Mapping of active dopants across p-n junctions in silicon and germanium using electron holographic tomography

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The fact that electronic and magnetic properties of a semiconductor can be precisely tuned by adding dopants provides an abundance of physical effects exploited by an extensive range of applications. In particular, tailoring the dopant distribution, i.e. the local concentration of donor and acceptor impurities on length scales reaching down to a few nm, is crucial for the functionality of semiconductor devices, e.g. diodes, transistors or solar cells. Measurement schemes facilitating a 3D characterization of dopant profiles with a few nanometers spatial resolution are rare, whereas the shrinking process of modern devices rapidly continues.

Different concentrations of donors N_D and acceptors N_A across a p-n junction lead to diffusion of the free charge carriers. Therefore, an electrostatic potential, the so-called built-in potential V_{pn}, is formed at the p-n junction that locally bents the band structure. Under equilibrium conditions the potential is determined by a (suitably scaled) Poisson equation

$$-\lambda^2 \Delta V_{pn}(\mathbf{r}) = N_D(\mathbf{r}) - N_A(\mathbf{r}) - n_c(\mathbf{r}) + p_v(\mathbf{r}), \qquad (1)$$

where λ denotes a characteristic length (the Debye-length) and n_c (p_v) the carrier concentrations of the mobile electrons (holes) in the conduction (valence) band. Here, the latter two are also determined by V_{pn}, because the occupation statistic depends on the distance of the bent conduction (valence) band to the Fermi level. Consequently, by rearranging (1) one gains access to the doping concentrations if the potential distribution is known.

The only technique currently capable of reconstructing three-dimensional (3D) electrostatic potentials on a nanometer scale is electron holographic tomography (EHT), that is, the combination of off-axis electron holography with electron tomography [1-3]. It is based on the linear relationship between reconstructed phase and projected electrostatic potential, which can be inverted by tomographic reconstruction schemes. Here, we apply EHT to reconstruct the 3D potentials in p-n doped silicon and germanium, which are subsequently used to retrieve the dopant concentration. Cylindrical specimens for tomography are prepared by Focused Ion Beam (FIB). A holographic tilt series is recorded covering a tilt range of about ±75°; the symmetry of the samples is exploited to extend the tilt range to ±90°. For tomographic reconstruction, we use a Weighted Simultaneous Iterative Reconstruction Technique (WSIRT) [2].

The reconstructed 3D potential including V_{pn} is depicted in Figure 1. However, because V_{pn} vanishes at the borders (dead layer), only the electrically intact core is considered (Figure 2a-c) to determine the concentrations of electrically active dopants. The result (solid black line in Figure 2d) shows an abrupt concentration change (<5nm). This is due to the fact that the doped layers in the silicon sample have been epitaxially grown. The comparison of our result with secondary ion mass spectrometry (SIMS) (dashed black line in Figure 2d), which includes information about both electrically active and inactive dopants, reveals that only 10% of the dopants are electrically active.

References

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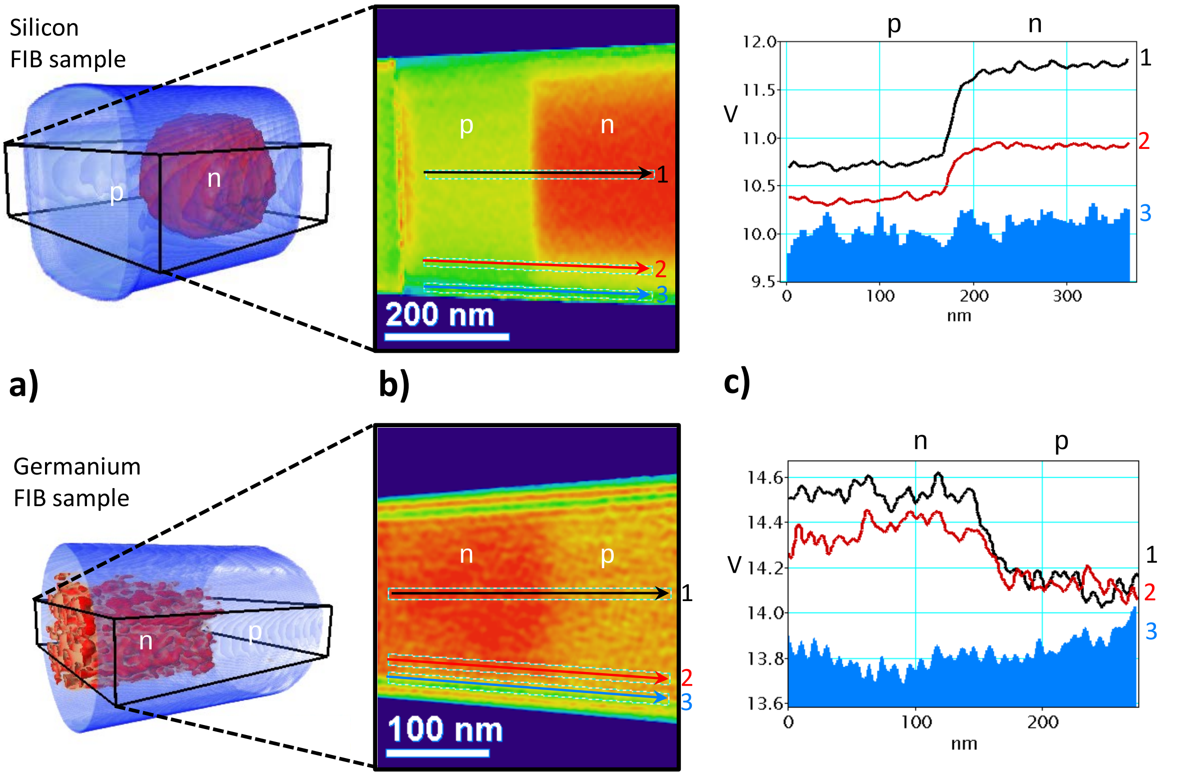

