axis.

For the SPEES experiments presented here, surface scattering of 25 keV Ne^+ ions is used to study the emission of spin-polarized produced as a consequence of

particle-surface interaction. Figure 4a shows for an angle of incidence $\alpha=1^{o}$ the angle-resolved energy distribution (ARED) (relative to the vacuum level) and the ESP of electrons emitted along the surface normal from clean (solid line) and O-covered (dashed line) Fe surfaces (Rau et al., 1993). At this angle, the Ne^{+} ions are specularly reflected and do not penetrate the Fe surfaces. For both, clean Fe and O/Fe, the ARED of the emitted electrons peaks at around 4 eV. However, at O-covered Fe, a strong increase in the intensity of emitted electrons is found as compared to that of clean Fe.

The ESP of electrons excited at the topmost surface layer of clean Fe is P=(33±2)% for E=10 eV and increases to P=(48±2)% for E=4 eV. These values are far above the 28% average bulk magnetization value of Fe. For Fe surfaces with one monolayer of O, the average ESP of electrons at E=10 eV remains nearly unchanged ((32±2)%), but for electrons with E=4 eV, the ESP drops from (48±2)% to -(14±2)% eV indicating the presence of a magnetically live surface layer.

It is of considerable interest to determine whether the measured ESP of the emitted electrons reflects the layer-dependent net magnetization of a material. From ion- (Kirschner et al., 1987, Rau et al., 1990) and electron-induced electron spectra (Landolt, 1985), there is evidence that the ESP of electrons emitted at high energies (≈10 eV above the vacuum level) scales roughly with the average net magnetization.

For $\alpha=8^{o}$, $E_{\perp}$ amounts to 32.8 eV, and the ions can penetrate the topmost surface layer and excite electrons from the second layer. The shape of the ARED's of the emitted electrons are similar to those of Fig. 4a with the peak maximum shifted upwards to about 5 eV (see Fig. 4b). In this case, the average ESP of the electrons emitted from clean Fe increases from P=29% at E=10 eV to P=50% at E=4 eV. For the O/Fe surface, the average ESP of electrons with E=10 eV remains unchanged ((32±2)%), whereas for electrons with E=4 eV, the ESP decreases from (50±2)% to (14±2)% eV.

Fig. 4c shows for $\alpha=45^{o}$ the ARED's and the ESP's of electrons emitted from clean (solid line) and O-covered (dashed line) Fe surfaces. For $\alpha=45^{o}$, $E_{\perp}$ amounts to 12.5 keV, and the ions can penetrate deeply into the solid and excite electrons from bulk layers. For this case, the ARED's of clean and O-covered Fe surfaces are similar to those obtained in electron-induced secondary electron emission experiments (Baragiola et al., 1979, Kirschner et al., 1987, Landolt, 1985) peaking at 2 eV. For O/Fe surfaces, however, a strong increase in the intensity of the emitted electrons is observed. For electrons excited in bulk layers, electron cascading and multiple scattering are the dominant processes occurring during electron transport to the surface, which causes the well-known 2 eV peak in electron- or ion-induced electron spectra. This is consistent with the data for $\alpha=1^{o}$ and $\alpha=8^{o}$ where the ARED's of the emitted electrons peak at higher energies (around 4-5 eV) showing that electron cascading and multiple scattering processes are less pronounced. As regards the

average ESP of the electrons emitted from clean Fe, an increase from P=(25±2)% for E=10 eV to P=(45±2)% for E=4 eV is observed. For the O/Fe surface, the average ESP of electrons with E = 10 eV remains unchanged ((25±2)%), whereas whereas for electrons with E=4 eV, the ESP drops to (15±2)% eV.

