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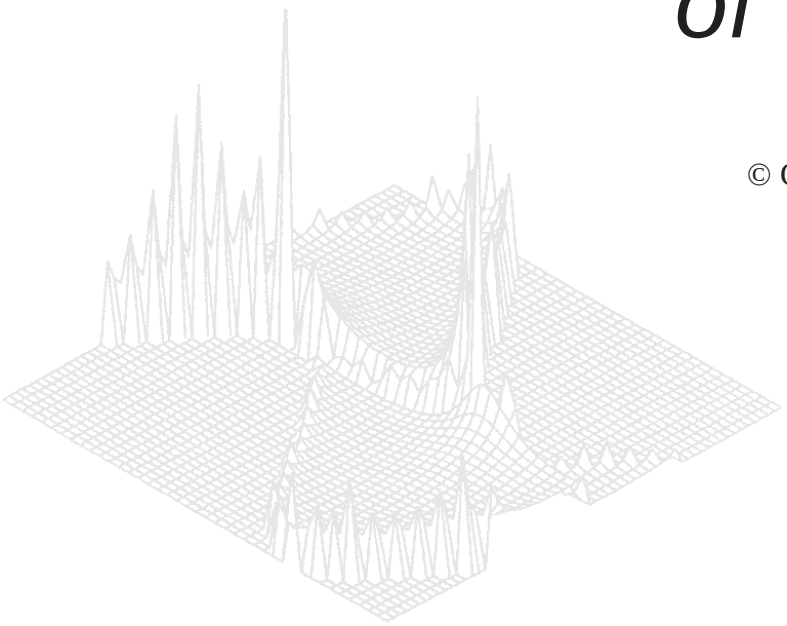

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Spin-polarised Electron Studies of Low-dimensional Magnetic Systems*

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Abstract

Spin-polarised electrons provide unique experimental access to magnetic properties of surfaces and layered structures. The combined use of different techniques allows us to develop a microscopic picture of the physics underlying the macroscopic magnetic properties, e.g. magnetic phase transitions, magnetic coupling phenomena, exceptional surface magnetic properties. In this paper, two techniques are described together with the kind of questions addressed by them. Spin-resolved appearance potential spectroscopy gives local magnetic information about multi-component systems by probing the spin-dependent local density of unoccupied states. Spin-resolved inverse photo-emission measures specific electron states above the Fermi level. In particular, two-dimensional states serve as magnetic sensors at surfaces. Examples from surfaces as well as thin-film structures of band and local-moment ferromagnets are presented.

1. Introduction

Ferromagnetism is a collective phenomenon ordering the electron spins in solids below a critical temperature called the Curie temperature T_C. It is a many-body effect of quantum-mechanical nature caused by the Coulomb interaction. There can be a significant influence of the crystal lattice through spin–orbit interactions as well. These effects partly explain the complexity of the phenomenon and the difficulty in describing collective magnetism with theoretical models. The situation becomes even more complicated in systems of reduced dimension, i.e. surfaces, ultra-thin films and layered structures. At the interface the symmetry is broken, the local environment is changed, and the dimensionality reduced. As a consequence, modified or even novel properties are expected concerning magnetic properties, e.g. the magnetic moments, the magnetic domain structure, the magnetic phase transition, the sign and strength of exchange coupling, or the magnetoresistance (Siegmann 1992; Donath 1993; Gradmann 1993; Allenspach 1994; Elmers 1995; Farle 1998).

One class of experiments focuses on the *macroscopic* quantity of magnetisation by detecting a signal proportional to the net magnetisation or net moment. This signal is measured as a function of an applied magnetic field to study the hysteresis behaviour (coercivity, remanence) and as a function of the temperature

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to characterise the magnetic phase transition. With spatial resolution this can be used to learn more about the magnetic domains and their properties, and with time resolution there may be insight into the spin-lattice dynamics. To understand the magnetic properties on a more *microscopic* level, other experiments are employed to determine the spin-dependent electronic states, which underlie the primary magnetic quantities. The energy levels $E_{\uparrow,\downarrow}$, dependent on the electron spin magnetic moment parallel ($\uparrow$) or antiparallel ($\downarrow$) to the magnetisation direction, are studied as a function of the wave vector $\mathbf{k}$ and the temperature T. The energy difference between $E_\uparrow$ and $E_\downarrow$ is called the exchange splitting ΔE_{ex} which depends on the energy E, the wave vector $\mathbf{k}$, and the temperature T. Connected with the exchange-split bands close to the Fermi energy E_{F}, i.e. the spin-dependent Fermi surface, is an imbalance in occupation of the spin-up (majority) and spin-down (minority) energy levels which leads to a net magnetic moment. The spin-dependent local density of states (DOS) provides element-specific information about multi-component systems. In momentum space, however, the valence- and conduction-band region is measured as a function of the electron wave vector $\mathbf{k}$ to characterise specific electron states and their role in magnetism.

