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Evaluation of real-space images of Pt-single crystals produced by backscattered electrons in the kiloelectronvolt range

Markus Lambrigger

Laboratorium für Festkörperphysik, ETH-Zürich, CH-8093 Zürich, Switzerland

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Abstract. — The strongly forward-peaked nature of electron-atom scattering in the kiloelectronvolt range is responsible for the fact, that electrons which are backscattered from single crystals loosing less than 5% of their energy in the scattering process, show a strong rise of intensity along directions defined by atomic rows. The spatial imaging of such electrons, reveals the crystallography of the near-surface regions in real-space. The surface sensitivity of this imaging method with backscattered electrons, can be influenced by choosing the angle of the primary-electron incidence and the energy of the incident primary-electrons. In this paper, an evaluation concept is displayed which allows to determine the mean depth of the image-forming electron sources and scattering atoms, if the single crystal structure of the measured sample is already known. The model also enables the identification of unknown near-surface structures, taking into account crystallographical restrictions.

1. Introduction.

The angular intensity-distribution of backscattered electrons from Au-polycrystals, using primary-electron energies between 10 and 50 keV, was investigated by Kanter [1]. He showed, that the angular intensity-distribution is mainly affected by the angle of electron incidence \( \Phi \), i.e. by the angle between the surface-normal \( \mathbf{n} \) of the sample and the direction of the incident electron beam. He explained this fact by intense elastic and inelastic multiple-scattering of the detected backscattered electrons, for in this case the angular intensity-distribution can be nearly treated as a diffusion problem [2]. Using this approach, the angular intensity-distribution is merely a function of the absorption strength which, finally, is determined by the angle of electron incidence. But Kanter [1] also found that a reflection part has to be added with increasing angle \( \Phi \) to the diffusion part of the backscattered electrons, which is calculated by use of the diffusion approach cited above, in order to explain the experimental results completely.

Low-energy electrons, which are elastically and coherently backscattered form single crystals, give rise to the well-known low-energy diffraction (LEED) patterns. In most cases these LEED patterns can be interpreted as a coherent sum of waves, scattered once at different
lattice sites. In distinction, patterns formed by X-ray photoelectron diffraction (XPD) arise from a purely incoherent sum of electron sources, which are localized at the sites of atoms undergoing a photoemission process [3]. The gross features of these patterns, namely the bright spots, display the directions of the atomic rows due to the strongly forward-peaked nature of the electron-atom scattering at energies above 300 eV [4]. The fine structure being observed around these bright spots, preserves details of multiple-scattering between atomic rows.

Similar patterns as those obtained in XPD, can also be generated by using primary-electrons as an excitations source instead of X-rays. Harp et al. [5] have reported patterns obtained at 1.075 eV from Cu with a (001) surface, showing the crystalline symmetry of the substrate. The authors are aware of the fact, that the observed pattern was built up by contributions of atomically localized sources of incoherent, quasi-elastically scattered electrons (emitters).

Fig. 1. — Real-space image pattern obtained from a Pt-single crystal with a (110)-surface using a primary-electron energy of 2 keV. The angle of electron incidence \( \Phi \) is 64°. The bright spots, which show a three-fold symmetry, are produced by atomic rows in \( \langle 110 \rangle \)-directions. The centre of the display unit is nearly parallel to the \( \{111\} \)-direction. It has been shaded by one of the electron sources.
Furthermore, calculations of Xu et al. [6] show that multiple-scattering remains negligible, if only a limited number of atoms are involved in the scattering process. Recently, Aebi et al. [7] have reported that the influence of the reciprocal space, i.e. the coherent part of the scattering, decreases with increasing energy of the excitation electrons. The conclusion was based on observations made with different experimental parameters and was justified by the strongly forward-peaked nature of the electron-atom scattering at a primary-electron energy of 2 keV (see Fig. 1). In this work, an intensity evaluation concept for the method described above, which enables the imaging of real-space of single crystals in real time by detecting quasi-elastically backscattered electrons and using primary-electrons as excitation sources, is solved.

