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Ion-induced emission of spin-polarized electrons to study surface magnetism

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A novel technique, ion-induced, angle- and energy-resolved, spin-polarized electron emission spectroscopy (SPEES) has been used to probe the electron spin polarization (ESP) at the surface of Ni(110) picture-frame single crystals which are well characterized using AES, LEED, RHEED and STM. The energy distribution of the emitted electrons (0–70 eV), which includes spin-polarized Auger electrons, is significantly different from that of electron-induced secondary electrons and contains fundamental, spin-dependent information on the local surface magnetic structure of Ni(110).

Grazing-angle ion–surface interaction provides a powerful means to study surface magnetic and electronic properties of magnetic materials [1]. At small angles of incidence, ions cannot penetrate a flat surface, they are specularly reflected and, therefore, probe the physical properties of the topmost surface layer. In addition, grazing-angle particle–surface interaction experiments allow us to study electronic transition processes occurring near surfaces. Many of these processes should depend on the local surface electronic structure and on the ion species used in the experiments.

Quite recently, we reported on first experimental data using spin-polarized, angle-resolved electron emission spectroscopy (SPEES) during reflection of hydrogen ions at various magnetic surfaces [2, 3].

In this paper, we present more detailed information about SPEES experiments performed at Ni(110) surfaces. Investigating the energy- and angle-resolved electron spin polarization (ESP) of electrons emitted from Ni(110) during grazing-angle surface reflection of hydrogen *and* helium ions, we find that the energy distribution of the emitted electrons is *completely* different from that of electron-induced secondary electron spectra. It consists of a series of characteristic peaks which can be linked, either to various electronic processes where spin-split, local surface electronic states of Ni(110) and electronic states of the reflecting particles are involved, or to spin-polarized, element-specific Auger electrons emitted from Ni or, in case of a C or O surface contamination, from C or O atoms. In the latter case, the ionic species are solely used to produce (ion-induced) holes in electron shells of Ni, C or O atoms.

We exploit the advantage of using different ion species for SPEES, a fact which helps to separate "true" Auger electron peaks from other Auger-type transitions occurring at Ni(110) surfaces. Here, we take advantage of the well known energetic shift in atomic or ionic final electron states when incident hydrogen ions are replaced by helium ions.

In SPEES, we use grazing-angle surface reflection of 15 to 30 keV H^+ or He^+ ion beams and study the emission of spin-polarized electrons as a measure of surface ferromagnetic order [2, 3]. Using an einzellens system, we detect electrons emitted along the surface normal (emission cone angle: 11°) of a remanently magnetized Ni(110) picture-frame single crystal. For energy analysis, we use an electrostatic energy analyzer and for spin analysis, we employ a calibrated detector for ESP [4]. In this ESP detector, the electron beam

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is precisely focussed on a Au target of 2 mm in diameter. The count ratios of electrons, backscattered from the Au target in two channeltrons, provides a direct measure of the ESP. For zero ESP calibration, the Au target is replaced by an Al target.

Zero ESP calibration can also be performed by replacing the ferromagnetic Ni(110) target by a *nonmagnetic* sample such as Cu where, as expected, over the whole investigated energy range, zero ESP is detected. Zero ESP values are also found when the ESP measurements are taken far above the Curie temperature of Ni where Ni exhibits a loss of ferromagnetic order.

A magnetizing field is applied in the Ni(110) surface plane to produce a macroscopic remanent magnetization along which sign and magnitude of the ESP are measured. With P, the ESP along the magnetizing axis, we obtain $P = (n^+ - n^-)/(n^+ + n^-)$, where n^+ and n^- are the fractional numbers of electrons emitted with moment parallel (majority spin electrons) and antiparallel (minority spin electrons), respectively, to this axis.