Changing α from 45^{o} to 1^{o}, which corresponds to a reduction in the probing depth from deep lying layers, where bulk physical properties are probed, to the surface layer, results in an increase in the ESP of "high-energy" electrons from 25% to 33%. This would imply that for Fe surfaces, the net magnetization increases in going from the bulk to the surface. Assuming that the ESP of electrons emitted at high energies (≈10 eV) scales roughly with the average net magnetization, it is tempting to interpret this surface enhancement of the ESP, which amounts to approximately 32%, in terms of theoretically predicted magnetic surface states which cause enhancements of the magnetization of 32% and 20% for Fe(100) and Fe(110) surfaces (Fu et al., 1985, Krewer and Feder, 1991).

For low emitted electron energies, the measured ESP's from clean Fe are substantially enhanced above the bulk polarization values, as has been observed also for electron- and ion-induced electron emission. This enhancement can be attributed to Stoner excitations across the ferromagnetic exchange gap which occur during inelastic exchange scattering of minority electrons (Kirschner, 1988, Landolt, 1985, Tamura and Feder, 1986, Penn et al., 1985).

The fact that the enhancements are observed to be approximately the same for electrons emitted from the topmost surface layer ($\alpha=1^{o}$) and from subsurface and deeper layers ($\alpha=8^{o}$ and 45^{o}) suggests that the mean free path

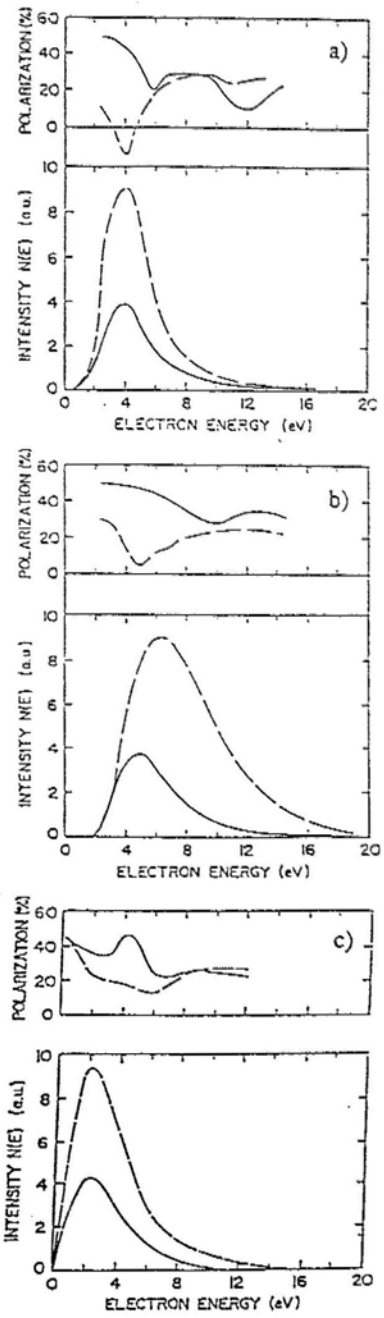

Fig. 4. ARED and ESP as function of the energy E of electrons emitted from clean (solid line) and O-covered (dashed line) Fe surfaces for 25 keV Ne^{+} ions and $\alpha=1^{o}$ (a), $\alpha=8^{o}$ (b) and $\alpha=45^{o}$ (c).

path for Stoner excitations is of the order of one monolayer.

The substantial polarizations of electrons emitted from O/Fe and the pronounced dependence of the ESP at low energies on the angle of incidence of the ion beam clearly demonstrates the absence of a magnetically dead layer at the surface are consistent with the existence of spin-split electronic bands in the occupied and unoccupied parts of the band structure of O/Fe surfaces (Clarke et al., 1990).

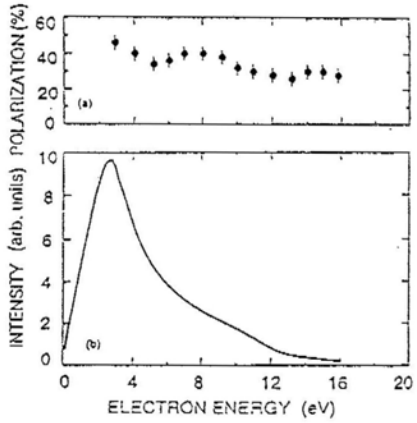

Fig. 5. ESP (a) and ARED (b) of electrons emitted from a 2 ML thick Fe(100) film deposited on Pd(100) and using 150 keV H^+ ions for SPEES (incidence angle $\alpha = 1^o$.)

