Spin-polarized electron emission during impact of fast ions on a magnetized Fe(100) surface

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We report on the emission of spin-polarized electrons during grazing and oblique impact of 2–100 keV H^+, He^+, Ne^+, and Ar^+ ions upon a magnetized Fe(100) surface. A combined analysis of spin state and energy of emitted electrons elucidates processes occurring in inelastic ion-surface scattering such as electron cascading or plasmon-assisted electron emission and indicates a significant enhancement of the spin moment at the topmost layer of Fe(100).

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I. INTRODUCTION

Emission of electrons induced by collisions of energetic ions with surfaces is an important phenomenon to study inelastic ion-surface scattering. Ample work has been devoted to ion-induced electron emission in studies on, e.g., number and statistical distribution, electron energy and angle of emission, and projectile beam and target properties.[1] For scattering from a ferromagnetic surface, the spin state of emitted electrons as an additional observable has received less attention, presumably owing to experimental complexities of a spin analysis of electrons.

From a spin analysis of electrons ejected by impact of ions, one expects to identify various processes occurring in inelastic ion-surface scattering and yield information on magnetic and electronic properties of surfaces. Although, for the analysis of magnetic surfaces, spin-polarized electron emission excited by fast *electrons* has evolved into an established technique,[2] excitation by *ions* bears interesting aspects as sputtering for magnetic depth profiling of films,[3] or the sensitivity to the topmost atomic layers of flat surfaces by using grazing incidence ion scattering.[4,5] In the latter case, grazingly scattered ions are specularly reflected from the surface without penetration of the bulk ("surface channeling"[6]).

Here we report on ion-induced emission of spin-polarized electrons from a magnetized Fe(100) surface with the emphasis on grazing incidence impact of ions. Spin- and energy-resolved spectra of electrons emitted in direction of the surface normal of the target are measured for different projectile ions and beam energies. In our studies we have investigated effects such as cascading of electrons and plasmon-assisted electron emission. We explore magnetic properties of the Fe(100) surface, which is predicted to show significantly enhanced spin moments at the topmost layer.[7]

II. EXPERIMENT

The experiments were performed in an ultrahigh-vacuum chamber (base pressure around 10^{-11} mbar), attached via differential pumping stages to the beam line of a small electrostatic ion accelerator with a 10 GHz electron cyclotron resonance (ECR) ion source. A well-collimated ion beam (H^+, He^+, Ne^+, Ar^+) (angular divergence 0.02°) is incident at a small angle Φ (typically 1°) upon the (100) surface of a bcc Fe crystal mounted on the gap of a soft-magnetic yoke. The azimuthal angle of incidence is a few degrees off the [010] direction in the surface plane ("random azimuthal orientation"). The surface is prepared by cycles of grazing sputtering ($\Phi \approx 3°$) with 25 keV Ar^+ ions and subsequent annealing to about 700 °C. During measurements the crystal is kept at room temperature in a remanent, single-domain state of magnetization along an easy axis [001] or $[00\overline{1}]$ in the (100) surface plane ("in-plane magnetization"), generated by current pulses through a coil and checked by the magneto-optical Kerr effect. Residual magnetic fields in the region of the target crystal are compensated to a few μT by three orthogonal Helmholtz coils and a μ-metal shield forming the inner wall of the UHV chamber.

Electrons emitted normal to the surface plane are collected within a detection cone of 30° full opening angle and enter a cylindrical sector field energy analyzer via a transfer lens (Focus CSA300). The CSA features a 300 mm dispersive distance and 90° deflection. After energy separation, electrons are imaged by a subsequent lens into a spin-polarized low-energy electron diffraction (SPLEED) detector.[8] In this detector electrons are backscattered at a constant energy of 104.5 eV from a clean W(100) surface and the intensities of (2,0) and $(\overline{2},0)$ low-energy electron diffraction (LEED) spots are recorded by means of a pair of channeltrons. From the asymmetries A of signals of corresponding channeltrons, caused by different cross sections for left-right scattering, the "in-plane" component of the electron spin polarization can be deduced. In order to correct for instrumental asymmetries (typically 20%) owing to different detector efficiencies, misalignment of incident beam, etc., the polarization P is obtained from measurements under reversed magnetizations (electron spin polarization) according to[9]

