Mapping of dopants in silicon by electron injection

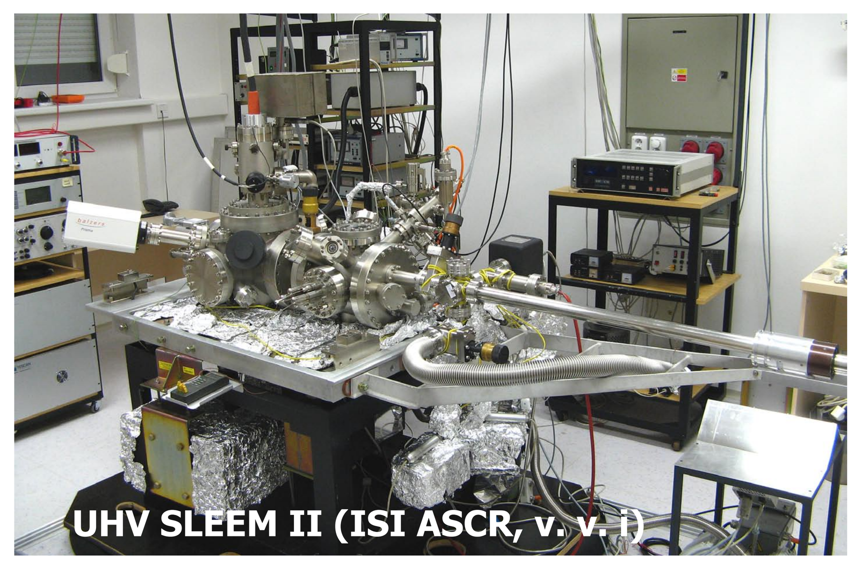
Miloš Hovorka[1*], Ivo Konvalina[1], Luděk Frank[1], Petr Mikulík[2]

[1] Institute of Scientific Instruments of the ASCR, v. v. i., Brno, Czech Republic
[2] Faculty of Science, Masaryk University, Brno, Czech Republic

Introduction

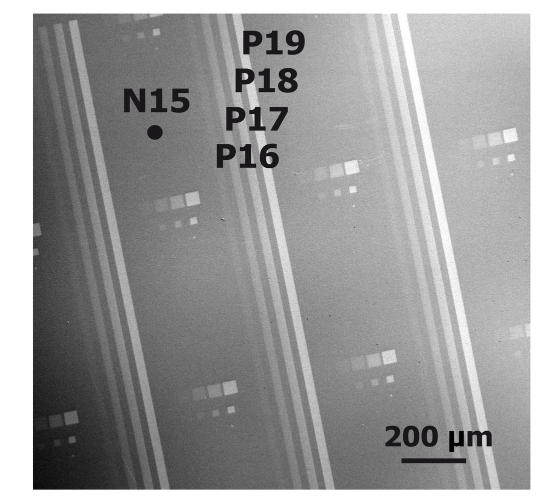
Dopants in silicon based structures locally modify the secondary electron emission, revealing in this way their distribution over the sample. For probing the doped structures usually the electron beam is used at energies around 1 keV. However, the very low landing energy range has proven itself an efficient tool for mapping dopants in semiconductors [1, 2].

We have focused on p-type structures of various dopant densities. UHV scanning low energy electron microscope allowed studying samples with arbitrarily low landing energy of the primary electron beam in the range from few keV to units of eV. Imaging by means of secondary electrons and its quantifiability was verified and the method was extended to very low energies where the dynamical changes of contrast were observed.

