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# Secondary electron images obtained with a standard photoelectron emission microscope set-up

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## Abstract

The first results of secondary electron images excited by 3–4.3 keV electrons are presented. The images are obtained with a standard FOCUS-PEEM set-up equipped with an imaging energy filter (IEF). The electron gun was mounted on a standard PEEM entrance flange at an angle of  $25^\circ$  with respect to the sample surface. A low extraction voltage of 500 V was used to minimize the deflection of the electron beam by the PEEM extraction electrode. The secondary electron images are compared to photoelectron images excited by a standard 4.9 eV UV lamp. In the case of a Cu pattern on a Si substrate it is found that the lateral resolution without the IEF is about the same for electron and photon excitation but that the relative electron emission intensities are very different. The use of the IEF reduces the lateral resolution. Images for secondary electron energies between  $eV_1$  and  $eV_2$  were obtained by setting the IEF to  $-V_1$  and  $-V_2 \approx -(V_1 + 5V)$  potentials and taking the difference of both images. Images up to 100 eV electron energies were recorded. The material contrast obtained in these difference images is discussed in terms of a secondary electron and photoelectron emission model and secondary electron energy spectra measured with a LEED-Auger spectrometer.

## 1. Introduction

In recent years commercial photoelectron emission microscopes (PEEMs) have become available for studying surface processes. In standard PEEM set-ups, common laboratory UV sources are used to excite electrons from the vicinity of the Fermi level. In this case the contrast of photoelectrons emitted from different surface regions is due mainly to the different local work function, and PEEM techniques can be used to investigate adsorption processes, which change the work function, directly in real time [1, 2]. Information about the chemical composition of the observed objects cannot be obtained. This disadvantage can be overcome if photons with high enough energies from a laboratory or a synchrotron x-ray source are used [3].

In this work we present the first results of electron emission microscope images for secondary electron emission induced by 3–4.3 keV electrons. The emission contrast of different surface regions depends only weakly on the local work function, but on other local parameters, such as the mean escape depth of the excited secondary electrons, and it depends also on the energy of the emitted electrons. From this energy dependence information on the elemental composition of the observed surface region can be obtained.

## 2. Experimental details

A standard FOCUS IS-PEEM with integrated sample stage (IS) and imaging energy filter (IEF) was used in this investigation. The energy filter is a high-pass energy filter, i.e., only electrons with energies larger than an energy  $E_1$  corresponding to a filter potential  $-V_1$  with  $eV_1 = E_1$  can pass the filter and will contribute to the image produced by a multi-channel plate on a fluorescence screen. The photon source is a standard high-pressure mercury UV lamp with an emission maximum at 4.9 eV. The incidence angle of the photons relative to the sample surface is  $25^\circ$ . Symmetrically to the UV lamp a 5 kV electron gun was attached to the PEEM. The electron beam can be deflected laterally in order to hit the sample and it can be focused to a minimum diameter of about 0.5 mm.

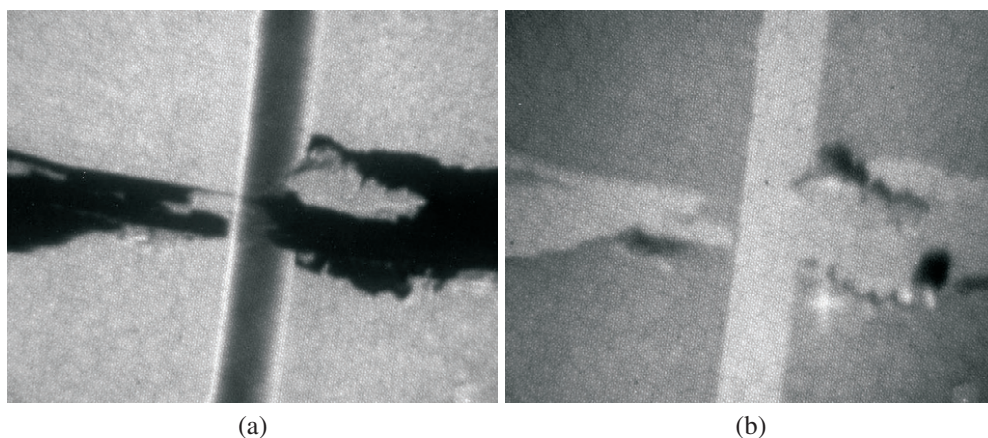
The main problem in achieving electron incidence on the sample is the deflection of the electron beam on the way to the sample by the PEEM extraction electrode. To minimize this deflection a small extraction voltage of 500 V was applied. Due to this deflection the incidence angle of electrons relative to the sample surface is smaller than the nominal  $25^\circ$ . The minimum electron energy for which electron emission could be observed was about 3 keV. In this case the incidence angle is close to  $5^\circ$ . Using this deflection effect, the incidence angle of the electron beam can easily be changed by varying the beam energy and subsequent adjustment of the beam impact spot on the sample to the centre position of the PEEM. Typical beam currents were about 2–5  $\mu\text{A}$  for measurements of emitted electrons with energies up to 30 eV, and about 20–50  $\mu\text{A}$  for electrons with higher energies.