2. Experimental techniques.

An electron beam in the energy range of 1.5-2.5 keV with an intensity of a few μA was focussed on a Pt(110)-single crystal surface. The surface was always prepared until the contamination was no more detected by low-energy diffraction (LEED) patterns. The experiments were carried out in an ultra-high vacuum chamber, equipped with a hemispheric LEED-type display system, placed concentrically with regard to the specimen. Two electron sources having had different positions with respect to the display system, were available (see Fig. 2a). Thus, electron backscattering patterns (EBSP) not only close but also remote from the incidence of the electron beam, could be compared with no need of changing the position of the sample with respect to the display unit. The retarding voltage was set 40 eV below the value of the primary-electron energy, in order to allow only the quasi-elastically scattered electrons with low energy losses to contribute to the pattern formation. The patterns were recorded by a LynxXMC CCD digital imaging system having an image size of 165 × 192 picture elements (pixel) and using a 24 mm objective lens. The exposure was, as a rule, less than a few seconds at an aperture of f/8. The angular resolution of the overall system was 0.5°/pixel in the central position of the screen.

3. Evaluation model for single crystals.

Multiple-scattering calculations of Xu et al. [8] for Cu-single crystals and primary-electron energies of 1 keV show, that the imaging of the atomic rows is mainly caused by the electrons, which are scattered just once elastically after the last incoherent, quasi-elastic scattering event. This effect describes the defocussing of the backscattered electrons caused by multiple-scattering and is, therefore, generally called « defocussing effect ». Now we assume, that the defocussing effect is also essential for Pt-single crystals, if the primary-electron energies being used are in the range between 1.5 and 2.5 keV. Besides, the background intensity-distribution is then approximately equivalent to the hypothetical, angular intensity-distribution of the backscattered electrons before they experience their last incoherent scattering event. Furthermore, the background intensity-distribution is, following this approach, comparable to the angular, overall intensity-distribution of the corresponding amorphous or polycrystalline materials.

Taking the two assumptions mentioned above into account, the imaging of the atomic rows is due to the last elastic, forward-peaked scattering of these electrons, which are just scattered once elastically after the last incoherent, quasi-elastic scattering event. Other electrons, such as electrons which are elastically multiple-scattered or not scattered anymore after the last incoherent scattering event, only contribute to the background intensity, following this approach. The above-mentioned assumptions lead to the consequence that intensity profiles are symmetrical with respect to the intensity-peak of a highly symmetrical atomic row, if the background intensity is constant in the evaluated crystallographical region and if the profile passes through the intensity-peak of this atomic row. A further consequence of this evaluation
Fig. 2. — a) A schematic drawing of the apparatus. The specimen is in the center of a spherical display unit, consisting of two grids and a fluorescent screen. It can be rotated in the drawing plane. Two electron guns are available, one having its axis coinciding with the axis of the display unit, the other one perpendicular to it. The angles between the two possible directions of electron incidence (electron gun 1 or 2) and the [110]-surface normal n are denoted by $\Phi_1$ and $\Phi_2$. b) A (001)-section of an fcc single crystal with a (110)-surface can be seen in this figure. Emitters and scattering atoms, which image atomic rows along the [100]-, [110]-, [210]-, and [310]-directions are displayed. Only half of the atomic layers with emitters and scattering atoms are visible, because there exist two types of (001)-planes in the fcc-lattice with respect to the direction of the surface-normal n.
model is the fact, that the mean depth of the image-forming emitters, is a function of the crystallographical direction. Therefore, the depth-distribution of the image-forming emitters can be evaluated, if crystallographical models for the bulk and the near-surface region are available.

The number of atomic layers parallel to the surface containing emitters and scattering atoms, which create the image of certain atomic rows, is principally limited in every lattice. The number of possible atomic layers with emitters is always equal to those with scattering atoms, and the atomic layers with scattering atoms are immediately followed by the layers with emitters according to our assumptions (see Fig. 2b). For Pt-single crystals, which consist of an fcc-lattice, the number of possible atomic layers with emitters \( e \) and scattering atoms \( s \), is given by equation (1), if the sums of the indices of the surface-normal \( [n_1 + n_2 + n_3] \) and the imaging direction \( [a_1 + a_2 + a_3] \) are both even or odd, by equation (2), if \( [a_1 + a_2 + a_3] \) is even and \( [n_1 + n_2 + n_3] \) is odd, and by equation (3), if \( [a_1 + a_2 + a_3] \) is odd and \( [n_1 + n_2 + n_3] \) is even:

\[
e = s = b \left[ \sqrt{a_1^2 + a_2^2 + a_3^2} \cos \gamma \right] \quad \left( \sqrt{n_1^2 + n_2^2 + n_3^2} \right) \tag{1}
\]