The use of spin-polarised electrons provides a direct experimental probe of the spin-split bands in ferromagnets. Either the spin polarisation P of electrons ejected into the vacuum is measured, or a spin-polarised electron beam is directed onto the sample and the spin asymmetry A of an emitted signal I is detected. The spin polarisation is defined as the normalised difference between the number of electrons with spin magnetic moment parallel and antiparallel to the magnetisation direction: $P = (N_\uparrow - N_\downarrow)/(N_\uparrow + N_\downarrow)$. The spin asymmetry is defined correspondingly: $A = (I_\uparrow - I_\downarrow)/(I_\uparrow + I_\downarrow)$. A further important characteristic of electron spectroscopies is their surface sensitivity which is of a few atomic layers only. This depends somewhat on the electron energy and the material under investigation (Passek *et al*. 1996 and references therein).

In this paper two spin-resolved electron spectroscopies are described together with the kind of questions addressed by these techniques. Both measurements use a spin-polarised electron beam in the excitation channel and look for the spin asymmetry in the detection channel. Both investigate the spin-dependent electronic structure, but in different ways. Spin-resolved appearance potential spectroscopy (APS) is employed to probe the spin-dependent local DOS of a ferromagnetic compound. Spin-resolved inverse photoemission (IPE) is used to detect two-dimensional electron states serving as magnetic sensors in thin-film systems.

2. Spin-resolved Appearance Potential Spectroscopy

APS is an experimental technique with a long history and is used to determine binding energies of core levels or to analyse the elemental composition of surfaces (Thomas 1925; Park and Houston 1972; Park 1975). The surface of a solid is bombarded with electrons of variable energy while the total yield of emitted X-rays or electrons is monitored. At energies high enough to excite a core electron into the unoccupied states, also called the critical or appearance potentials, the yield of emitted particles increases owing to recombination of the created core hole via X-ray or Auger electron emission. The early use of this technique in the 1920*s* and 1930*s* was hampered by the low signal-to-background ratio

of typically 10^{-4}. The development of the modulation differentiation technique caused a revival of APS in the 1970*s*. The detected recombination signal was then studied in more detail. The intensity and shape of the APS signal reflect the density of unoccupied states because both the exciting and the excited electron are scattered into unoccupied states.

Within a one-particle approximation, the APS signal is proportional to a self-convolution of the unoccupied DOS. As a consequence, APS was used to investigate the unoccupied DOS (Powell *et al*. 1992). Characteristic spectral features originating from critical point energies in the unoccupied DOS (Dose and Reusing 1983) were used to identify structural details like the short-range order in metallic glasses (Dose *et al*. 1984) and changes during the solid–liquid phase transition (Dose *et al*. 1986). In ultrathin Fe films on Cu(001), the transition from fcc growth to bcc growth, with increasing thickness, was followed by APS (Detzel *et al*. 1995). As indicated, APS is element specific because of the core levels involved, it is surface sensitive due to the short inelastic mean free path of the electrons used for excitation, and it provides structural information via details of the local DOS.

APS, with spin-polarised electrons, is a very powerful tool in the study of magnetic samples. Ferromagnets exhibit a spin-dependent electronic structure, in particular there are more unoccupied minority states than majority states. As a consequence, the APS signal depends on the spin polarisation of the exciting electron beam. This was first shown by Kirschner (1984) for the $2p_{3/2}$ threshold in Fe. Further experiments followed for Fe and Ni, and the results were well described by a weighted self-convolution of the unoccupied DOS with empirical weighting coefficients (Ertl *et al*. 1993). A theoretical description of these data were given by Ebert and Popescu (1997) based on a proper treatment of the transition matrix elements involved, but still in a single-particle picture. The influence of electron correlations on APS spectra was studied by Nolting *et al*. (1992) and Potthoff *et al*. (1993), but so far only in the context of model calculations. The spin asymmetry of the APS signal can, without going into details of the electronic structure, also be used to monitor the surface magnetisation as a function of the film thickness (Detzel *et al*. 1995) and/or the temperature (Detzel *et al*. 1996).

To illustrate the power of spin-resolved APS, recent experiments on the ferromagnetic compound $FeNi_3$ are highlighted. These experiments made use of the element specificity as well as the magnetic sensitivity of spin-resolved APS (Reinmuth *et al*. 1997, 1998). The spin-polarised electron beam used for excitation is emitted from a GaAs photocathode irradiated with circularly polarised laser light, as described by Kolac *et al*. (1988). The APS signal is detected via soft X-ray emission. The detector arrangement consists of a multichannel plate with filters and a CsI layer acting as photon-to-electron converter (Rangelov *et al*. 1998). The $FeNi_3(111)$ surface was prepared structurally, chemically, and magnetically to ensure a clean and presumably compositionally ordered surface with remanent in-plane magnetisation during measurement (Reinmuth *et al*. 1997).