The vacuum chamber is also equipped with a LEED-Auger system and an ion gun for sample cleaning. Electron emission energy spectra of Si and Cu samples were measured with the LEED-Auger system in the Auger mode with primary electron beam energies of 3 keV.

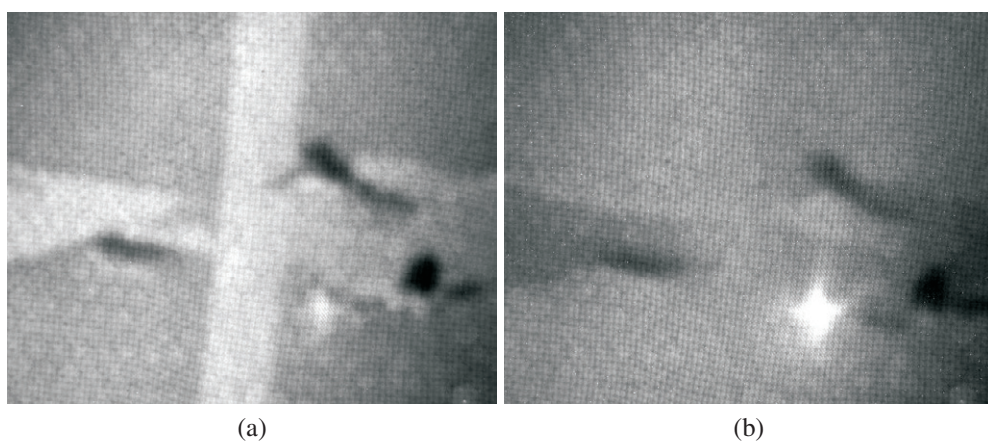
The test samples of Cu and Si were prepared by evaporation of Cu on Si(100) wafers and shadowing some parts of the Si substrate by thin (20  $\mu\text{m}$ ) wires. Subsequently, the Cu was scratched away on some regions to produce sharp Cu edges and clean Si regions. Onto one of the Cu/Si samples Al was evaporated through small holes of a mask. The thickness of the Cu and Al layers was about 100 nm.

## 3. Results

The first secondary electron images were recorded without use of the energy filter. The extraction voltage was set to 500 V and the column and projective lens electrodes voltages were set to values smaller than 500 V. In figures 1(a) and (b) images obtained from a Cu–Si sample are compared for excitation with photons and 4 keV electrons, respectively. The dark areas in the case of photon impact (figure 1(a)) correspond to Si and the bright ones to Cu. For electron impact (figure 1(b)) the relative intensities are reversed and the Si appears more bright than the Cu. The stripe in the centre of the images is due to the shadowing wire during Cu evaporation; its width on the sample is about 20  $\mu\text{m}$ . The dark parts in figure 1(b) are due to the shadowing of the primary electrons by scratched Cu film parts. It can also be seen that the lateral resolution is a little worse for electron as compared to photon excitation.



