Quantitative 3D characterization of semiconductor nanostructures using electron-holographic tomography

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Holographic tomography, i.e. the combination of off-axis electron holography with tomography, provides a unique access to intrinsic electrostatic potentials of materials in three dimensions on a nanometer scale. Thereby the fact is exploited that the phase shift, reconstructed by holography, is proportional to the projected (object) potential hence satisfies the projection requirement for tomography. By applying this technique on various objects, e.g. semiconductors [1], ferro- and piezo-electric nano-particles, the revealed electrostatic 3D potentials can be evaluated locally and quantitatively, i.e. measurements of mean inner potential, built-in voltage across p-n junction or surface morphology, can be performed. In order to enhance the method we had developed automation procedures to perform the laborious holographic tilt series acquisition and reconstruction, as well as the tomographic reconstruction within a reasonable amount of time [2].

Here we present two examples of how holographic tomography can be used successfully to characterize potential distributions in 3D. The first example is a FIB prepared, p-doped Ge-needle with an n-doped region on top [3]. The SIRT ("Sequential Iterative Reconstruction Technique") reconstruction of this sample reveals the two major contributions to the electrostatic 3D potential (Figure 1), namely the mean inner potential V_0 and the built-in voltage across the p-n junction ΔV_{pn}. The quantitative values of both contributions can be gained from the line profile in Figure 1, where the mean value $V_0 = 14.7V$ is in good agreement with DFT calculations of Kruse et al. [4] ($V_{0,DFT} = 14.67V$); and the potential step $\Delta V_{pn} = 0.5V$ is corresponding to the band gap of Germanium ($V_{band\ gap\ in\ Ge} = 0.66V$).

As a second example, we present a reconstructed 3D potential of a GaAs/AlGaAs core-shell nanowire (150 nm diameter), grown by the Au-catalyst assisted MOVPE method [4], again reconstructed by the SIRT algorithm. Figure 2 shows the core-shell structure of the nanowire, i.e. the GaAs core with the AlGaAs shell around. Based on the DFT calculations of [5], the mean inner potential difference between GaAs and AlGaAs can be estimated as 0.9 V. This potential difference is visible in the right line profile corresponding to the dashed arrow in Figure 2. Furthermore, according to the left line profile in Figure 2, there is a small dip in the AlGaAs potential close to the Au catalyst nanoparticle of about 0.5 V. This is presumably caused by the Schottky contact between Au and AlGaAs, which may show up depending on the AlGaAs doping type and carrier concentration.

Although problems, e.g. missing wedge, dynamic diffraction and charging effects, limit the precision of the reconstructed 3D data, these two examples indicate that holographic tomography provides a unique insight into the (potential) structure of materials on the nanometer scale in three dimensions.

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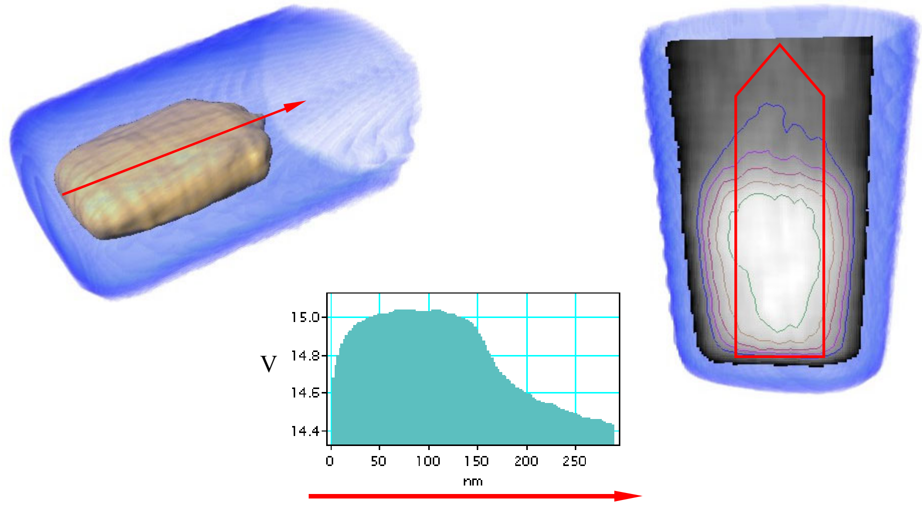

Figure 1. Reconstructed 3D potential of a p-doped Germanium needle with n-doped region. Left: Voltex view with internal 14.7 V iso-surface representing the n-doped region. Right: Central slice through the 3D volume with iso-potential lines. Center: Line profile along the arrow showing pn-voltage

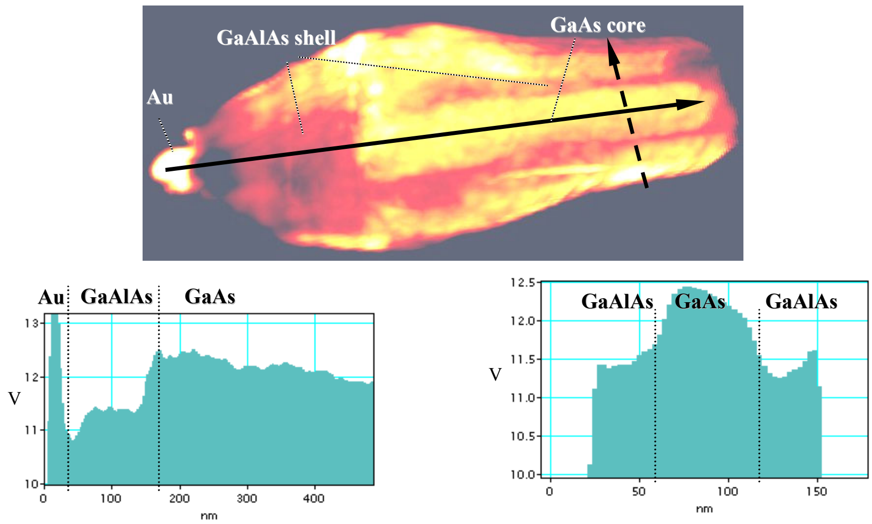

Figure 2. Reconstructed 3D potential of GaAs/AlGaAs core-shell nanowire grown by Au-catalyst MOVPE. The GaAs core and the AlGaAs shell can be well distinguished. Top: Rendered voltex view. Bottom left: Line profile corresponding to the solid arrow averaged over an area of 45 nm by 15 nm perpendicular to the line scan. Bottom right: Line profile corresponding to the dashed arrow averaged over an area of 140 nm by 55 nm perpendicular to the line scan.

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