Spin-resolved APS data of the pure elements, bcc Fe and fcc Ni, are known and quite well understood (Ertl *et al*. 1993; Ebert and Popescu 1997). We studied the $2p_{3/2}$ levels of Fe and Ni in the binary compound $FeNi_3$ with fcc crystal structure and looked for the changes of the spin-dependent local DOS between the elements and the compound. At the composition under consideration the

changes are expected to be more pronounced for Fe than for Ni. Therefore we restrict our discussion to the results for Fe. Concerning the Ni results, the reader is referred to the literature (Reinmuth *et al.* 1997).

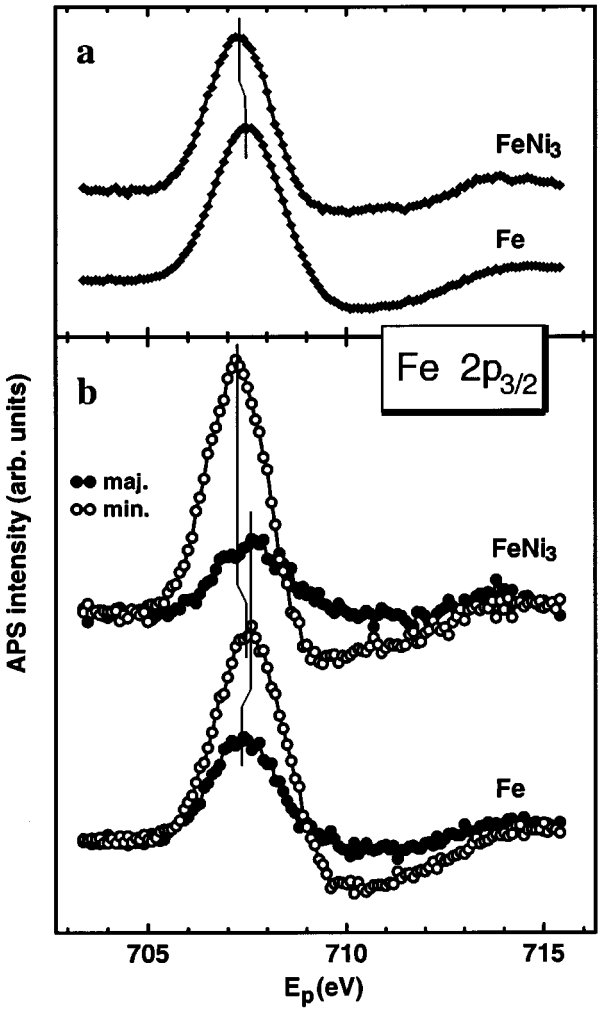

Fig. 1. Spin-averaged (a) and spin-resolved (b) soft X-ray APS spectra for the Fe $2p_{3/2}$ core level in $FeNi_3$ in comparison with spectra from the pure element (Reinmuth *et al.* 1997).

Fig. 1 shows (a) the spin-averaged and (b) the spin-resolved APS spectra for the Fe $2p_{3/2}$ core level in pure Fe and in $FeNi_3$. The abscissa gives the primary energy of the electrons used for excitation $E_\mathrm{p} = eU + \Phi_\mathrm{C}$, where U denotes the potential difference between cathode and sample, and Φ_C the work function of the cathode. The relevant number for the negative-electron-affinity photocathode used as electron source in our experiment is $1{\cdot}4$ eV and represents essentially the band gap of the semiconductor GaAs. The spin-averaged data in Fig. 1 exhibit

an energetic shift of about $-0{\cdot}15$ eV and some line narrowing between the pure element and the compound, in agreement with the literature (Wandelt and Ertl 1976). Based on the spin-averaged results, it was concluded that the Fe spectra, as opposed to the Ni spectra, are practically unaffected by alloying. This was a rather surprising result, because the local environment of the Fe atoms is strongly affected by alloying at the given composition. In the compound, Fe is not only surrounded mostly by Ni atoms, but also the crystal symmetry is changed to fcc compared with bcc in the pure element.

Our spin-resolved data shed new light on this issue by revealing more pronounced changes. The partial spin intensities both shift in energy, but with different sign, and the spin asymmetry almost doubles from -33% to -55% between Fe and $FeNi_3$. To understand the observed changes, we compare the experimental data with calculations of the local DOS and a simulation of the corresponding spin-dependent APS intensities. The latter are given by a weighted self-convolution of the DOS above the Fermi level and broadened to account for the various intrinsic and apparative broadening mechanisms.