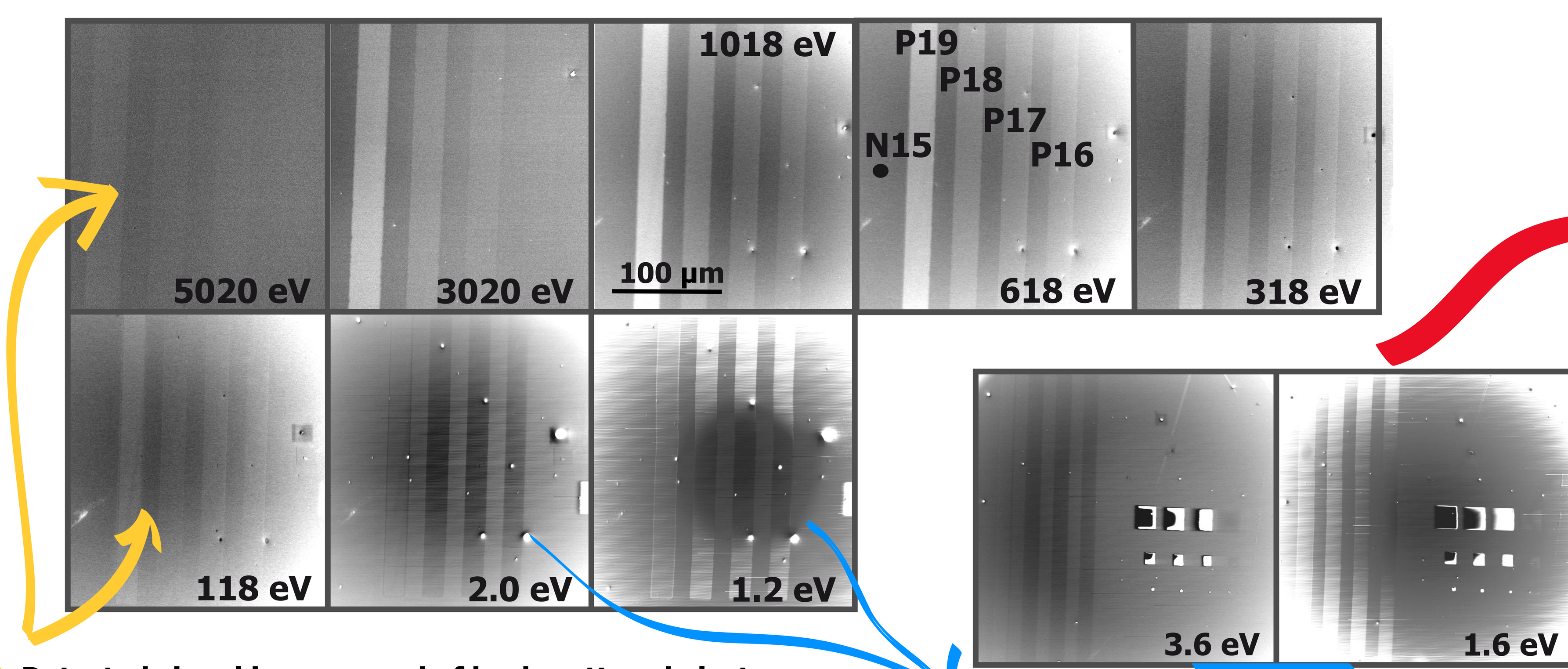


Samples

- planar silicon structures: boron doped p-type patterns on phosphorus doped n-type substrate (100)
- nominal concentration of boron varied from 1.1×10^{16} (P16) to 1.1×10^{19} (P19) cm^{-3} and that of phosphorus was 1.2×10^{15} (N15) cm^{-3}
- regular structure of the doped patterns consisted of stripes 25×2000 μm and squares 40×40, 20×20 and 5×5 μm
- surface preparation: native oxide removed by etching in buffred HF
- samples were produced in a clean room laboratory for silicon device technology at the Masaryk University