$$P = \frac{A}{S} = \frac{1}{S}\,\frac{\sqrt{N_1^{\uparrow}\cdot N_2^{\downarrow}} - \sqrt{N_2^{\uparrow}\cdot N_1^{\downarrow}}}{\sqrt{N_1^{\uparrow}\cdot N_2^{\downarrow}} + \sqrt{N_2^{\uparrow}\cdot N_1^{\downarrow}}}, \tag{1}$$

where ↑ and ↓ refer to the direction of magnetization, N_1 and N_2 are counts for corresponding channeltrons, and $S \approx 0.2$ is the analyzing power (effective Sherman function). The assumption in our analysis is that electron trajectories are not affected by the reversal of the magnetization. Previous studies using a similar experimental setup[5] showed that this holds only approximately for low-energy electrons. We therefore checked the asymmetries A against asymmetries A_{Ta} measured for unpolarized electrons emitted during ion scattering from a paramagnetic Ta sheet attached directly near the Fe crystal and translated to its position. Then one has

$$A = \frac{PS + A_{\mathrm{Ta}}}{1 + PSA_{\mathrm{Ta}}}. \tag{2}$$

Measurements were performed at constant pass energy (usually 80 eV) and energy resolution (3.0 eV FWHM) with primary ion currents of 1 to 100 nA, depending on projectile sort and beam energy, with electron count rates of up to some $10^4\ \mathrm{s}^{-1}$. Emitted electrons were accelerated by a bias voltage of $U_B = -10$ V applied to the target, in order to reduce effects of residual stray fields and discriminate against secondary electrons emitted from the chamber wall. From electron-trajectory calculations using the electron-optics simulation program SIMION,[10] we infer that the bias voltage increases count rates at low electron energies (e.g., about 30% at 5 eV and 10% at 20 eV for -10 V bias voltage), resulting in apparently "steeper" electron-energy spectra, whereas energy shifts of spectral features (in addition to the intended 10 eV shift) are negligible. In test measurements, this has been found to hold for bias voltages $-U_B > 5$ V so that measured energy spectra are expected to represent the original energy distributions. Moreover, we checked that a bias voltage on the target does not affect count rate asymmetries (spin polarizations), provided $-U_B > 5$ V.

III. RESULTS AND DISCUSSION

A. Dependence on beam energy for $H^+ \rightarrow Fe(100)$

Figure 1 shows energy spectra and spin polarization spectra of electrons emitted under grazing bombardment of Fe(100) with H^+ ions for different beam energies E_0. Energy spectra [Fig. 1(a)] exhibit the behavior well established for oblique incidence of ions or electrons: a pronounced peak at $E = 2$–3 eV (E measured from vacuum level) and a gradual decrease towards higher electron energies with a slope decreasing with increasing ion beam energy, as observed for other d-metal targets.[11] The spin polarization [Fig. 1(b)] is highest for small electron energies and falls to a lower level for energies exceeding about 8 eV. The spectra thus resemble spectra of polarized electrons excited by keV electrons.[12,13] Yet, the spin polarization is slightly higher for ion excitation compared to conventional excitation with electrons, where

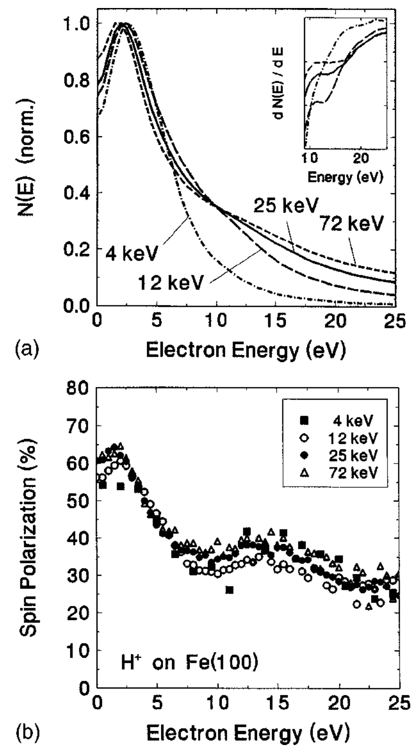

FIG. 1. Normalized energy spectra $N(E)$ (a) and spin polarization (b) of electrons emitted during grazing impact of H^+ ions on a magnetized Fe(100) surface. The incidence angle Φ to the surface plane is adjusted to warrant constant transverse energy $E_\perp = E_0 \sin^2\Phi = 8$ eV. Target temperature 300 K, beam energy as indicated. Inset: derivative spectra $dN(E)/dE$.