\[
e = s = b \left[ \sqrt{a_1^2 + a_2^2 + a_3^2} \cos \gamma \right] \quad \left( 2 \sqrt{n_1^2 + n_2^2 + n_3^2} \right) \tag{2}
\]

\[
e = s = b \left[ 2 \left( \sqrt{a_1^2 + a_2^2 + a_3^2} \cos \gamma \right) \right] \quad \left( \sqrt{n_1^2 + n_2^2 + n_3^2} \right) \tag{3}
\]

where \( \gamma \) is the angle between the surface-normal \( \mathbf{n} \) and the imaging direction \( \mathbf{a} \), and \( b \) the number of types of planes parallel to the surface, which are atomically different occupied with respect to the direction of the surface-normal \( \mathbf{n} \).

Equations (1) to (3) show that atomic rows along directions with high indices can be formed through scattering atoms and emitters originating in a wide range of atomic layers. If the values of the indices of a direction is even high enough, that the angle between this direction and a low-indexed direction becomes smaller than about \( 3^\circ \), then Kikuchi bands can be generated because of a highly increased reflection of the backscattered electrons at the dense crystal planes containing this low-indexed direction, provided that the mean penetrations depth of the primary-electrons is sufficiently high to produce emitters in the required, deeply situated atomic layers and the primary-electron is in the range of 2 keV [9].

Following our evaluation model, the distances between the emitters and the scattering atoms are equal to the atom-to-atom distances in the imaged atomic rows. Moreover, Poon et al. [10] have found that the forward-peaked electron-atom single-scattering is, in a first approach, only dependent on the energy of the scattered electrons and the distances between the emitters and the scattering atoms. An increase of the electron-energy leads to an enhanced focussing in forward direction, whereas a decrease of the distance between an emitter and the corresponding scattering atom results in an increased intensity of the scattered electrons in forward direction. We now define a specific quotient \( Q \) for each atomic row:

\[
Q = \frac{e g^2}{d^2} \tag{4}
\]

where \( g \) is the lattice parameter and \( d \) the atom-to-atom distance in the corresponding atomic row. \( Q \) is defined in a way, that the ratios of the integrated intensities of imaged atomic rows, measured under optimum imaging conditions, are equal to the ratios of the corresponding specific quotients \( Q \). Following our model, which neglects any interference effects, optimum imaging conditions exist, if the background intensity in the evaluated crystallographical region is constant, and if the activation of the emitters in all atomic layers, which can contribute to the imaging of the investigated atomic row, is a maximum. The specific quotient \( Q \) is proportional
to the number of possible atomic layers with emitters $e$, because the emitter-density in the relevant atomic layers can be considered as being about the same and the intensity of the imaged atomic rows, under optimum imaging conditions, as being proportional to the overall number of image-forming emitters. The squared atom-to-atom distance $d^2$ is defined as being proportional to $1/Q$, on the assumption that the scattering cross-sections of all atoms are identical and that the backscattered electrons are homogeneously distributed over the investigated, crystallographical regions immediately after undergoing their last incoherent scattering event in the sample. Thus, the scattering probability of an emitted electron along any atomic row, is proportional to the solid angle occupied by the corresponding scattering atom, and therefore, it is also proportional to the reciprocal of $d^2$. The values of $Q$ for various atomic rows are listed in table I.

<table>
<thead>
<tr>
<th>Atomic row</th>
<th>Atomic layers with scattering atoms</th>
<th>Atomic layers with emitters</th>
<th>Normalized distance between atoms [d/g]</th>
<th>Specific quotient</th>
</tr>
</thead>
<tbody>
<tr>
<td>[110]</td>
<td>1-2</td>
<td>3-4</td>
<td>0.71</td>
<td>3.96</td>
</tr>
<tr>
<td>[100]</td>
<td>1-2</td>
<td>3-4</td>
<td>1.00</td>
<td>2.00</td>
</tr>
<tr>
<td>[210]</td>
<td>1-6</td>
<td>7-12</td>
<td>2.24</td>
<td>1.20</td>
</tr>
<tr>
<td>[310]</td>
<td>1-4</td>
<td>5-8</td>
<td>1.58</td>
<td>1.60</td>
</tr>
<tr>
<td>[320]</td>
<td>1-10</td>
<td>11-20</td>
<td>3.61</td>
<td>0.76</td>
</tr>
<tr>
<td>[430]</td>
<td>1-14</td>
<td>15-28</td>
<td>5.00</td>
<td>0.56</td>
</tr>
<tr>
<td>[530]</td>
<td>1-8</td>
<td>9-16</td>
<td>2.92</td>
<td>0.94</td>
</tr>
<tr>
<td>[540]</td>
<td>1-18</td>
<td>19-36</td>
<td>6.40</td>
<td>0.44</td>
</tr>
<tr>
<td>[980]</td>
<td>1-34</td>
<td>35-68</td>
<td>12.04</td>
<td>0.24</td>
</tr>
<tr>
<td>[120]</td>
<td>1-6</td>
<td>7-12</td>
<td>2.24</td>
<td>1.20</td>
</tr>
<tr>
<td>[111]</td>
<td>1-2</td>
<td>3-4</td>
<td>1.73</td>
<td>1.34</td>
</tr>
</tbody>
</table>