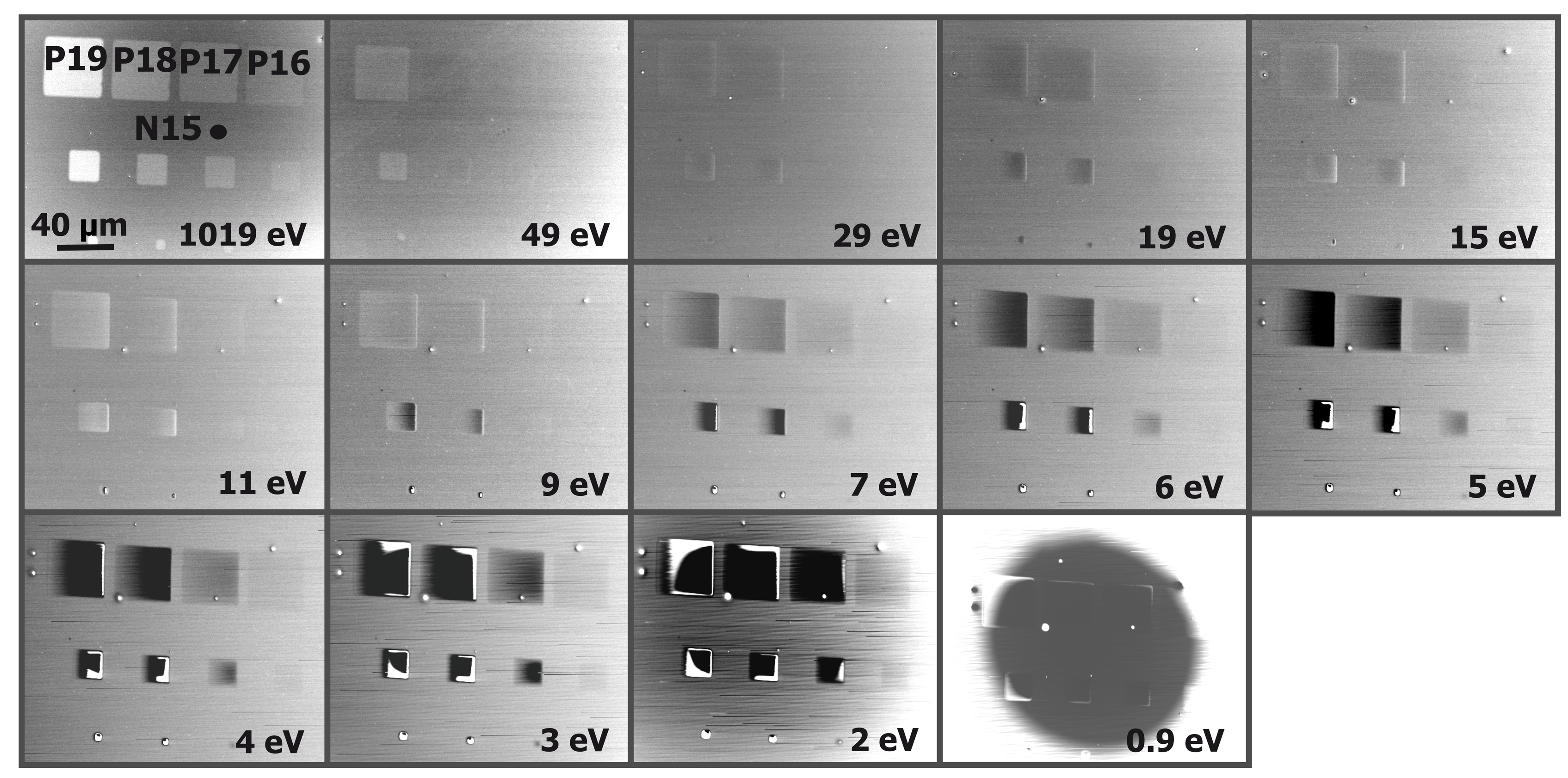
Electron emission from p-type patterns for various landing energies



Detected signal is composed of backscattered electrons (BSE) and secondary electrons (SE). At around 5 keV the signal is dominated by BSE and the contrast between p- and n-type areas disappears. SE yield increases with decreasing landing energy and there is a distinct contrast when SE dominate the signal. Highest contrast is observed around 1 keV and then it noticeably weakens (see 118 eV).

Nevertheless, at units of eV the contrast revives and p-type areas can be easily distinguished. Notice the contrast difference between large (stripes) and small (squares) patterns and its inversion across the square area.

