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Two-Dimensional Dopant Profiling in Silicon by SEM in Combination with Electrostatic Calculations

B. Wolpensinger,* M.A. Kessler,* P.P. Altermatt**

* Institut für Solarenergieforschung Hameln (ISFH), 31860 Emmerthal, Germany
** Leibniz University of Hannover, Inst. Solid-State Physics, Dep. Solar Energy Research, Appelstr. 2, 30165 Hannover, Germany

Purpose of the work Using secondary electron (SE) images of cleaved semiconductors from a scanning electron microscope (SEM) is a promising method for measuring the dopant density. However, a reliable conversion of the SE signal to dopant density has been notoriously difficult, for example because the signal may be sensitive to undefined conditions at the surface [1]. Here, we report on a procedure where we assume that the local variation of the SE signal is proportional to the change in work function which, in turn, depends mainly on the variation of the electrostatic potential (the band bending B) caused by the dopant gradient [2]. We cleave both a sample of interest and a small part of a reference sample. The reference sample – with known dopant profile – gives us a linear correlation between B and the SE signal, from which we derive a two-dimensional mapping of the dopant density of the sample of interest.

Approach A planar n-type Si wafer with a homogeneously diffused boron profile serves as a reference. Its dopant profile is independently measured using the electrochemical capacitance-voltage (ECV) method [3]. A small part of this reference sample is cleaved in air along the {110} plane at the same time as a sample of interest, and both are introduced together into the Hitachi S4800 FE-SEM. The imaging parameters are: an accelerating voltage of 1 keV, an emission current of 5 µA, and working distances in the range of 2–3 mm. The brightness and contrast settings are kept constant throughout the session. Doped regions are scanned once and images are acquired with a through-lens upper secondary electron detector. Fig. 1 shows a representative SEM micrograph, where the p-doped boron-diffused region appears brighter than the n-doped region. The pixel intensity I of the SE image is sampled along a wide line (Figs. 1 and 2) using ImageJ. The I of the reference sample is then correlated to $B(x) = v_{th}\ln(N_A(x)N_D/n_i^2)$, where v_{th} is the thermal voltage (25.85 meV at 300K), n_i the intrinsic carrier density of Si (10^{10} cm^{-3} at 300K), and N_D (or N_A) is the dopant density of the wafer (or of the diffused boron, known from ECV measurements along the coordinate x). A linear correlation $B = mI + b$ is obtained using the least-squares method (Fig. 3). Finally, the I of the sample of interest is converted to boron density using $N_A(x) = (n_i^2/N_D)\exp[(mI(x)+b)/v_{th}]$, see Figs. 4 and 5.

Results Figure 3 confirms the linear correlation between I and B in the reference sample. Fig. 4 indicates that N_A can be determined with a standard deviation of $2N_A$. Fig. 5 shows the extrapolated boron dopant mapping at the front surface of a pyramidally textured Si solar cell: the tops of the pyramids have a deeper diffusion than the valleys. The quantification of these inhomogeneities is a current topic of interest in the photovoltaic industry in its efforts to apply lighter doping to the emitter in order to increase solar cell efficiency.

References

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[4] We gratefully acknowledge the support from the State of Lower-Saxony.

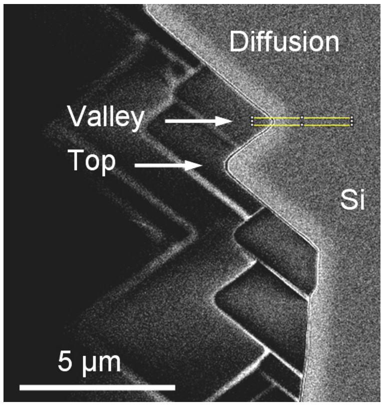

FIG. 1. SE image at a pyramidally etched Si surface after cleaving (raw image). The yellow box indicates the sampling range in a valley for Fig. 2.