Fig. 2*a* gives the calculated spin-dependent Fe local DOS in the compound $FeNi_3$ and in bcc Fe. The calculations predict Fe to change from a 'weak' ferromagnet with considerable DOS of empty majority d states to a 'strong' ferromagnet with only minority d states empty in the compound. The occupation of formerly empty majority d states explains also the reported increase of the spin magnetic moment from $2{\cdot}1$ μ_B for bcc-Fe to about 3 μ_B for Fe in $FeNi_3$ (Cable and Wollan 1973). Fig. 2*b* shows the simulated APS spectra. Note that the energy scale is now referenced to the Fermi level of the sample. Comparing theoretical and experimental APS spectra offers a way of determining core-level binding energies. The experimental data shown as open and filled dots are shifted in energy in such a way that they match the calculated ones. The energy zero of the calculations represents a final state with two electrons at the Fermi level and, thereby, defines the core-level binding energy in the experimental data. The $2p_{3/2}$ core-level binding energy for pure Fe determined in this manner is $706{\cdot}1 \pm 0{\cdot}2$ eV. The APS result for $FeNi_3$ had to be shifted by additional $0{\cdot}8$ eV to match the calculations. This directly indicates an increase of the core-level binding energy by $0{\cdot}8$ eV in the compound compared to the pure element. The observed peak shifts as well as the change in spin asymmetry are fairly well described by the calculations within a single-particle picture. Both the binding energies and the core-level shift obtained by spin-resolved APS are in good agreement with X-ray photoemission results and theoretical predictions (Reinmuth *et al.* 1997 and references therein). APS spectra contain combined information about the spin-dependent unoccupied DOS and the core-level binding energy. The comparison presented with calculations enabled us to separate the two influences. The differences still remaining between calculation and experiment may be caused by electron correlation effects not yet included in the calculation.

The spin asymmetry of the APS signal as a function of the temperature can be used as an element-specific magnetisation signal in the study of the magnetic phase transition. In view of the rather complex origin of the APS signal, the relation between spin asymmetry and surface magnetisation is not clear *a priori*. Previous experiments on Fe, Ni (Vonbank 1992) and Fe/Cu(001) (Detzel *et al.* 1996) essentially suggest a direct proportionality between the spin asymmetry and the surface magnetisation. Fig. 3 shows temperature-dependent results for the APS line of Fe from $FeNi_3$(111) (Reinmuth *et al.* 1998). The curve represents the bulk magnetisation of $FeNi_3$ rescaled to fit the spin-asymmetry data. The temperature behaviour of the spin asymmetry does not show deviations from the temperature behavior of the bulk. The data confirm proportionality of the

spin asymmetry $A(T)$ from APS measurements and the magnetisation $M(T)$. In particular, no spin asymmetry of the APS signals for Fe and Ni (not shown) is detected above the bulk Curie temperature, i.e. the data give no indication of unusual surface magnetic properties of $FeNi_3(111)$ as previously reported by Mamaev *et al.* (1987).

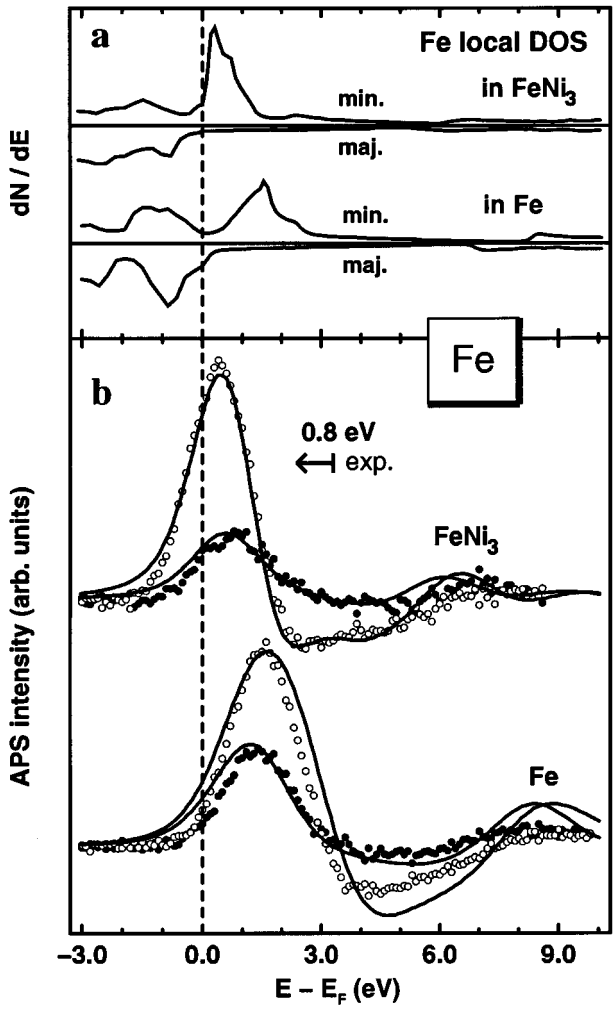

Fig. 2. (*a*) Calculated spin-dependent local density of states at the Fe sites in $FeNi_3$ and in bcc Fe. (*b*) Theoretical spin-resolved APS spectra in comparison with the experimental data of Fig. 1*b* (Reinmuth *et al.* 1997).

The example of $FeNi_3$ shows that APS with spin-polarised electrons is a powerful tool to study multi-component magnetic systems. It is of particular use for the determination of element-specific magnetic properties in multilayers exhibiting interesting coupling phenomena (Fert *et al.* 1995; Bovensiepen *et al.* 1998). Experiments along this line are under way.