Figure 1. *Electrostatic potential of p-n doped silicon (top) and germanium (bottom) reconstructed in 3D by holographic tomography. a) The iso-potential surface (red) separates n and p region in the 3D rendering. b) The 2D central slice is obtained by averaging over 170 nm in Si (60 nm in Ge). c) 1D Profiles along the lines 1-3 shown in (b) exhibit the decreasing potential change from the center (1) via a transition zone (2) to the dead layer (3).*

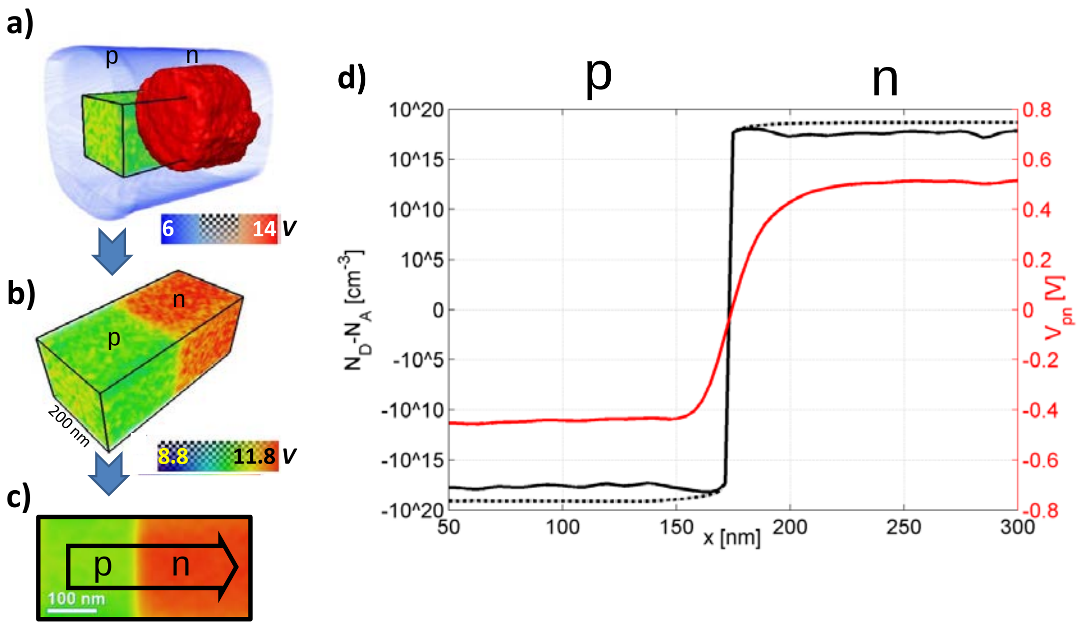

Figure 2. *Revealing of active dopants across a p-n junction in a needle-shaped Si sample from the 3D potential, reconstructed by holographic tomography. a) The iso-potential (red) within the volume rendering surrounds the n-doped region. b) Sub-volume extracted from (a). c) 2D potential after averaging in depth and smoothing with a median filter. d) The red line shows the built-in potential V_{pn}, gained from the 1D profile along the direction indicated by the arrow in (c) and after averaging over the arrow width. The difference of the concentrations for donors N_D and acceptors N_A (solid black line) is computed from V_{pn} with eq. 1 and compared with the SIMS profile (dashed black line).*