the spin polarization of 10–20 eV electrons is close to the mean polarization of conduction electrons in bulk Fe (27%).[14–17]

The pronounced peak in the polarization spectra [Fig. 1(b)] at about 13 eV was observed previously on Fe(100) (Refs. 5,14,15) and Fe(110) (Ref. 16) and attributed to the spin-dependent band structure above the vacuum level[18] or the crystallinity of the sample.[16] The question rises whether this peak is related to structures in energy spectra $N(E)$. We therefore show derivative spectra dN/dE in the inset of Fig. 1(a), in order to discern weak structures. For high beam energies E_0 we indeed observe a feature at about 13 eV, which, however, does not appear at 4 keV beam energy, where the spin-polarization peak is well developed.

The feature in the energy spectra at 13 eV may be attributed to bulk plasmon excitation in Fe with an energy $E_p = 17.8$ eV.[19,20] It has been proposed theoretically that excitation of bulk plasmons is effective even under grazing scattering where ions do not penetrate the surface.[21] Decay of plasmons into electron-hole pairs leads to a structure in the energy spectra at $E = E_p - \Phi = 13.4$ eV with $\Phi = 4.4$ eV being the work function of Fe(100).[5] In order to estimate different threshold energies for plasmon excitation by electrons and ions, we use a Fermi wave number $k_F = 1.1\ \text{Å}^{-1}$ (Fermi energy $E_F = 4.61$ eV), deduced from Fermi-surface measurements of Fe with the simplifying assumption of a spherical Fermi surface.[22] The threshold energy for direct plasmon ex-

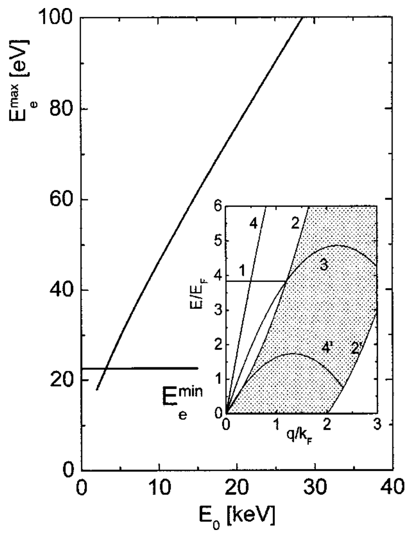

FIG. 2. Dependence on impact energy of the maximum energy E_e^{max} of excited electrons produced in proton-electron collisions. E_e^{min} is the minimum electron energy for direct plasmon excitation as explained in the inset. Inset: elementary excitation spectrum of conduction electrons in Fermi units. 1: plasmon, 2 and 2′: upper and lower borders of electron-hole-pair excitation. 3, 4, and 4′: maximum energy transfer of an electron with energy E_e to conduction electrons for $E_e = E_e^{min}$, $E_e > E_e^{min}$, and $E_e < E_e^{min}$ (no plasmon excitation), respectively.

citation in the conduction electron system by an energetic particle of mass M is given by[23]

$$E^{th} = E_F \frac{M}{m_e}\left(1 + \frac{1+m_e/M}{2}\frac{q_c}{k_F}\right)^2 \quad (3)$$

with electron mass m_e and

$$\frac{q_c}{k_F} = \sqrt{1+E_p/E_F} - 1, \quad (4)$$

the plasmon cutoff wave number q_c as deduced from the intersection of the plasmon dispersion curve with the upper border of the electron-hole pair continuum (curves 1 and 2 in the inset of Fig. 2). The resulting threshold for plasmon excitation in Fe by direct proton-electron interaction is $E_0^{th} = 21.7$ keV.