Table I. — The possible atomic layers parallel to the surface with emitters and scattering atoms, the normalized atom-to-atom distances and the specific quotients $Q$ are tabulated for different atomic rows of a single crystal with an fcc-lattice and a (110)-surface.
4. Results and discussions.

4.1 Background intensity.

4.1.1 General considerations concerning the background intensity. — All the experiments with Pt-single crystals having an (110)-surface were achieved by using primary-electron energies between 1.5 and 2.5 keV and by detecting only quasi-elastically backscattered electrons, whose loss of energy had been less than 40 eV. Moreover, the electron incidence occurred along the line through the [011]- and the [110]-direction in all evaluated measurements. The measured angular distributions of the background intensities settled quite well with the results of Kanter [1], who investigated Au-polycrystals using a primary-electron energy of 10 keV, with respect to the reflection part of the background intensity, but it did not at all agree with respect to the diffusion part; for the measured background intensity was in no case maximum along the direction of the surface-normal, as it is required by the diffusion approach and as it was found experimentally by Kanter [1] using primary-electron energies of 10 keV, but it was always close to maximum along the direction of electron incidence. This can be explained in the way, that the electron-atom scattering in the kiloelectronvolt range, shows a strong maximum in the forward direction, but also a smaller local maximum in the backward direction [8], which decreases, if the primary-electron energy increases or the atomic number of the investigated material decreases. The scattering maximum in forward direction, however, increases with increasing primary-electron energy or increasing atomic number of the samples. Therefore, atomic scattering in backward direction can influence the angular background intensity distribution as in our experiments (atomic number of Pt equals 78, primary-electron energy between 1.5 and 2.5 keV), or it is negligible as in the case of the measurements of Kanter (atomic number of Au equals 79, primary-electron energy 10 keV), where the angular background intensity-distribution is mainly the result of the angle-dependent absorption strength. Hence, a maximum of the background intensity along the direction of the primary-electron incidence can be interpreted in the way, that the detected quasi-elastically backscattered electrons are mainly electrons, which are mostly scattered in forward direction, but which are also, at least once, atomically scattered in backward direction. Moreover, the number of scattering events, which the detected quasi-elastically backscattered electrons are undergoing in the sample, is not sufficiently high enough to allow an interpretation on the basis of a diffusion approach [2]. Consequently, in the case of scattering experiments with Pt-samples using primary-electron energies in the kiloelectronvolt range, it is more convenient to distinguish between a, at least once, atomically backscattered part (oab-part) and a pure, atomically forwardsbackscattered part (paf-part) of the background intensity, instead of distinguishing between a diffusion and a reflection part, as it was proposed by Kanter [1].

4.1.2 Background intensity in the scattering-angle range between 45 and 140°. — These background intensity measurements have been performed by using electron gun 1 (Fig. 2a) with primary-electron energies of 1.5, 2.0 and 2.5 keV and by choosing angles of electron incidence $\Phi_1$ of 45, 63.4 and 84°. The electron incidence occurred along the line through the [011]- and the [110]-direction.

The background intensity in the range of the scattering-angle $\gamma$ between 45 and 110° ($\gamma$ = angle between the imaging direction and the direction of electron incidence) has been found to be nearly constant. The decreasing oab-part of the background intensity with growing angle $\gamma$, is merely compensated by the increasing paf-part. The influence of the scattering-angle-dependent absorption strength can be neglected, since the scattering paths are rather short in the discussed scattering-angle range.