Ni(110) surfaces are prepared in a target preparation chamber at 1×10^{-10} mbar as described in ref. [1]. The samples are characterized using AES, LEED, RHEED and STM. Then the samples are transferred to the SPEES measurement chamber operating, at present, at a working pressure of 9×10^{-10} mbar where 90% of the residual gas consists of hydrogen. In order to be able to show that SPEES is sensitive to residual surface contaminants, the final cleaning of the Ni(110) surfaces, using Argon ion sputtering, is terminated when a residual C and O surface coverage of a few percent is reached.

The energy distribution of the ejected electrons is characterized by a low-intensity peak at around 2.5–3 eV, followed by a maximum at around 4.5 eV and a decrease of $n(E)$ with increasing energy (see fig. 1a). The corresponding spin distribution $P(E)$ (see fig. 1b) of the emitted electrons shows pronounced, characteristic peaks which will be used to identify various mechanisms involved in SPEES.

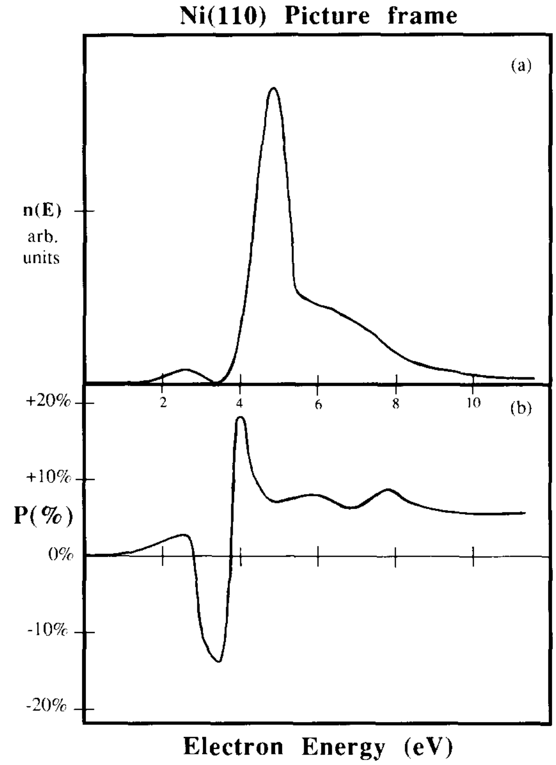

Fig. 1. Intensity distribution $I(E)$ (a) and electron spin polarization $P(E)$ (b) of spin-polarized electrons emitted during grazing-angle surface reflection of 25 keV protons at magnetized Ni(110) as function of electron energy E. (The data points are 0.3 eV apart of each other and are represented by full lines.)

From Ni(110) ground-state, one-electron band structure calculations [5] and from spin-sensitive experiments at Ni(110) surfaces [1, 5–8], it is known that valence band (V) electrons, originating from energy levels near (< 0.5 eV) the Fermi energy, possess a predominant minority spin orientation (negative ESP) of nearly −100%, whereas V electrons from energy levels below his energy range overwhelmingly possess a majority spin orientation (positive ESP). This information can be used to identify various physical processes involved in SPEES. V electrons originating in k-space from energy levels located 0.5 eV or less near the Fermi level, being emitted without any spin-flip process involved, would contribute to the negative part of the $P(E)$ curve. On the other side, V electrons originating from levels located at least 0.5 eV below the Fermi level would contribute to the positive part of the $P(E)$ curve.

We discuss the electron emission in terms of two-electron charge exchange XVV Auger electron emission denoting by X an electronic level either of the incoming ion (process (a)) or of atoms located at the surface (process (b)).