It has been shown[24–27] that plasmon formation may take place also at lower beam energies via secondary electrons of sufficient high energies $E_e > E_e^{th} = 22.4$ eV for Fe (E_e refers to bottom of conduction band, i.e., $E_e = E + E_F + \Phi$), as well as during electron capture processes by the moving ion.[25,27,28] Figure 2 shows the calculated beam energy dependence of the maximum energy of excited electrons produced in direct proton-conduction-electron collisions

$$E_e^{max} = E_F(1 + 2\sqrt{m_e/M}\sqrt{E_0/E_F})^2. \quad (5)$$

We observe electrons clearly above E_e^{th} even for 12 keV beam energy, which is below E_0^{th}. However, with decreasing beam energy E_e^{max} approaches E_e^{th}. Approximately at 4 keV, the effect of plasmon excitation by secondary electrons vanishes. In addition, taking into account the velocity dependent binding energy of the bound state calculated with a screening of the moving proton based on an extension of the Friedel sum rule to finite velocities, we derive a threshold energy for plasmon creation during the capture process of $E_{0,capt}^{th} \approx 8$ keV.[29] This could explain the absence of a contribution to electron emission at 13 eV for the lowest beam energy (4 keV) and suggests an interpretation of the spectral feature in terms of plasmon decay, instead of effects as diffraction of electrons.[30]

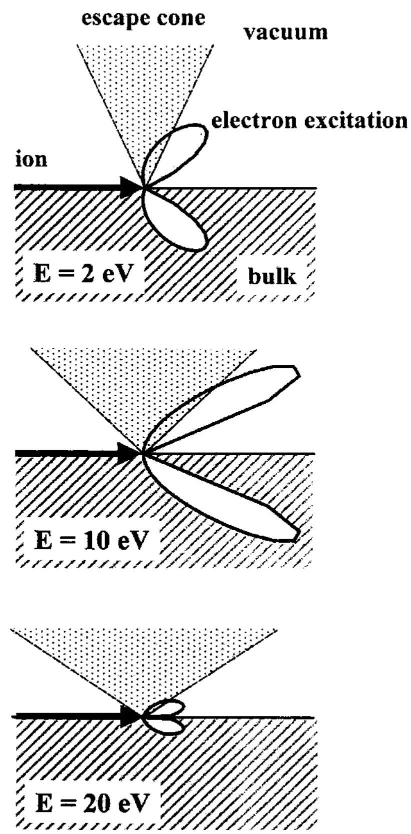

FIG. 3. Angular dependence of electron excitation in direct collisions of grazingly incident 25 keV protons with conduction electrons for electron energies $E = 2$ eV, 10 eV, and 20 eV. Escape cones are given by maximum emission angle with respect to surface normal $\alpha_c = 25.2°$, 46.5°, and 56.1°.

The enhancement of the spin polarization of emitted electrons towards low excitation energies [Fig. 1(b)] is known from electron-induced electron emission, where it has been related to the formation of an electron cascade. Due to spin dependent electron scattering cross sections, caused by an excess of unfilled minority-spin electronic states in Fe over unfilled majority-spin states, minority-spin electrons are scattered more effectively during their transport to the surface, resulting in enhanced emissions of majority-spin electrons ("spin-filter effect").[31] Our observation of an enhanced polarization of low-energy electrons indicates that cascade effects are important also for grazing impact of energetic ions.

The presence of electron cascades in grazing ion-surface collisions seems plausible considering electron excitation functions. Figure 3 shows polar plots of the calculated angular dependence of electron excitation in screened proton-electron collisions for a projectile energy $E_0 = 25$ keV and energies of excited electrons $E = 2$, 10, and 20 eV.[23] Excitation takes place with a preference in the direction of the ion beam with large momenta of excited electrons parallel to the surface plane. Only a minor part of the excited electrons has a normal component of momentum sufficient to surmount the surface barrier directly and escape into vacuum. This requires excitation angles with respect to the surface normal smaller than the opening angle α_c of the so-called escape cone.[23] The majority of electrons, however, undergo elastic and inelastic electron-electron scattering prior to emission and initialize an electron cascade.