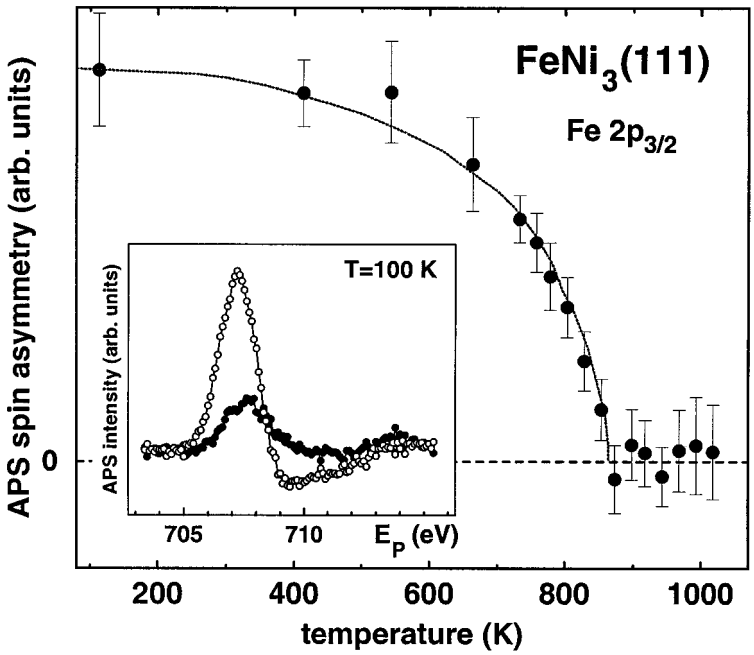

Fig. 3. Temperature-dependent spin asymmetry of the Fe $2p_{3/2}$ APS signal for $FeNi_3(111)$. The curve represents the bulk magnetisation of $FeNi_3$ rescaled to fit the spin-asymmetry data. The low-temperature spin-resolved APS data of Fig. 1*b* are shown in the inset (Reinmuth *et al.* 1998).

3. Spin-resolved Inverse Photoemission

Spin-resolved IPE also provides information about the spin-dependent electronic structure, and yet is complementary to APS. While APS probes the local unoccupied density of states IPE, in its angle-resolved mode, is able to determine the $E(\mathbf{k})$ relation of the bands above the Fermi level. Electrons impinging on a sample couple to electronic states within the sample and, as one of many decay channels, undergo radiative transitions to lower lying empty states. In the isochromate mode, the emitted photons with a given energy are detected as a function of the kinetic energy of the incoming electrons. In the constant-initial-state mode, the spectrum of emitted photons is detected for a given kinetic energy of the exciting electrons. The technique started in the keV range as bremsstrahlung spectroscopy more than fifty years ago. The use of an effective energy-selective Geiger–Müller counter for photon detection in the VUV range about 20 years ago established IPE as a surface-science technique (Dose 1985).

IPE adds to the information obtained from 'traditional' photoemission (PE) by probing the electronic structure at energies above the Fermi level, in particular the unoccupied states between Fermi level and vacuum energy which are inaccessible to PE. Since the electronic states just below and above the Fermi level are of special importance for the understanding of chemical processes, transport phenomena, and the formation of the magnetic moment, the combined information of PE and IPE is often necessary to answer important questions. Note though that IPE is far more resolution limited near the Fermi level than PE.

The use of spin-polarised electrons for excitation in IPE allows us to study the exchange-split unoccupied energy bands in ferromagnets separately (Unguris *et al.* 1982; Donath 1989 1994). Spin-polarised electrons emitted from a GaAs photocathode (Kolac *et al.* 1988) impinge as a parallel beam on a sample. Radiative transitions between empty states are detected via the emitted photons at a fixed energy of 9·4 eV with an overall experimental resolution of 450 meV. Spectra show the IPE intensity as a function of the kinetic energy of the incoming electrons. The energy scale is referred to the Fermi level of the sample, and zero corresponds to an electron kinetic energy of 8 eV.

A lot of spin-resolved IPE work has attempted to address the ground-state properties of ferromagnets, though clearly the measurements must still be undertaken at finite temperature. Such insight is accessible via low-temperature results of the magnetic exchange splitting of bulk-derived bands as a function of energy, momentum, and point-group symmetry. The loss of long-range magnetic order at the magnetic phase transition is a further topic of interest. The temperature behaviour of the magnetic exchange splitting depending on the energy and wave vector is crucial for evaluating different models of ferromagnetism (Donath and Dose 1989; Borgieł *et al.* 1989; Donath 1994).

Unique access to surface magnetic properties is provided via the spin dependence of electronic surface states (Donath 1995). The importance of surface states for monitoring and modifying properties of metal surfaces was reviewed recently (Bertel and Donath 1995; Memmel 1998). Surface states appear in gaps of the projected bulk band structure. Their wave functions are localised near the surface of solids. Truly magnetic surface states, i.e. partially occupied bands with different occupation for the two spin components, contribute directly to the surface magnetic moment. The actual amount of the contribution depends on the band character (Memmel 1997, 1998). Completely occupied or empty states carry magnetic information due to hybridisation with the truly magnetic bands and, thereby, give valuable information about the surface magnetic properties. In the following, two examples will be described where the study of surface states by spin-resolved IPE helps to resolve, or at the very least gain insight into, some of the controversies related to magnetic surfaces.