Differently doped p-type patterns imaged at units of eV

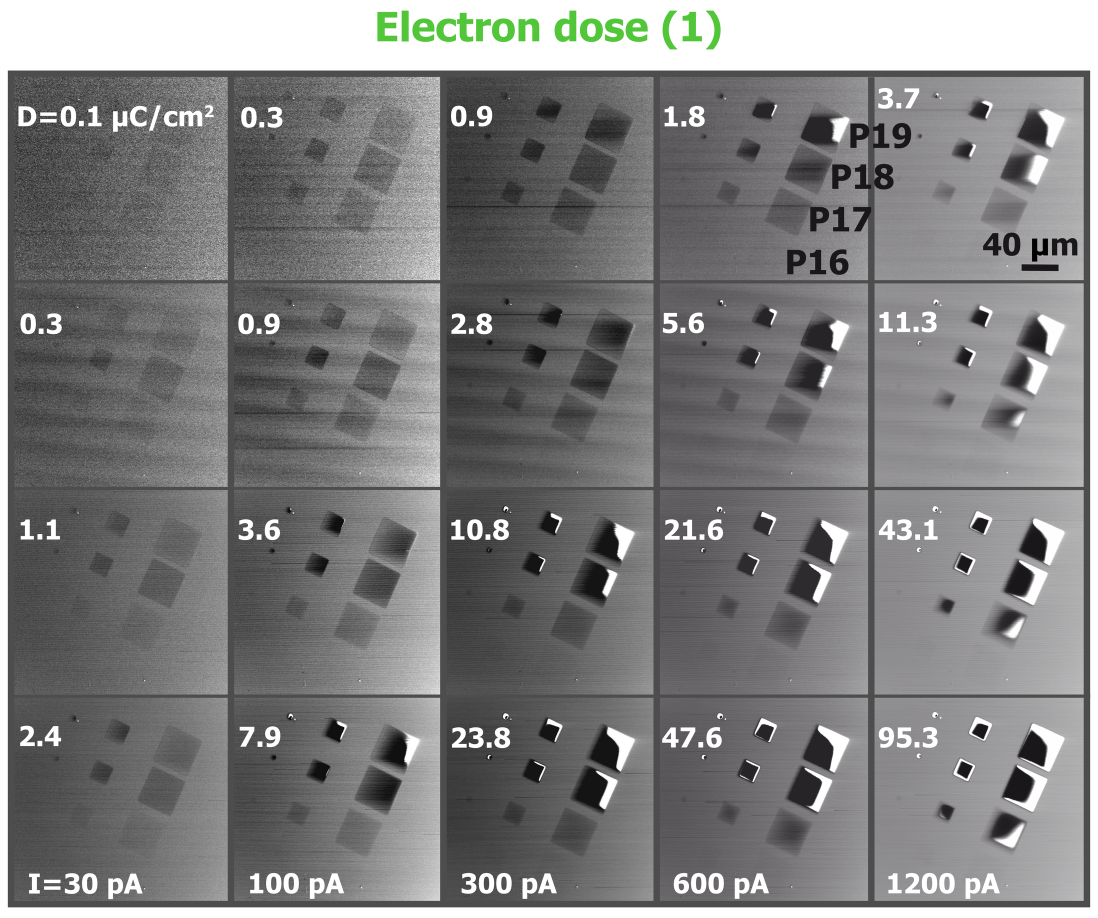


Squared p-type patterns observed at very low energies. The signal from patterns is a function of the landing energy and the contrast strongly increases at units of eV. Contrast depends on the size of squares and the amount of dopant and it increases with boron concentration and diminishing square area (see e.g. 6 eV). The contrast inversion across the square area is connected with the position of patterns within the field of view (see 2 eV and 0.9 eV). The black area at 0.9 eV corresponds to the bore in the scintillator (see below).