In passing we note that our energy spectra differ from spectra recorded by Rau *et al.*[4,32] for comparable experimental conditions. For 27 keV H^+ ions impinging upon Fe(100) a shift of the maximum to 4 eV and, more importantly, a nearly complete suppression of higher-energy electrons ($E >$ about 14 eV) is reported for grazing-incidence conditions ($\Phi = 1.0°$). Those authors have pointed out that the spectra are significantly different from spectra obtained for excitation by electrons or ions at larger Φ. As an important consequence, they concluded that electron cascade processes are absent for grazing impact. These findings are in contrast to results of our study, where differences between excitation by ions and electrons seem to be more subtle for energy and polarization spectra. This becomes particularly clear for the dependence of electron emission on the incidence angle Φ for a fixed beam energy.

As a comment to this controversy we mention that for the specific experimental conditions here total electron emission yields amount to about 10. This cannot be explained without substantial contributions from kinetic emission. A detailed discussion of this problem can be found in a recent review paper.[33]

B. Dependence on incidence angle for $H^+ \rightarrow Fe(100)$

In Fig. 4 we show energy and spin polarization spectra of electrons emitted under 25 keV H^+ bombardment for different incidence angles Φ. We observe that polarization spectra have a similar shape for all incidence angles [Fig. 4(b)], although polarization values increase with decreasing Φ, in particular at low electron excitation energies. This becomes clearer from Fig. 5, where the average spin polarization of low-energy (0–4 eV) and higher-energy electrons (10–20 eV and 20–30 eV) is displayed as function of incidence angle. The critical angle for surface channeling ($\Phi_c \approx 2.1°$) is marked by a dashed line. For incidence angles below Φ_c, penetration of protons into the bulk is suppressed, unless mediated by structural defects as surface steps. We see that for all electron-energy intervals the electron spin polarization increases with decreasing incidence angle from large Φ up to about Φ_c. For $\Phi > \Phi_c$, the ions penetrate into the bulk and excite electrons in layers beneath the surface, the excitation depth being limited by the escape depth of excited electrons [typically 10 Å (Ref. 34)]. In comparison with the regime of surface channeling, no impact-parameter selection is effective. These conditions are similar to excitation by keV electrons, which explains why the spin polarization observed for large incidence angles Φ of ions is similar to polarizations measured for electron-induced electron emission [Fig. 5, open symbols (data taken from Ref. 17)]. With decreasing Φ, the relative contribution of the surface layer to the excitation volume is increasing and, for $\Phi \leq \Phi_c$, electrons are predominantly excited at the topmost surface layer.

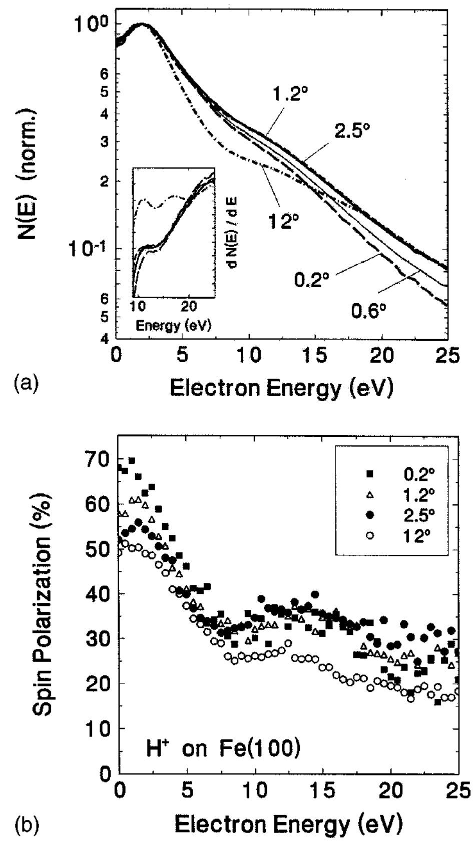

FIG. 4. Normalized energy spectra $N(E)$ (a) and spin polarization (b) of electrons emitted during grazing impact of 25 keV H^+ ions on Fe(100) for different Φ. Target temperature 300 K. Inset: derivative spectra $dN(E)/dE$.