(3a) Surface as Magnetic Driver in fcc-like Fe Films on Cu(001)

The study of one and the same ferromagnetic element, but in different crystal structures, is essential for understanding the interplay between structure and magnetism. Since the equilibrium crystal structure of Fe is bcc up to 1179 K, which is well above the Curie temperature of 1043 K, the magnetic properties of fcc Fe were not accessible until epitaxial films could be prepared.

Ultrathin Fe films deposited on Cu(001) at room temperature exhibit a metastable fcc-like stucture up to a film thickness of about 10 monolayers (ML) (Thomassen *et al.* 1992; Detzel *et al.* 1995, and references therein). The magnetic properties, however, are not straightforward. Complicating matters, up to 5 ML, the fcc structure is tetragonally distorted, while the films are completely ferromagnetic with out-of-plane anisotropy. Between 5 and 10 ML, the crystal structure is fcc with a reconstructed surface, but the magnetic signal is reduced and almost independent of film thickness. This was interpreted as

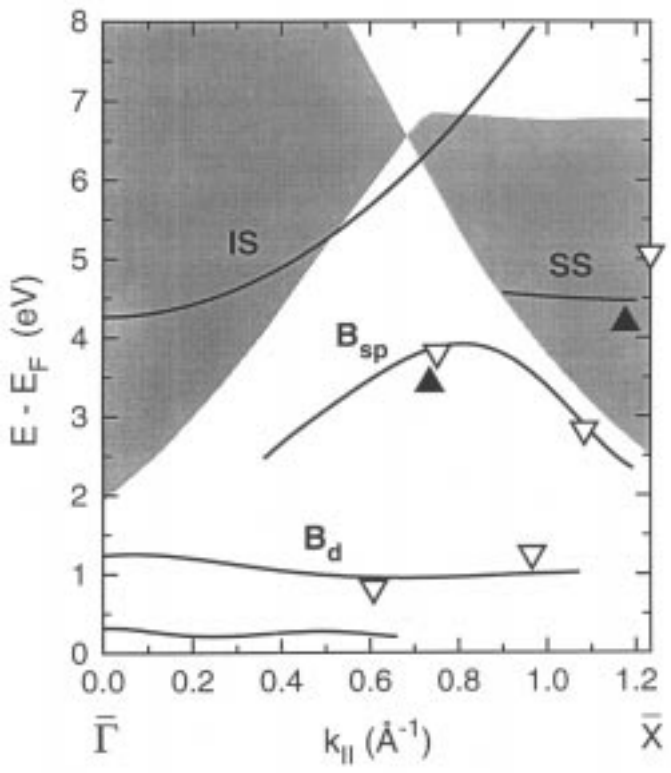

Fig. 4. Final-state energies as a function of $\mathbf{k}_{\|}$ for IPE results from fcc-like Fe films on Cu(001). Solid lines represent spin-averaged results for 8 ML (Glatzel *et al.* 1992): transitions into an image-potential-induced surface state (IS), into a crystal-induced surface state (SS), and into bulk-like *sp* (B_{sp}) and *d* states (B_d). Open and filled triangles give spin-resolved results for 6 ML for minority and majority electrons, respectively (Gubanka *et al.* 1996*b*). The shaded areas are gap regions of the projected bulk band structure for paramagnetic fcc Fe.

magnetic live surface layers with nonferromagnetic layers underneath, but no surface-layer-sensitive technique had been used to remove uncertainty and doubt.

Based on the great depth of knowledge about the surface electronic structure of fcc-(001) surfaces, spin-resolved IPE results helped to solve this problem. Owing to the $L_{2'} - L_1$ energy gap of the bulk electronic structure, the (001) surfaces of fcc crystals exhibit an *sp*-derived surface state SS around the $\overline{X}$ point of the surface Brillouin zone. A spin-averaged IPE experiment had identified SS at about 4·5 eV above the Fermi level for 8 ML of Fe (Glatzel *et al.* 1992). The wave function of SS is strongly peaked within the outermost atomic layer, in particular at $\overline{X}$, where it is energetically located in the middle of the gap as shown in Fig. 4. Studying SS with spin-resolved IPE is a rather unique experiment, because it is not only magnetically sensitive, but also structure selective. The appearance of surface states at certain values for energy and wave vector is characteristic of a particular crystal structure.