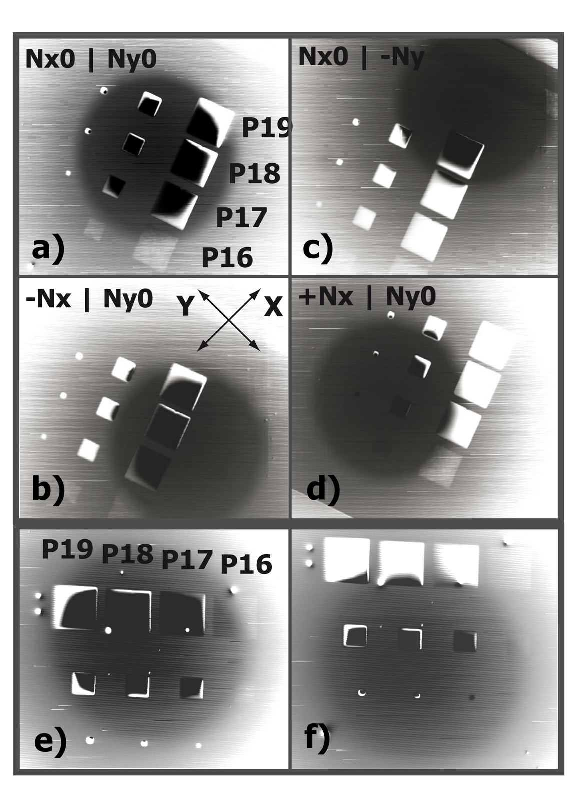
Consequences of electron injection in doped areas

The strong contrast increase at units of eV (see above) is caused by total reflection of the primary electron beam from negatively charged p-type patterns. This is due to injection of electrons, which recombine the holes and leave the ionized acceptors uncompensated as regards their charge [1]. An important question is whether this phenomenon can be used for mapping the dopants in silicon. Suitable electron dose enables one to distinguish differently doped patterns. Factors influencing the contrast at units of eV are shown below.

Electron dose (1)



Sample tilt and position of patterns inside the field of view (2)



- Contrast formation depends on whether the reflected beam hits the scintillator (bright area) or its central bore (dark area). See figure "3".
- Detected signal changes with position of the patterns inside the field of view (see figure "2e" for centered and "2f" for off-centered patterns) and with the sample tilt (see figure "2a": not tilted and "2b-d": tilted around axis X, Y, what is symbolically labeled as Nx, Ny).
- Contrast increases with the electron dose (D) and depends on the boron concentration when the dose is not too high. At higher beam currents (I) the same dose seems to be more efficient for negative charging. See figure "1".

Total reflection of primary beam on charged patterns (3)