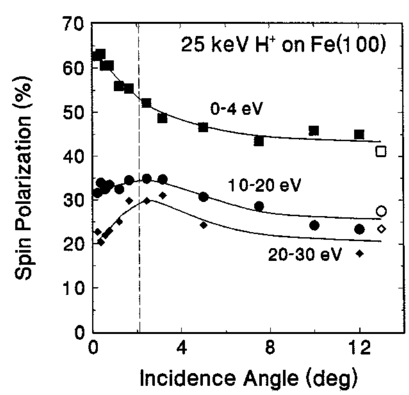

FIG. 5. Spin polarization of electrons emitted during grazing impact of 25 keV H^+ ions on Fe(100) versus incidence angle Φ, averaged over electron-energy ranges as indicated. Solid lines are drawn to guide the eye. The dashed line shows the critical angle for penetration of ions into the bulk ($\Phi_c \approx 2.1°$). Open symbols refer to the spin polarization measured for oblique impact of 2 keV electrons.

An enhancement of the spin polarization of ion-induced electrons for incidence angles approaching the critical angle for surface channeling was also reported by Rau *et al.*[35,36] at higher beam energies E_0. For 150 keV H^+ ions impinging upon 4 ML Fe(100) films grown on Pd(100) surfaces, an increase of the spin polarization for 10–12 eV electrons from 28% for oblique incidence angles to 37% for grazing angles is observed. Similar data are found for 25 keV Ne^+ ions scattered off the (100) surface of bulk Fe.[35] Assuming that the polarization of electrons with energies between 10 and 20 eV scales roughly with the average net magnetization, this would imply an enhancement of the magnetization at the surface layer. From Fig. 5, we infer for 10–20 eV electrons an enhancement of the polarization from about 27% for large Φ to 35% for $\Phi \approx \Phi_c$ at a temperature $T=300$ K. In order to deduce from these values an enhancement of the ground state magnetization $m(0)$ at $T=0$, enhanced thermal spin excitations at the surface compared to the bulk should be taken into account. Pfandzelter and Potthoff[37] have reported a reduction of the ground state magnetization for Fe(100) at $T=300$ K of $m(T)/m(0)=0.91$ for the topmost surface layer. We thus deduce an enhancement of the ground state magnetization $m(0)$ at the surface of about $(35\%/0.91-27\%)/27\% = 42\% \pm 10\%$. This finding corroborates theoretical predictions of an increase in ground-state spin moment at the surface of Fe(100) films over that of bulk layers by 30–32 %.[7,38] We note that an experimental verification of enhanced surface moments requires a sensitivity to the topmost surface layer, because already from the second layer bulk electronic properties are expected.[7,38]

For incidence angles smaller than the critical angle $\Phi < \Phi_c$ we observe that the spin polarization of electrons with higher energies (10–20 eV and 20–30 eV) decreases with decreasing Φ (see Fig. 5). This finding may be explained as follows. Within the regime of surface channeling, impact parameters in collisions of ions with surface atoms increase with decreasing incidence angle. *Ab initio* calculations of the electronic structure of Fe(100) (Refs. 7,38) show that the spin density decreases strongly with distance from atomic sites, thereby changing from predominantly *d* character to *sp* character away from the surface layer. Low-energy electrons (0–4 eV) have a cascade character and originate from primary excited electrons with higher energy. Because for grazing ion impact most electrons involved in the cascade formation stem from the surface layer with a higher electron spin polarization, electrons enriched by the cascade mechanism (spin-filter effect) will have higher spin polarizations. Following Siegmann,[39] the polarization of low-energy cascade electrons is $P_c \approx P_0 + P_t$, where P_0 is the average polarization of primary electrons and P_t the transport polarization, given by the spin-dependent scattering cross sections ($P_t = 0.28$ for Fe). With $P_0 \approx 35\%$, as measured for grazing incidence angles (Fig. 5, circles), we deduce $P_c = 63\%$ for low-energy electrons, in agreement with the experiment (Fig. 5, full squares).