The angular distribution of the background intensity in the $\gamma$-range between 110 and 140° has been proved to be strongly dependent on the angle of electron incidence $\Phi_1$, but only
weakly dependent on the energy of the primary electrons. This can be explained by the \( \Phi_1 \)-dependent influence of the absorption strength on the angular distribution of the background intensity; for the absorption strength is generally not weak enough in this scattering-angle range to be negligible. In fact, the mean penetration depth of the backscattered electrons and, consequently, the angle-dependent absorption strengths and lengths of the scattering paths can be influenced more efficiently by the variation of \( \Phi_1 \) between 45 and 84°, than by the variation of the primary-electron energy between 1.5 and 2.5 keV (at least in the case of Pt with a high atomic number).

4.1.3 Diffraction features. — In the case of measurements performed with an angle \( \Phi_1 = 84° \), the absorption effect has been found to be negligible in the whole measured \( \gamma \)-range probably because of the small scattering paths. Unsuccessfully, the electron backscattering patterns (EBSP) produced in this case do not clearly image the real-space, because most of the paf-electrons are diffraacted at the surface or in the near-surface region without undergoing an incoherent scattering event. Therefore, the real-space image is mixed up with features of medium energy diffraction (MEED) in a hardly to separate manner.

4.2 INTENSITY MEASUREMENTS REMOTE FROM THE DIRECTION OF ELECTRON INCIDENCE. — The intensity measurements along the line through the [011]- and the [110]-direction, displayed in figures 3a and 3b, show a nearly constant background intensity over the whole, presented crystallographical region. The angle of electron incidence \( \Phi_1 \) has been 63.4° in both measurements and the electron gun 1 has been employed (see Fig. 2a). The mentioned constant background intensity can be interpreted in the way, that the decreasing oab-part of the background intensity is just counterbalanced by the increasing paf-part with growing angle to the direction of electron incidence. Moreover, the scattering paths of the quasi-elastically backscattered electrons are all rather short in the measured range of scattering-angles around the [110]-surface-normal and, therefore, the influence of the scattering-angle-dependent absorption strength can be neglected with regard to the angular distribution of the background intensity.

In figure 3a, intensity-peaks of the atomic rows in [110]- and [120]-direction are visible. The intensity-peak in [110]-direction is very strong, however, the peak in [120]-direction is rather weak. Following our evaluation model, the emitters must be situated between the 3 and 12 and the scattering atoms between the 1 and 6 atomic layer parallel to the surface. But in fact, the main part of the scattering atoms might be situated in the 1 and 2 atomic layer and the main part of the emitters in the 3 and 4 atomic layer contributing to the imaging of the [110]-peak, because the ratio of the integrated intensities of the [110]- and the [120]-peak is much higher than the ratio of the corresponding specific quotients \( Q \) listed in table I. The atomic rows in [110]-, [120]-, [320]-, [230]-, [530]- and [350]-direction can be identified in figure 3b. The ratios of the integrated intensities of the peaks of the imaged atomic rows agree approximately with the ratios of the corresponding specific quotients. Therefore, the emitter and scattering atoms might be homogeneously distributed between the 3 and 20 atomic layer respectively between the 1 and 10 atomic layer in the case of the scattering atoms. Following our evaluation model, a symmetrical intensity-distribution of the intensity profiles is required with regard to the [110]-peak. As it can be seen in the figures 3a-b, this criterium is nearly fulfilled in both cases. In the intensity profile of figure 3b, intensity modulations near the [110]-peak can be observed, which do not at all fulfill the symmetry condition. Therefore, these modulations are probably the result of interference and multiple-scattering effects, which are not integrated in our evaluation model. The focussing of the [110]-peak in figure 3a is quite weak. The width at half maximum intensity is about 13.5°. This low focussing quality can be explained by the fact, that the intensity modulation occurs in a whole crystallographical region, which is centered in
Fig. 3. — In this figure, intensity profiles are displayed, which have been obtained by performing experiments using primary-electron energies of a) 1.5 and b) 2.5 keV. The angle $\Phi_i$ between the direction of electron incidence and the [110]-direction of the surface-normal $n$, is chosen to be 63.4°. The intensity profiles have been taken along the line through the [011]- and the [110]-direction. The horizontal axis gives the angle with respect to the [110]-direction of the surface-normal and the vertical axis, the measured intensity in arbitrary units.