Figure 5 shows results of SPEES experiments on the ESP (a) and the ARED (b) of electrons emitted from 2 ML thin Fe(100)/Pd(100) films. The H^+ ion energy is 150 keV and α is 1^o. The ESP increases from a value of +32% at E~10 eV to +45% at E~ 3 eV (Lu et al, 1993). This enhancement of the ESP is due to Stoner excitations as discussed before. The fine structure in the ESP at around 6-8 eV is caused by the influence of unfilled spin-polarized electron states of Fe above the vacuum level as discussed by Tamura and Feder (1986).

Figure 6 shows the dependence of the magnetization, or the average ESP (electron energy 10 to 12 eV) as function of the incidence angle, α, for 4 ML thin Fe(100)/Pd(100) films. The highest ESP value (= 37%) is obtained for $\alpha < 0.6^o$ where the incident ions cannot penetrate the topmost surface layer. Therefore, this ESP value should represent a measure of the surface magnetization. A drop in the average ESP from 37% to 28% is observed when α is increased above 0.6^o where the ions start probing subsurface and bulk layers. Therefore, ESP values for larger α ($> 2^o$) can be related to the bulk magnetization. This enhancement of the average ESP in going from the bulk to the surface amounts to 32% compared to that of the bulk, which is in

excellent agreement with theoretical predictions ((Fu et al.. 1985, Krewer and Feder, 1991).

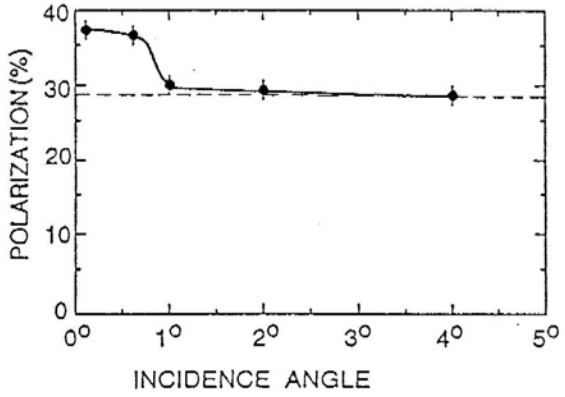

Fig. 6. Average ESP for 4 ML thin Fe(100) films epitaxially deposited on Pd(100) as function of the angle of incidence of the ions.

We have studied the ion-induced emission of spin-polarized Auger electrons from 2ML thin Fe(100)/Pd(100) films. The ESP of Fe(MVV, E=44 eV) Auger electrons emitted from the surface layer amounts to approximately 36% whereas the ESP of Pd(MVV, E≈40 eV) Auger electrons is zero. Changing α from 0.6° to larger angles enables us to probe the Pd/Fe interface layers. For large α, we observe at new peak in the ESP of the emitted Auger electrons located at the Pd Auger electron peak. We interpret this peak to be due to the nonzero positive ESP of Pd(MVV) Auger electrons emitted from the Fe/Pd interface. The magnitude of the ESP value for Pd(MVV) Auger electrons can not be extracted from these data because of the uncertainty in the contribution of Fe(MVV) Auger electrons to this peak at 40 eV. For 4 ML thick Fe(100)/Pd(100) films, such a Pd Auger electron peak does not exist in the ESP at around 40 eV. This is obvious because the mean free path of Pd(MVV) Auger electrons amounts only to a few Angstroms. Therefore, at present, we can only confirm that Pd Auger electrons are spin-polarized and that the ESP is oriented parallel to that of the Fe(MVV) Auger electrons.

In conclusion, the experiments discussed here provide clear evidence that ECS and SPEES are a powerful techniques for the study of topmost and interface layer magnetic properties.

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