The tails at high excitation energies in the energy spectra [Fig. 4(a)] have slopes which decrease with increasing ion incidence angle Φ up to $\Phi \approx \Phi_c$ and stay constant when penetration into the bulk becomes possible. This can be attributed to a preponderance of large-impact parameters in the regime of surface channeling, which impedes high-energy electron excitation. The situation is different for low-energy cascade electrons, where a steeper decrease in (normalized) energy spectra is observed for $\Phi > \Phi_c$. This points to a well-developed electron cascade at large incidence angles, comparable to conventional excitation with keV electrons.[5,17]

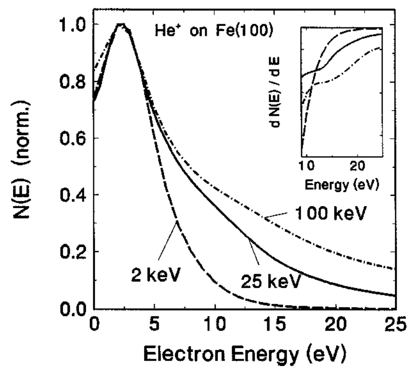

FIG. 6. Normalized energy spectra $N(E)$ of electrons emitted during grazing impact of He^+ ions on Fe(100). Incidence angle to the surface plane $\Phi = 1.6°$, target temperature 300 K, beam energy as indicated. Inset: derivative spectra $dN(E)/dE$.

C. He^+, Ne^+, $Ar^+ \rightarrow$ Fe(100)

In Fig. 6 we show direct and derivative (inset) energy spectra for grazing impact of He^+ ions ($\Phi = 1.6°$) on Fe(100) for different beam energies. The spectra show a similar behavior as discussed for excitation by H^+ ions. The maximum energy transfer by direct projectile-electron collisions calculated from Eq. (5) is $E_e^{\max} = 10.2$ eV for 2 keV beam energy, 34.2 eV for 25 keV, and 91.2 eV for 100 keV. This implies for the lowest beam energy (2 keV) a maximum energy of emitted electrons of $E = E_e^{\max} - E_F - \Phi = 1.2$ eV. Thus, potential electron emission with a maximum electron energy estimated by $E = I - 2\Phi - V_{\mathrm{im}} \approx 14$ eV dominates ($I = 24.6$ eV ionization potential, $V_{\mathrm{im}} \approx 1-3$ eV image potential).

The derivative spectra (Fig. 6, inset) show a structure around 13 eV for $E_0 = 25$ keV and more pronounced for 100 keV. The formal threshold energy for plasmon formation in direct ion-electron interaction is $E_0^{\mathrm{th}} = 86.4$ keV. Thus the faint structure for 25 keV beam energy is ascribed to plasmon formation via secondary electrons, because $E_e^{\max} = 34.2$ eV $> E_e^{\mathrm{th}} = 22.4$ eV. This process is not possible for $E_0 = 2$ keV, in agreement with our observation.

Figure 7 a shows direct and derivative (inset) energy spectra for grazing scattering ($\Phi = 1.6°$) of H^+, He^+, Ne^+, and Ar^+ ions from the Fe(100) surface for a beam energy of 25 keV. The behavior of the nearly exponential tail at large electron energies is consistent with Fig. 1(a), in the sense that the probability for excitation of high-energy electrons increases with projectile velocity, i.e., from Ar^+ to H^+. From derivative spectra [Fig. 7(a), inset] we see the feature attributed to plasmon-decay induced electron emission for H^+ and He^+. For Ne^+ and Ar^+ plasmon formation is not possible, because