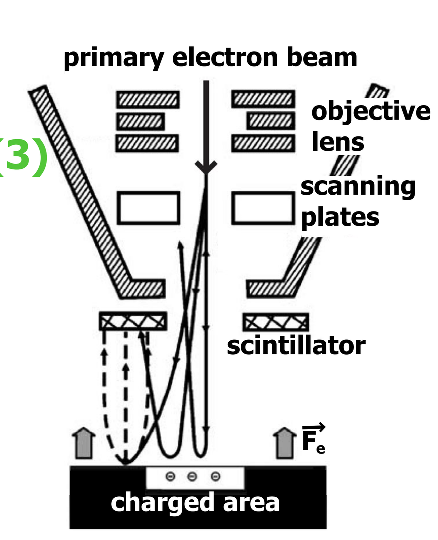
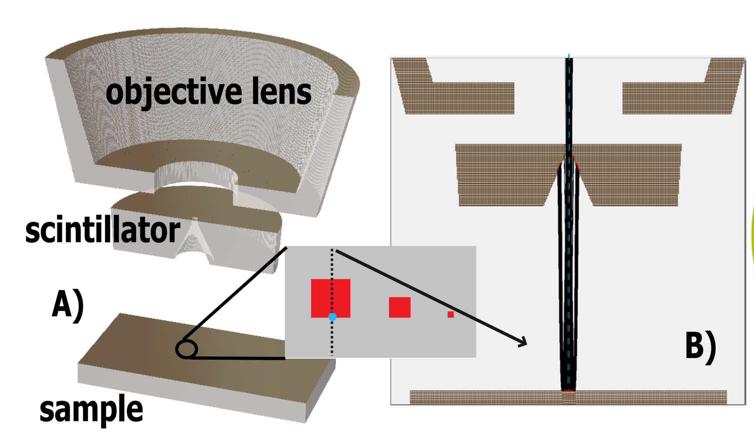
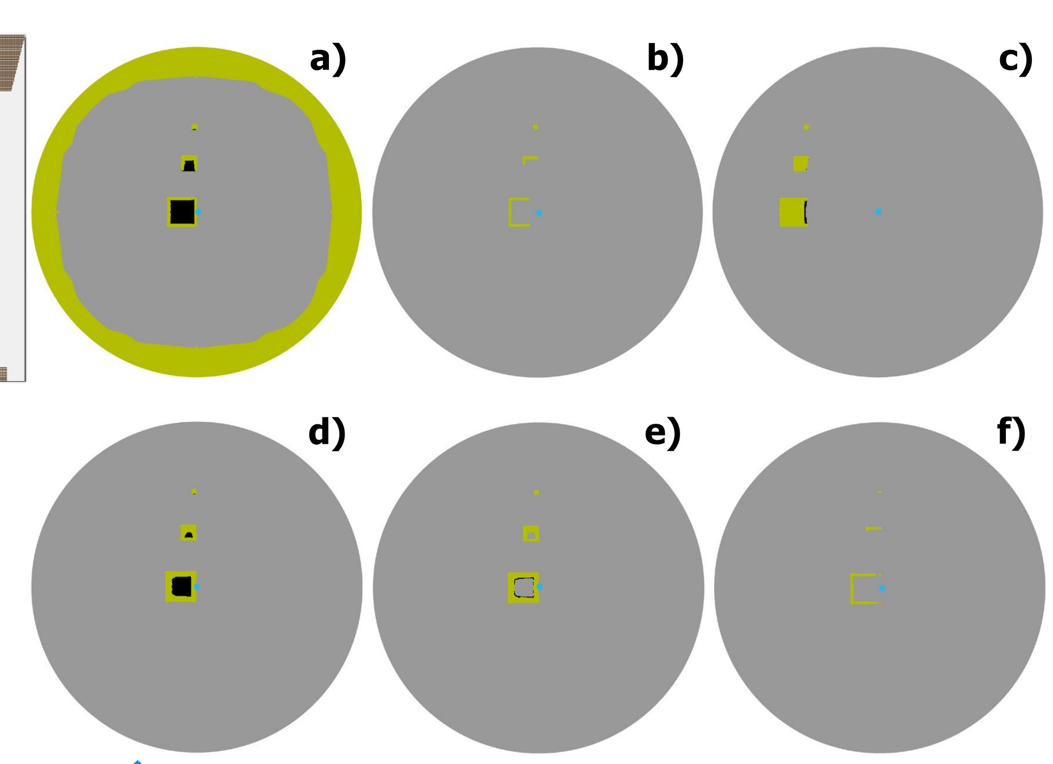


Image signal distribution in the presence of negatively charged areas





A) Setup for simulation of electron trajectories within the cathode lens when areas negatively biased with respect to the substrate are scanned. Simulation was performed in SIMION 8.

B) Electron trajectories when the primary beam is scanned along the black dashed line indicated in A.

Fig. a-f show the behavior of incident electrons under presence of squares negatively biased with respect to the substrate. Those areas represent the p-type patterns charged owing to the electron injection. In Fig. a the potential difference of -1 V was applied between the squares of sides 40, 20, 5 μm and the substrate, and electrons landed at 0.5 eV. The green color indicates total reflection of electrons on the YAG scintilllator, black color means reflection of electrons into the detector bore, and the gray area of the sample is where electrons impact on its surface. Blue point indicates the centre of the field of view.

In Fig. b and c the landing energy was changed to 1.1 eV and in Fig. c the squares were moved 100 μm off the optical axis. Obviously the bright rims are caused by reflection of the primary beam on the scintillator. When slightly increasing the simulated landing energy the bright rims and black areas suddenly disappear, which does not fit the experiment. However, the simulation disregards e.g. the energy spread of the primary beam, dynamic behaviour of the electron injection and any local surface tilts. The surface tilt significantly modifies the lateral component of the cathode lens field, which deflects electron trajectories.

Fig. d-f ilustrate the intensity distribution on the screen for a higher potential difference of -4 V; the landing energy was 3.9 eV for Fig. d, 4.1 eV for Fig. e, and 4.5 eV for Fig. f.

References: [1] Frank L., Müllerová I., Ultramicroscopy 106 (2005), p. 28-36. [2] Hovorka et al., Book of abstracts of 6th international workshop on LEEM-PEEM (2006), Trieste, p. 110.

*e-mail: hovorka@isibrno.cz