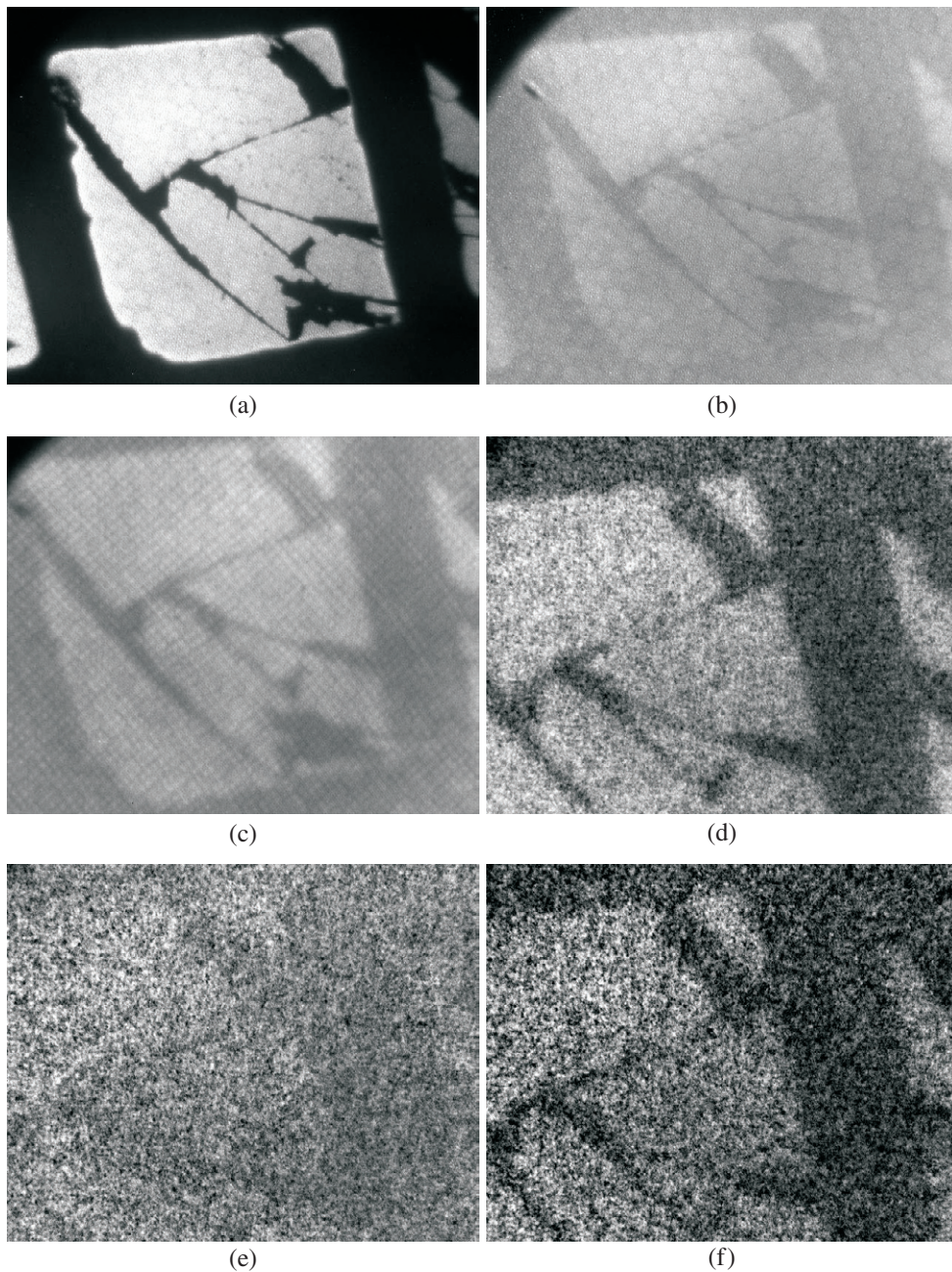
**Figure 1.** Cu pattern on Si; the IEF is not in operation. (a) Excitation by photons, (b) excitation by 4 keV electrons. Image sizes  $150\ \mu\text{m} \times 120\ \mu\text{m}$ .