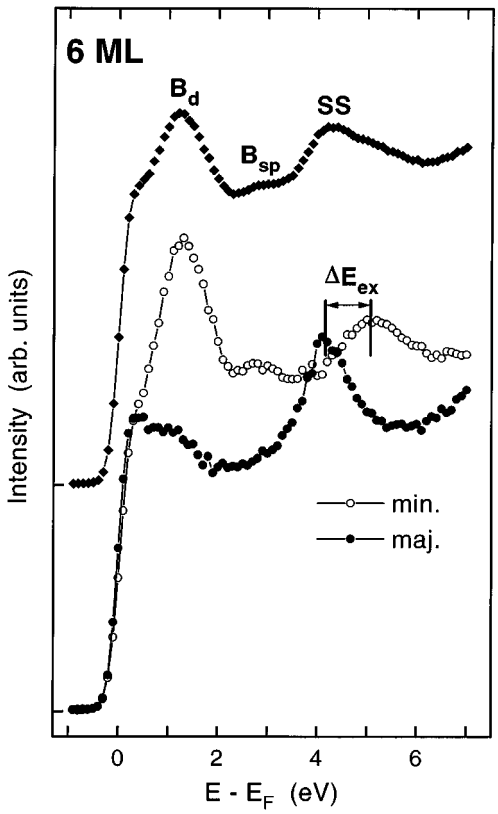

Fig. 5. Spin-averaged (diamonds) and spin-resolved (open and filled dots) inverse-photoemission results for 6 ML of Fe grown at room temperature on Cu(001). The data are taken at $T = 90$ K and $\Theta = 50°$. The experimental parameters locate the surface state SS in **k** space close to the $\overline{X}$ point of the surface Brillouin zone (Gubanka *et al.* 1996*a*).

Fig. 5 shows our spin-resolved IPE results for 6 ML of Fe on Cu(001) (Gubanka *et al.* 1996*a*, 1996*b*). The experimental parameters were tuned in such a way that SS is observed close to $\overline{X}$. The surface state is clearly exchange split by about 0·9 eV, which is a direct and unambiguous proof of ferromagnetic order within the surface region. A detailed analysis of transitions into *sp*- and *d*-derived bulk states showed that the ferromagnetic order is not restricted to the topmost layer. The size of the splittings, however, indicated that the magnetic moment of the sublayers is reduced compared with the surface.

An adsorption experiment suggested that the ferromagnetic properties for film thicknesses between 5 and 10 ML are driven by the surface (Gubanka *et al.* 1996*a*). This supports the assumption that a structural peculiarity of the surface region, i.e. the lattice expansion between first and second layer, is responsible for its exceptional ferromagnetic properties. The polarisation of the bulk by the surface was recently also discussed and theoretically described by Skomksi *et al.* (1998).

(3b) Role of Magnetic Surface States for Gd(0001)

Gd is the prototypical local-moment ferromagnet. Unlike in Fe, where the conduction electrons are responsible for the magnetic moment, the magnetic moment in Gd originates primarily from the localised $4f$ electrons (7 μ_B). They are indirectly exchange coupled via the $5d$ conduction electrons, which contribute another $0{\cdot}63$ μ_B.

The surface of Gd(0001) with hexagonal symmetry is reported to show unusual magnetic properties with respect to Curie temperature and magnetic alignment relative to the bulk (Dowben *et al*. 1997; Donath *et al*. 1998). A truly magnetic surface state at the centre of the surface Brillouin zone is believed to play a key role in these phenomena. Theory expects a majority state below and a minority state above the Fermi level for zero temperature (Wu and Freeman 1991). Their experimental identification is one topic of interest. A further important issue is the temperature behaviour of the surface state. The way in which the spin polarisation vanishes upon approaching the Curie temperature may tell something about the degree of localisation of this d-like surface state. A Stoner-like decrease of the exchange splitting would indicate band-like behaviour, while spin-mixing, i.e. depolarisation with remaining exchange splitting even above T_C, would favour localised moments at the surface. The experimental problem is that no technique so far was able to detect the occupied and the unoccupied surface state with spin resolution in one single measurement. Spin-resolved PE detected the occupied part, spin-resolved IPE the unoccupied part, while scanning tunneling spectroscopy (STS) measured both parts, but not with spin resolution yet.

Spin-resolved PE identified the surface state at about $0{\cdot}2$ eV below the Fermi level with primarily majority character at low temperatures (Li *et al*. 1995). With increasing temperature the spin polarisation was found to vanish, but no peak shifts were observed. Therefore, the spin mixing scenario was favoured, at least in the near vicinity of the Curie temperature. The analysis of a combined PE and IPE study without spin resolution found evidence of a Stoner-like temperature behaviour with a surface Curie temperature far above the bulk Curie temperature (Weschke *et al*. 1996). The occupied part and the unoccupied part of the surface state were found to merge towards each other with increasing temperature. Attempts were made to address the problems arising from of the Fermi level cutoff in combination with a limited experimental resolution in both experiments by a sophisicated curve fitting procedure. Among other things, it was assumed that there is one majority and one minority component. STS experiments which monitor the density of states at the surface on both sides of the Fermi level in a single experiment (Getzlaff *et al*. 1998) lead to the conclusion that the exchange splitting decreases with increasing temperature from 700 to about 400 meV upon approaching the Curie temperature and remains constant above it. Recent spin-resolved PE measurements with improved energy resolution support the energetic shift towards the Fermi level with increasing temperature (Fedorov *et al*. 1998). At low temperature (80 K), they detect the occupied part of the surface state well separated from the Fermi level with predominantly majority, but nonvanishing minority character.