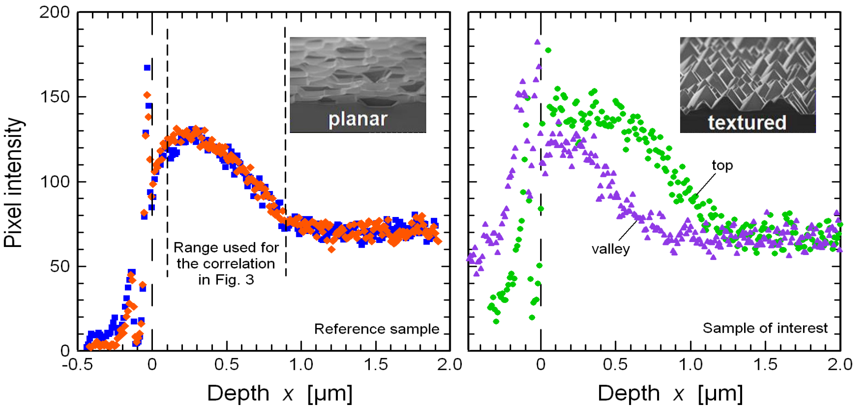

FIG. 2. Line plots at two different locations of the reference sample (left) to test the reproducibility, and of the sample of interest (Fig. 1) (right).

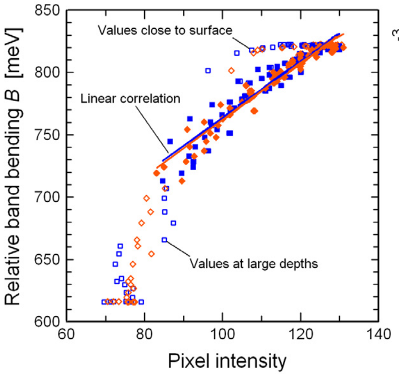

FIG. 3. Correlation between pixel intensity and dopant-induced band bending in the reference sample. Values originating from close to the edge of the cleaved surface are affected by the flanking surface, and those at $N_A < 10^{17}$ cm^{-3} are affected by surface charges. These values are not taken into account for the correlation (empty symbols).

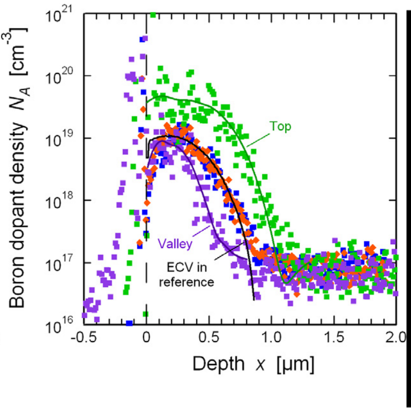

FIG. 4. The dopant profiles obtained from the SE images in Fig. 2, using the correlation of Fig. 3. The independently measured ECV profile is shown as black line. The green and violet lines are a smoothing spline fit of the values sampled at the top and the valley of the pyramids, respectively.

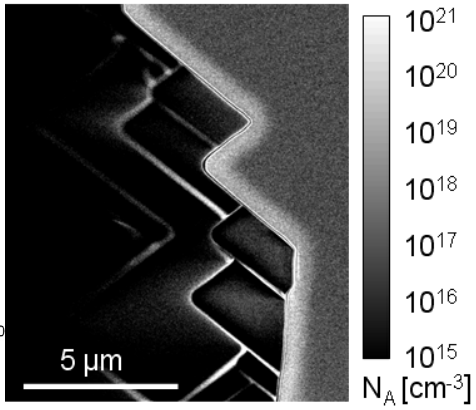

FIG. 5. Resulting two-dimensional mapping of the boron dopant density N_A of the sample of interest. This sample is measured together with a reference sample of known N_A, from which we routinely attain a linear correlation between the local electrostatic potential and the dopant contrast. This allows us to reliably extrapolate N_A for the sample of interest. This is a valid procedure as long as the dopant contrast is mainly influenced by the band bending due to the dopant density gradient, i.e. for $N_A > 10^{17}$ cm^{-3}. At lower N_A, surface charge effects dominate the signal. Prior to the calculation the image was smoothed using the ImageJ “smooth” algorithm.