Process (a): Neutralization of the incoming ion and ejection of an Auger electron from the Ni(110) surface. For the work function of Ni(110), we use 5.04 eV and for the 1s ground state of hydrogen -13.58 eV which gives a maximum kinetic energy of the ejected Auger electrons of $13.58 - 2 \times 5.04\,\mathrm{eV} = 3.5\,\mathrm{eV}$. (Note that screening of the 1s hole of the incoming proton by the electrons at the Ni(110) surface would decrease the binding energy of the hydrogen 1s bound state and consequently reduce the maximum kinetic energy of the ejected Auger electron to slightly lower values.) Taking into account the surface band structure of Ni(110), $P(E)$ should exhibit a *negative* value at around 3 eV followed by an immediate change to *positive* P values with *decreasing* electron energy (see fig. 1b). This is indeed observed in the experiment.

In order to be able to possibly identify XVV Auger processes where process (b) is involved, we used, besides extending the experiments up to an electron energy of 70 eV, He^+ ions instead of H^+ ions for SPEES. Fig. 2a and b shows, over the energy range 0–70 eV, the spin $P(E)$ and the intensity $I(E)$ distribution of spin-polarized electrons emitted during grazing-angle (1°) surface reflection of 25 keV H^+ ions at magnetized Ni(110) surface at 300 K as function of the electron energy E.

From fig. 2b, we now observe three low-intensity (located at 2.5–3, 20 and 56 eV; see labels 1, 3, and 4 in fig. 2b) and one high-intensity peak (see label 2 in fig. 2b) located with a maximum at around 4.5 eV. The corresponding distributions $P(E)$ (see fig.2a and c) show several pronounced, characteristic peaks (see labels 1–4 in fig. 2a and labels 2–5 in fig. 2c). Replacing 25 keV H^+ ions

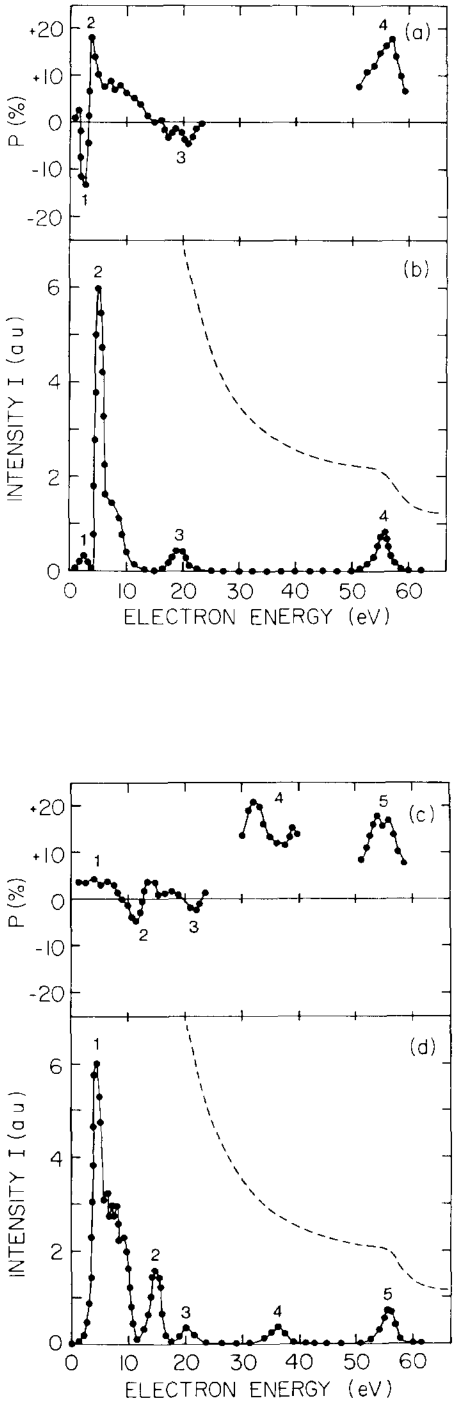

Fig. 2. Intensity distribution $I(E)$ (energy resolution: $\Delta E = 0.3\,\mathrm{eV}$) and electron spin polarization $P(E)$ (experimental error: $\Delta P = \pm 2\%$) of spin-polarized electrons emitted during grazing-angle surface reflection of 2 keV protons [(a) and (b)] and of 2 keV He^+ ions [(c) and (d)] at magnetized Ni(110) as function of electron energy E.

by 25 keV He^+ ions, results in the $I(E)$ and $P(E)$ data given in fig. 2c and d. We observe four low-intensity peaks (located at 14, 20, 36 and 56 eV; see labels 2, 3, 4 and 5 in fig. 2d) and one high-intensity peak (see label 1 in fig. 2d) located with a maximum at around 4.5 eV.