**Figure 2.** Cu pattern on Si; the IEF is in operation. (a) 0 V filter potential, (b)  $-5\ \text{V}$  filter potential. Image sizes  $150\ \mu\text{m} \times 120\ \mu\text{m}$ .

Images of the same sample area were then recorded with the IEF in operation for 4 keV electron excitation. In figure 2(a) the filter voltage is set to 0 V. In this case all emitted electrons pass the filter as in figure 1(b), but the lateral resolution is becoming worse due to the deceleration of the electrons. Figure 2(b) shows an image taken with  $-5\ \text{V}$  filter potential. The relative emission intensities from the Si and the Cu are now reversed, and the Cu appears more bright. In addition, a bright spot is obtained on the lower part of the image, which is due to fast electrons, which are scattered from the sample and can pass the complete PEEM column. When the filter potential is further increased, the intensity of the low energy electrons, which are focused in the image, is further reduced and the fast scattered electrons are completely dominant. This makes it impossible to get reasonable images at higher filter potentials.

To overcome this problem, the column and the projective lens electrodes were set to potentials larger than 500 V. The fast electrons are deflected by these high voltages and can no longer pass the complete PEEM column. It was then possible to get reasonable images for filter potentials up to  $-100\ \text{V}$ . Figure 3 shows images of another Cu pattern on Si for photon



**Figure 3.** Cu pattern on Si. (a) The IEF is not in operation, excitation by photons; (b) the IEF is not in operation, excitation by 4.3 keV electrons. (c)–(f) Difference images obtained for different IEF voltage settings: 10–15 V (c), 60–65 V (d), 85–90 V (e), 100–105 V (f). Image sizes (a) and (b)  $380 \mu\text{m} \times 300 \mu\text{m}$ ; note that the magnification increases with increasing emission energy (filter potential).

(figure 3(a)) and electron excitation (figures 3(b)–(f)). In figure 3(b) (IEF off), the Cu appears brighter than the Si, in contrast to figure 1(b), because the sample was sputter-cleaned for longer

than the sample of figure 1. Following the 'rule of thumb' which predicts for clean surfaces the lowest electron emission yield [4], an increase of the relative intensity of Cu compared to Si may not be expected. But an investigation of ion-induced kinetic electron emission [5] found that Cu surfaces deviate from this rule and result in lower yields when they are contaminated, in agreement with figure 3(b). Figures 3(c)–(f) show difference images of images recorded with different filter potentials. Figure 3(c) shows the image obtained by subtracting the image recorded with  $-15$  V filter potential from the image taken with  $-10$  V filter potential. Both images are recorded with the same measurement parameter setting (impinging electron current, focus potential, multi-channel plate voltage, etc). The image in figure 3(c) is therefore produced by electrons with emission energy between 10 and 15 eV. To get reasonable images for higher secondary electron energies, the electron beam current was increased up to  $30 \mu\text{A}$  and the multi-channel plate voltage was also increased for higher sensitivity. In order to get images with good lateral resolution the focus potential has also to be adjusted from 230 V, for 0 V filter potential, to 125 V for  $-100$  V filter potential. It can also be seen from the images that the magnification increases with increasing electron emission energies. The brightness contrast between the Cu and Si areas is largest for 60–65 eV electrons and almost not visible for 85–90 eV electrons. Higher energies again show an image with intensity differences similar to images obtained from low energy electrons.