The [110]-direction; for the [110]-peak in figure 3a is not bounded by near, local intensity maxima of further atomic rows, which would generate a enhanced focussing of the peak, since the relatively low energy of the primary-electrons leads to a very low mean penetration depth of the backscattered electrons. Thus, neither an emitter-formation in deeper atomic layers nor the imaging of further atomic rows are possible. In figure 3b, the focussing of the [110]-peak is much better because of the increased primary-electron energy. The half width of the [110]-peak is only about 5°. Moreover, in figure 3b can be observed, that the intensity-peaks of the imaged atomic rows are the better focussed, the deeper the image-forming emitters are situated. This can be explained by geometrical arguments, since with increasing distance between emitters and scattering atoms, the possible range of angles enabling the scattering of emitted electrons at a given atom becomes narrower (see Fig. 2b). This effect, results as a
better focussing of the intensity-peaks of the corresponding atomic rows, if it is assumed that the final forward-peaked scattering remains invariable. In addition, the focussing of intensity-peaks of atomic rows can always be improved because of elementary geometrical reasons, if the number of the imaged atomic rows in a given crystallographical region can be enhanced.

4.3 Intensity measurements close to the direction of electron incidence. — The angle of electron incidence $\Phi_2$ has been selected to $-26.6^\circ$ during the experiments displayed in the figures 4a-c. Electron gun 2 has been employed (Fig. 2a). The background intensity along the line through the [011]- and the [110]-direction is dominated in all three measurements in the displayed crystallographical region by the oab-part. Consequently, a clear decrease of the background intensity can be observed with increasing angle $\gamma$ to the direction of electron incidence. In addition, the background intensity in the vicinity of the [110]-direction is increased, with respect to the background intensity close to the direction of electron incidence, if the primary-electron energy is increased, as it is visible in figures 4a-c. This can be explained by a reduction of the oab-part of the background intensity, and a slightly enhanced influence of the scattering-angle-dependent absorption strength, if the primary-electron energy is increasing.

In figure 4a the atomic row in [110]-direction is not visible. The visible and the missing atomic rows in figure 4a indicate together, following Table I, that the image-forming emitters are situated approximately between the 5 and 28 as well as between the 35 and 68 atomic layer. The two separated regions with emitters can be interpreted in the way, that the atomic rows in [320]-, [530]- and [430]-direction are imaged by oab-electrons and the atomic rows in [980]-direction by paf-electrons. Hence, the two types of backscattered electrons might produce image-forming emitters in clearly separated depth-ranges. The focussing of the imaged atomic rows has generally been found to be improved with increasing primary-electron energy, as it can be seen in figures 4a-c. However, the intensity-peak of the atomic row in [980]-direction is diminished with enhanced electron energy, probably because of an increased mean penetration depth of the paf-part of the backscattered electrons, producing more emitters in even deeper atomic layers and leading to the imaging of Kikuchi bands passing through the [110]-direction [9]. The imaging of the atomic row in [110]-direction in figures 4b-c is, therefore, the result of the cross-over of Kikuchi bands produced by deeply situated emitters and not the result of emitters situated in the 3 and 4 atomic layer. The imaging of the atomic rows in figure 4c can be explained by such a high mean penetration depth of the oab-electrons, that the ranges of emitter-formation of the oab- and paf-electrons are overlapping. Furthermore, the atomic row in [430]-direction might not have been imaged in the experiment displayed in figure 4c because of the relatively low values of its specific quotient $Q$ and a reduced emitter-formation in the relevant atomic layers. The formation of Kikuchi bands is much stronger in figure 4c than in figure 4b. Moreover, the high energy and the high mean penetration depth of the backscattered electrons displayed in figure 4c was leading to a better focussing of the intensity-peaks, a diminished width of the Kikuchi bands [7, 8] and a minor influence of interference effects.