From fig. 2b and d, it is obvious that $I(E)$ is completely different from that of electron-induced secondary electron spectra (see dashed lines [9] in fig. 2b and d) which shows that, using grazing-angle ion–surface reflection, cascading effects, caused by energetic secondary ions or energetic secondary electrons, are nearly totally suppressed.

We assume that XVV Auger peaks, where X is a level of the incoming ion (process (a)), should undergo a shift in energy when H^+ ions are replaced by He^+ ions. XVV Auger transitions, where X is an empty state of a surface atom (process (b)), should not undergo a shift. Therefore, replacing H^+ ions by He^+ ions should cause an energetic shift of peak 1 (fig. 2b) by 11 eV, which is the difference between the $He^+(1s)$ ($E_X = -24.6$ eV) and $H^+(1s)$ ground state energies. This is indeed observed in the experiment (see peak 2 in fig. 2d) and corroborated by the occurrence of a change of P from negative (-5%) to positive values ($+5\%$) (peak 2 in fig. 2c) as discussed for the H^+ data.

The electron peak located at 36 eV (see peak 4 in fig. 2c) was already observed by Hagstrum and Becker [10] and by Niehaus and coworkers [11] and interpreted by the latter group as a two-electron capture process from He^{2+}–Cu(110) collisions leading to $He^{**}(2p^2)$ decaying to $He^+(1s)$ followed by the emission of an electron of 36 eV kinetic energy. We remark that, in the present experiments, a residual part of the ionic He beam consists of He^{2+} ions. We observe nonzero ESP values (see peak 4 in fig. 2c) which is consistent with the findings of Hagstrum [10] that this peak contains information on the local surface density of states, which for Ni should exhibit nonzero ESP values.

Process (b): Comparing fig. 2b and d, we observe that the three peaks located at around 4.5, 20 and 56 eV (see peaks 2, 3 and 4 in fig. 2b and peaks 1, 3, 5 in fig. 2d) are independent of the ion species used in the experiments and are not shifted to higher energies by the use of He^+ ions instead of H^+ ions. Therefore, we attribute these peaks to XVV Auger transitions where the ions are solely used to produce ion-induced holes in the electron shells of the surface atoms. Comparing our data with presently existing Auger electron data for Ni and with data obtained by Landolt and coworkers [9] using spin-polarized Auger electron spectroscopy at Ni(100) surfaces, we identify the peak located at 56 eV (see peak 4 in fig. 2b and peak 5 in fig. 2d) with a $M_{23}VV$ Ni Auger decay. We note, that, after background subtraction, these authors find similar P values for this peak.

Regarding the peak (see label 3 in fig. 2b and d) located at around 20 eV, we remark that the intensity of this peak depends strongly on surface cleanness, and therefore, can be attributed to Auger decays where X is, induced by the incoming ions, a hole level in the surface contaminants.

Due to similarities of the electron spectra (peak 2 in fig. 2b and peak 1 in fig. 2d) at around 4.5 eV, induced by H^+ and He^+, respectively, we correlate this feature with the substrate. A possible mechanism could be an ion-induced, *kinematically enhanced* XVV Ni Auger decay with X the level in the lower part of the valence band.

In conclusion, we note that, provided the future availability of a quantitative theory of SPEES and more refined experimental data, SPEES will advance towards an experimental technique of great potential for studies on the spin-polarized, local surface electronic structure of magnetic materials.

Acknowledgements

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