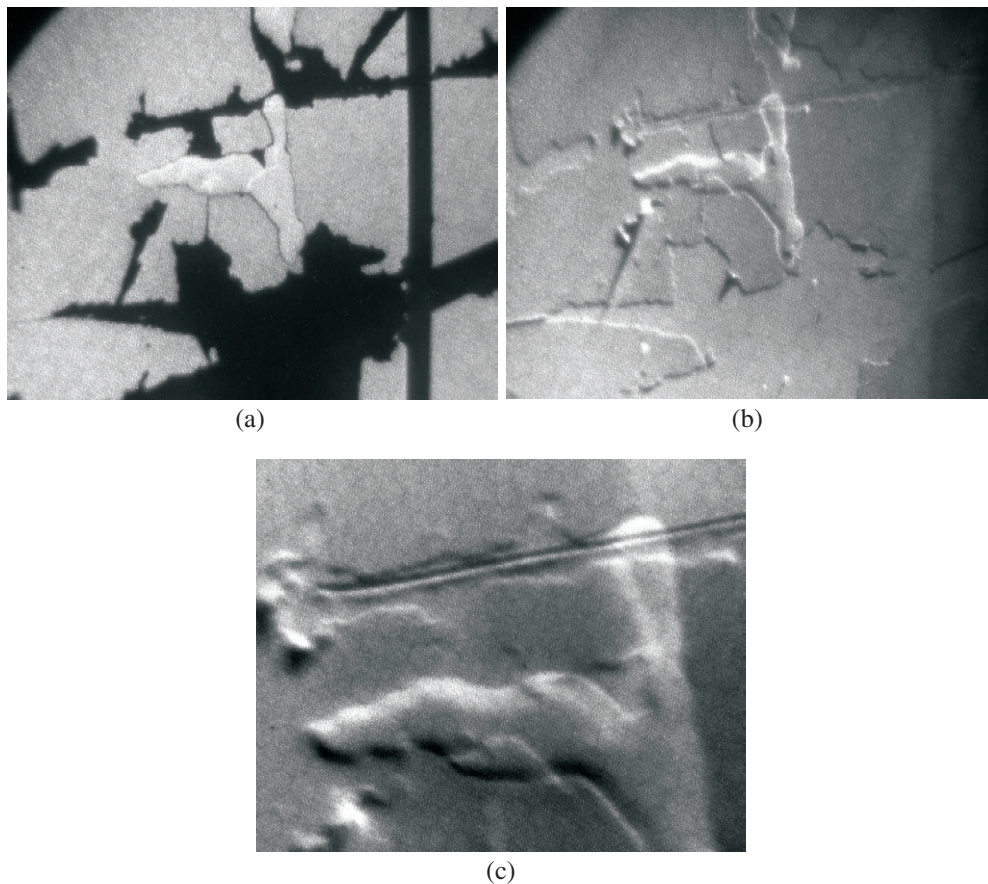
Figure 4 shows images of an Al–Cu-pattern on Si. Figure 4(a) is obtained with photon excitation and the energy filter not in operation. The dark areas are Si, and the small brighter pattern in the centre of the image corresponds to the evaporated Al. In figure 4(b), electron emission is induced by 3 keV electrons. In this case the incidence angle is very small, and shadows cast by the Cu and Al layers can be seen. Figure 4(c) shows the centre area in higher magnification. In the upper part a deep scratch into the Si substrate is seen and the Al centre pattern shows no step-like borders, but smooth edges, due to the half-shadow produced by the evaporation mask during Al deposition from the laterally extended evaporation source. These height structures cannot be seen in the photon image because of the larger incidence angle of the photons. Series of difference images were also recorded from this sample with different filter voltage settings. The difference of the filter potentials was always 5 V for recording the difference images.

In order to compare the measured intensity ratios of different sample areas and different electron energies quantitatively, electron energy spectra were measured using the LEED-Auger set-up in the Auger mode for individual Si and Cu samples. The measured spectra normalized to 5 eV emission energy are shown in figure 5. The humps due to Auger-electrons are clearly seen, at about 60 eV for Cu and about 90 eV for Si.

#### 4. Discussion

To understand electron emission, one can divide the process into three steps [4, 6]: (1) excitation of electrons in the sample by impinging projectiles; (2) transport of the excited electrons to the surface and excitation of electrons by excited energetic electrons; (3) escape from the surface of those electrons with high enough energy.