Kikuchi bands. — The scattering, which is caused by crystallographical planes and which gives rise to the formation of Kikuchi bands, overlaps with the forward-peaked electron-atom scattering along atomic rows in the vicinity of low-indexed crystallographical directions, leading to complicated scattering patterns, which are highly sensitive to the imaging-parameters (see Figs. 4a-c). The variation of the scattering patterns around such directions might be due to interference effects, as well as to the fact, that intensity maxima formed by cross-overs of Kikuchi bands are not as clearly focussed along the directions of atomic rows as the intensity maxima produced by atomical, forward-peaked scattering.
Fig. 4. — In this figure intensity profiles are displayed, which have been obtained by performing experiments using primary-electron energies of a) 1.5, b) 2.0 and c) 2.5 keV. The angle \( \Phi_s \) between the direction of electron incidence and the [110]-direction of the surface-normal \( \mathbf{n} \), is chosen to be \(-26.6^\circ\). The intensity profiles have been taken along the line through the [011]- and the [110]-direction. The horizontal axis gives the angle with respect to the [110]-direction of the surface-normal and the vertical axis, the measured intensity in arbitrary units.
Complicated, imaging-parameter-dependent scattering patterns can be specially expected, if the considered atomic rows are oriented along low-indexed directions, and if these atomic rows are also characterized by specific quotients $Q$ with quite low values. In these cases the scattering of crystallographical planes, which is responsible for the imaging of Kikuchi bands, can dominate the forward-peaked scattering along atomic rows under favorable imaging conditions, which guarantee a high mean penetration depth of the backscattered electrons; for each crystallographical direction, which is only slightly inclined (by an angle $\theta < 3^\circ$, if the primary-electron energy is in the range of 2 keV [9]) to a low-indexed direction with a low $Q$-value and which is contributing to the imaging of Kikuchi bands, is characterized by a clearly lower $Q$-value than a direction with emitters in the same depth range, which is slightly inclined to a low-indexed direction with a high $Q$-value, since low-indexed directions with low $Q$-values are always identical with surface-normals of very densely packed planes.

Following table I, the intensity-peaks of the atomic rows in [111]- and [210]-direction are mainly expected to produce scattering patterns of the type described above, if single crystals with an fcc-lattice and a (110)-surface are investigated as in the case of Pt(110).

5. Conclusions.

Intensity profiles of crystallographical regions forming scattering-angles $\gamma$ smaller than 40° with respect to the direction of electron incidence, are not suitable for a rigorous evaluation of intensity-peaks of atomic rows, because the mean penetration depth of the backscattered electrons is so large that different mechanisms influence concomitantly the angular intensity distribution: such mechanisms are the angular variation of the background intensity, the forward-peaked scattering along atomic rows, the formation of Kikuchi bands as well as interference and multiple-scattering effects. At somewhat higher primary-electron energies (about 5-10 keV in the case of Pt-single crystals) the cited mechanisms may give rise to the so-called channelling effects, which were observed to be highly dependent on the direction of electron incidence relative to the crystal lattice planes [12]. The channelling contrast created by channelling effects is also called crystal orientation contrast, and is a well-known effect in scanning electron microscopy (SEM).

Intensity profiles of crystallographical regions forming scattering-angles $\gamma$ between 45 and 110° with respect to the direction of electron incidence are suited best for an evaluation of intensity-peaks, mainly because the background intensity remains nearly constant and the penetration depth of the backscattered electrons is limited to only about twenty atomic layers. Furthermore, the influence of the scattering-angle-dependent absorption strength is negligible, the Kikuchi band formation is very weak and interference effects are nearly minimum. In the discussed scattering-angle range the depth-distribution of the image-forming emitters can be controlled rather efficiently by varying the angle of electron incidence $\Phi$ and/or the primary-electron energy $E$. Therefore, the optimum imaging condition for the intensity-peak of each imaged atomic row can be found experimentally by changing $\Phi$ and $E$ systematically. In addition, the information depth can also be influenced by the extent of inelastic processes allowed to contribute to the image formation [7, 11]. This can be managed by changing the retarding voltage. However, if the structure of the near-surface region is not already known, atomic models of the near-surface structure have to be developed, in order to obtain hypothetical values of $Q$. Intensity measurements, performed as described above, finally enable the verification of the structure model by comparing the hypothetical values of $Q$ with the experimentally obtained ones.

Using a two-dimensional display-type electron-energy analyzer, real-space images can be obtained with rapid recording times of the order of fractions of a second for primary currents in the $\mu$A range. In this way, transient phenomena such as epitaxial growth, phase transitions or
other processes in the near-surface region can be studied with quasi-elastically backscattered electrons. Since the spatial imaging reveals directly the crystallography in real-space, long-range order is not required to obtain real-space images. That means, that the method is also suitable for the structural analysis of, for instance, heavily deformed samples or quasicrystals.

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