Our spin-resolved IPE results add some more details to this puzzling situation. Fig. 6 shows the data for three different temperatures corresponding to 90%,

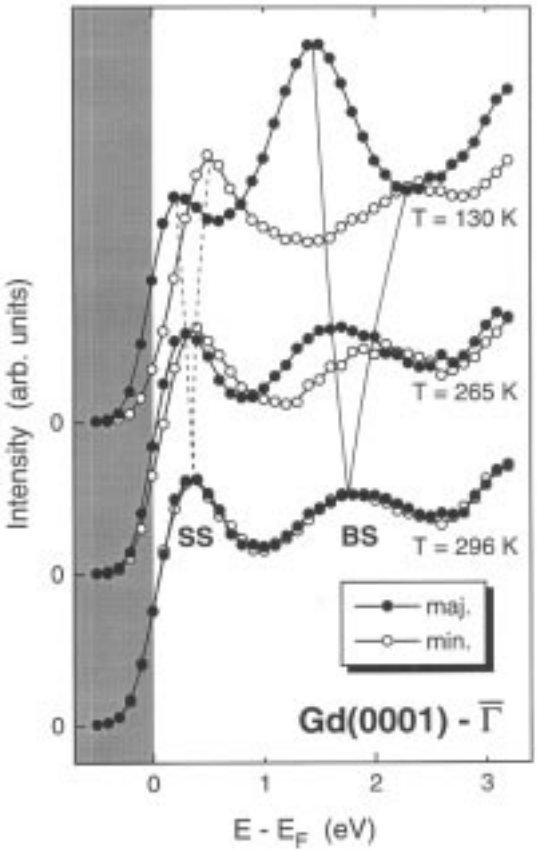

Fig. 6. Spin-resolved IPE spectra for normal electron incidence on Gd(0001) as a function of temperature. The temperature-dependent spin splittings are emphasised by solid and dashed lines for transitions into bulk (BS) and surface states (SS) respectively (Donath *et al.* 1996).

45% and 0% of the spontaneous $T = 0$ bulk magnetisation (Donath *et al.* 1996; Donath and Gubanka 1998). At low temperature, the surface-state emission consists of a minority *and* a majority part, separated in energy by at least $0{\cdot}25$ eV. These spin-split partners exhibit a Stoner-like temperature behaviour with vanishing exchange splitting at the Curie temperature. The spin-integrated spectral intensity, however, shifts slightly towards the Fermi level in agreement with STS and spin-averaged IPE work. The majority intensity above E_{F} can hardly be interpreted as tail of the occupied state, which is found well separated from E_{F} at low T. Thus, the combined results of PE, IPE, and STS lead to the conclusion that the expectation of a pure majority spin state below E_{F} and a pure minority spin state above E_{F} may be too simple. The strong localisation of the surface state may lead to considerable $f-d$ correlation effects responsible for the complexity of the observed spin-dependent spectral features. The spin polarisations of the occupied as well as the unoccupied states vanish at the Curie temperature, with a Stoner-like collapse of the spin splitting above the Fermi

level. The larger energy splitting of 700 meV between occupied and unoccupied states, however, does not collapse, it is only reduced. It exhibits a modified spin-mixing behaviour, a scenario not unexpected from model calculations (Nolting *et al*. 1994). Future theoretical as well as high-resolution experimental work will hopefully provide more insight into the nature of this puzzling surface state.

A further unresolved problem is the origin of the unusual surface magnetic properties observed for Gd(0001) in various experiments, but not supported by the electronic-structural data discussed above. Since the samples are usually prepared as thin films on various substrates, e.g. W(110), experiments combining structural and morphological information with a detailed analysis of the spin-dependent electronic structure will have to answer this question. Most experimental studies so far on the surface state were obtained from 80 to 100 Å thick Gd films on W(110), and did not confirm the findings of an enhanced surface Curie temperature and/or nonperfect magnetic alignment of surface and bulk.

The studies described show that spin-resolved IPE adds unique information to the understanding of magnetic phenomena on a microscopic level. Surface states are particularly important with respect to phenomena occurring at surfaces and in ultrathin films, where they serve as magnetic sensors.

4. Conclusions

Experimental techniques using spin-polarised electrons offer a very direct way of studying surface and thin-film magnetic properties. In this paper two techniques were described that give access to the spin-dependent electronic structure above the Fermi level. The particular strength of appearance potential spectroscopy is the element specificity, while inverse photo-emission provides detailed information about the wave-vector dependent surface electronic structure. Both techniques help to develop a microscopic picture of the physics underlying the macroscopic magnetic quantities in low-dimensional magnetic systems.

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