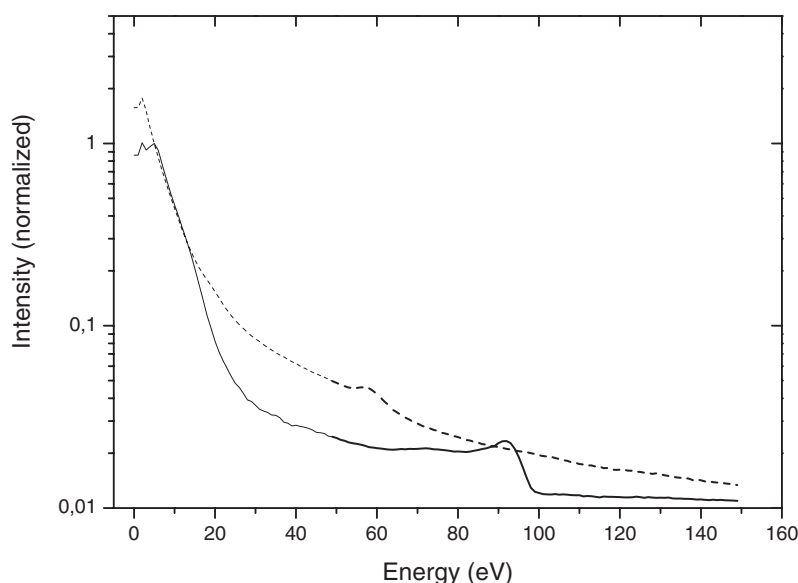
The measured relative emission intensities can now be understood in terms of parameters which are relevant for the individual steps. In step (1) the photoabsorption (photon impact) or the ionization cross section (electron impact) will determine the mean penetration length  $a$  of photons or electrons and the amount of excited electrons. The ionization cross section is related to the stopping power. In step (2) the elastic and inelastic scattering cross sections will determine the mean escape length  $b$  of the excited electrons. In step (3) the work function determines the minimum energy of the excited electrons to escape from the sample.



**Figure 4.** Al, Cu pattern on Si; the IEF is not in operation. (a) Excitation by photons; (b), (c) excitation by 3 keV electrons. Image sizes  $380\ \mu\text{m} \times 300\ \mu\text{m}$  (a), (b);  $160\ \mu\text{m} \times 130\ \mu\text{m}$  (c).

In the case of 4.9 eV photon impact on Cu,  $a$  and  $b$  are of the same order of magnitude, typically a few nanometres [2], and because the work function is close to the energy of the photons, the local work function determines to a large extent the emission intensity of electrons. In the case of 4 keV electron impact,  $a$  is larger than  $b$  because of the higher energy of the incident electrons, and  $b$  determines the information depth. For metals  $b$  is in the range of 2–50 nm [7]. The work function is of minor importance because of the higher average energy of the excited secondary electrons.

The large difference of the emission intensities for Cu and Si for photon impact (figure 1(a)) is due to the different work function of Si and Cu, whereas for electron impact (figure 1(b)) the work function is not that important and the emission intensities are thus not very different. The broad stripe in the centre of the images has a uniform intensity in figure 1(b) like the other Si region, whereas in figure 1(a) the intensity is not uniform and is a bit higher than the other Si region. This fact might be due to the smaller information depth for photon impact and the consequently higher sensitivity to the actual surface morphology and cleanliness: in the stripe and next to the edges, which are produced by shadowing of evaporated Cu, small amounts of Cu might be present due to incomplete shadowing or surface diffusion. Because of the larger