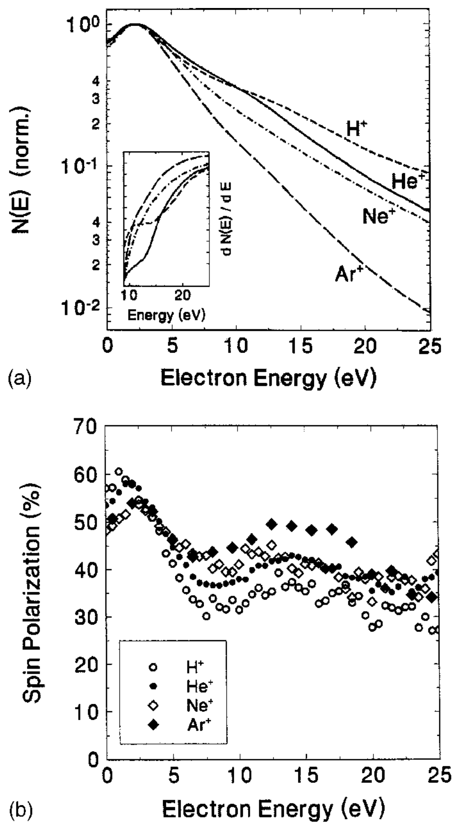

FIG. 7. Normalized energy spectra $N(E)$ (a) and spin polarization (b) of electrons emitted during grazing impact of 25 keV H^+, He^+, Ne^+, and Ar^+ ions on Fe(100). Incidence angle to the surface plane $\Phi = 1.6°$, target temperature 300 K, beam energy as indicated. Inset: derivative spectra $dN(E)/dE$.

E_0^{th} is much higher (435 keV for Ne^+) and $E_e^{\max}$ is too low (14.4 eV for 25 keV Ne^+). Note that for Ne^+ potential-electron emission may give a contribution to the electron emission spectra for electron energies up to $E_e^{\max} \approx 11$ eV (ionization energy 21.6 eV), thus rationalizing similar slopes of energy spectra for He^+ and Ne^+ excitation.

The spin polarization corresponding to those energy spectra [Fig. 7(b)] shows a similar behavior for all projectiles, irrespective of whether plasmon excitation is possible or not. In particular, the peak around 13 eV and the increase of the spin polarization towards low energies are found for all projectiles. This is in contrast with a relation between the plasmon feature in the energy spectra and the peak in the spin polarization.

It is interesting that the average spin polarization increases from H^+ to Ar^+ excitation. Tentatively, two effects may be envisaged to explain this finding. From concepts of surface channeling, the probability for penetration into the bulk is reduced, so that the sensitivity to the topmost surface layer is largest for Ar^+. The contribution of kinetic electron emission compared to potential emission decreases with decreasing projectile velocity, i.e., from H^+ to Ar^+. This should also enhance the sensitivity to the surface and entails differences in k-space selectivity of electron excitation. At low projectile velocities, potential emission favors emission of electrons close to the Fermi surface. *Ab initio* calculations,[7] find an enhanced surface magnetism at Fe(100) based on pronounced surface states made up from d orbitals. These surface states lie less than 1 eV below the Fermi energy. A predominant excitation of the surface-state electrons might explain the larger spin polarization observed for heavy ion impact. We note that these arguments are supported by our previous study on electron emission by impact of highly charged N^{q+} ions,[17,40] where an increase of the polarization of low-energy electrons with charge q was observed.

IV. CONCLUSIONS

In this work we report on electron emission during grazing and oblique impact of 2–100 keV H^+, He^+, Ne^+, and Ar^+ ions upon a magnetized Fe(100) surface. A combined analysis of energy and spin state of electrons shows that the spin may serve as an additional observable to unravel processes in grazing ion-surface scattering. The main observations are as follows.

(1) Energy spectra and spin polarization are similar for oblique and grazing incidence angles. In particular, the spin polarization is significantly enhanced towards the lowest electron energies. A similar enhancement is established for *electron*-induced electron emission and ascribed to a spin-filter effect of cascading electrons. A pronounced spin-filter effect for *ion*-induced electron emission thus shows a predominance of cascade electrons at low energies even for grazing incidence of ions. This finding corroborates results from our previous study on proton-induced electron emission from Cr films grown on Fe(100),[5] where the mean escape depth of emitted electrons increases from about one atomic layer for higher electron energies ($E > 8$ eV) to about four layers towards low electron energies.

(2) A polarization fine structure at electron energies around 13 eV, known for *electron*-induced electron emission, is observed also for excitation by *ions*, irrespective of ion sort, beam energy, or incidence angle. At the same electron energy, we observe a prominent feature in energy spectra, which is ascribed to plasmon-assisted electron emission. A relation between plasmon shoulder and polarization fine structure can be excluded owing to a different dependence on ion beam energy.

(3) We observe a significant effect of the electron spin polarization on the incidence angle of ions, depending on the electron energy. Assuming that the polarization of electrons with energies of 10–20 eV roughly scales with the average net magnetization, we find evidence for an enhancement of the ground state spin moment at the topmost layer of Fe(100). The observed effect of about 40% is in fair agreement with band structure calculations for the Fe(100) surface.[7]

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