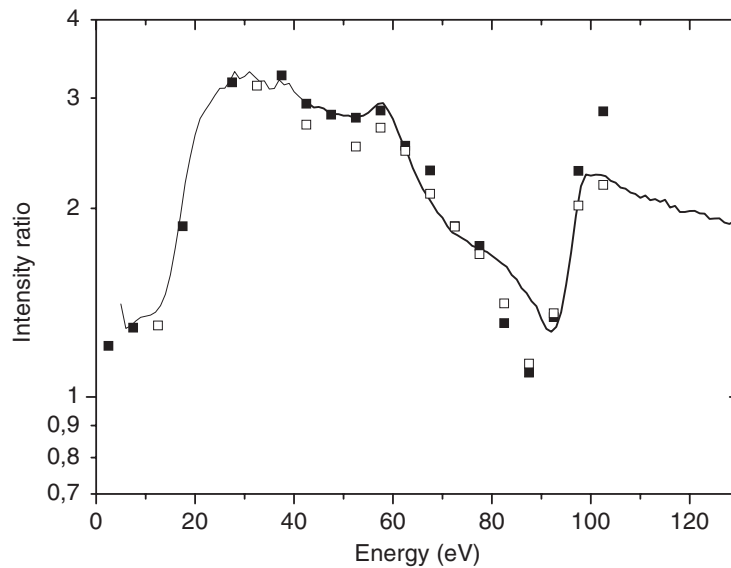
**Figure 5.** Electron energy spectra measured with the LEED-Auger set-up, normalized to 5 eV emission energy. Full curve: Si, dashed curve: Cu.

information depth for electron impact, this Cu is not seen in figure 1(b). After sputtering of the sample (and removal of residual Cu and other surface impurities) all Si regions, including the stripe, showed, indeed, the same intensity also in photon emission image.

In order to compare quantitatively the change of emission intensities of Cu and Si areas for different electron emission energies (figures 3(c)–(f)), the mean intensities of a centre Cu area and of an Si area in the right stripe were evaluated. The ratio of these intensities is plotted as a function of electron energy in figure 6 (open symbols) also for energies not shown in figure 3, together with the ratios of Cu and Si intensities obtained from the sample shown in figure 4 (full symbols). The measured intensity ratios of both samples show reasonably good agreement. The full line gives the intensity ratio measured with the LEED-Auger set-up for individual Si and Cu samples as shown in figure 5. The ratio is normalized to the value of the full symbols at a mean electron energy of 42.5 eV. A very good agreement of both measurements, the spatially resolved (PEEM) and the LEED-Auger measurement, is found. The increase of the Cu/Si intensity ratio at about 15 eV electron energy is in good agreement with the deviation observed in the low energy secondary electron spectrum between Cu and Si beginning at 15 eV (figure 5). The hump at 60 eV is due to the MVV Auger transitions of Cu. The minimum at 87.5 eV, where the intensities of Cu and Si are almost equal in figure 3(e), is due to Si LVV Auger transitions. Again this minimum nicely correlates with the step in the electron energy spectrum of Si (figure 5) at an energy of about 90 eV. The remaining difference of the minimum ratio at energies around 85 eV between the intensities evaluated from the PEEM images and the measured LEED-Auger spectra might be due to different excitation conditions: in the case of the LEED-Auger spectra the incidence angle of 3 keV electrons relative to the sample surface is 90°, whereas in the PEEM set-up the incidence angle of 4.3 keV electrons is smaller than 25°.

In conclusion, electron excitation should not generally replace 4.9 eV photon excitation, because the lateral resolution is worse and the secondary electron emission intensity is not very sensitive to the local work function, but it can provide interesting information that is





**Figure 6.** Ratio of the emission intensities from Cu and Si areas as a function of the electron emission energy. Open symbols: data obtained from the pattern shown in figure 3; full symbols: data obtained from the pattern shown in figure 4; full curve: data deduced from figure 5.

complementary to photon excitation. Without an imaging energy filter, information from deeper layers may be obtained due to the higher energy of the excited electrons. By varying the incidence energy of the electrons the incidence angle can easily be changed, and information on the height topography can be obtained from shadowing effects at grazing incidence. With an imaging energy filter, energy resolved difference images can be obtained, which are produced by emitted electrons within an energy interval determined by the filter potentials. From the energy dependence of the intensity ratios for different sample areas conclusions on emitted Auger electrons can be drawn, and chemical identification is possible.

In this work a low extraction voltage of only 500 V and small magnification was used. In the future we plan to investigate electron-induced emission at higher extraction voltages and magnification to improve lateral resolution. In order to reduce the deflection by the extraction electrode it is planned to shield a part of the path of the electron beam and to use an electron gun with higher maximum beam energy.

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