# Holographic Tomography of Fermi Level Pinning at Focussed Ion Beam Milled Surfaces

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Tailoring the distribution of dopants in semiconducting materials allows engineering their electronic band structure, which is the basis for modern electronic devices such as diodes, transistors, varistors and many others. It is furthermore well understood that surface states at semiconductor-metal/insulator/vacuum interfaces have a large impact on the band structure hence influence the electric properties of the devices. Therefore, large efforts have been put in engineering surface states in order to either suppress or enhance the pinning effect.

Since the early works of e.g. Rau et al. [1], electron holography (EH) was prospected to become a key technique for measuring dopant profiles in semiconductor devices via a two-step procedure: (i) reconstruction of a 2D map of the projected electrostatic potential from the phase through

$$\varphi = C_E \int V\left(x, y, z\right) \mathrm{d}z$$

and (ii) computation of the dopant distribution within an appropriate model relating potential and dopant concentration (e.g. drift-diffusion model). While it has been demonstrated that quantitative potential maps of diffusion potentials can be obtained at nm resolution (e.g. [2]), computed dopant concentrations frequently were significantly lower than SIMS reference data especially at lower dopant concentrations [3]. As part of large efforts invested into resolving that issue, several explanations have been put forward for the observed discrepancy. Among those, it was pointed out that the potential is not constant along projection direction because TEM sample preparation modifies the surfaces. In particular, the most frequent Focussed Ion Beam (FIB) preparation amorphizes the surface layer to a certain depth and dopes the adjacent crystalline layer by introducing Ga. To consider this effect, models of so-called “dead” or “electrically inactive” surface layers followed by a transition layer with increasing electrical activity have been introduced (e.g. [4]).

However, detailed investigations of the surface effect were hampered by the loss of resolution along electron beam direction during projection. Several groups tackled this projection problem by performing electron holographic tomography (EHT) [5,6]. Nevertheless, quality and focus of these investigations did not allow surface potential reconstructions so far. Here, we fill this gap by providing direct evidence for Fermi Level Pinning and thus band bending at FIB-prepared surfaces by employing EHT. We present the most crucial steps in the holographic (optimal filter, phase unwrapping) and tomographic reconstruction (reconstruction algorithm, regularization), facilitating an unambiguous band bending detection. This allows analyzing the characteristic parameters of the bending, i.e. built-in voltage and depletion layer width; and correlate the findings with dopant concentrations. For our investigations we use the two test materials Si and Ge containing differently doped pn-junctions. The needle structures suited for tomographic investigations have been prepared by standard FIB (30 kV $Ga^+$-ions) milling.

As an example, a reconstructed potential slice of a Si pnp structure is depicted in Fig. 1. One clearly observes opposite band bendings within p and n regions toward the surfaces. This indicates that the Fermi Level has been pinned by the surface states in the band gap most probably introduced by FIB induced damages. The widths of the corresponding depletion regions correlate with the dopant concentration. A similar behaviour is observed with the Ge structures (see second example in Fig. 2). In Ge, however, the surface states are close to the valence band (e.g. [7]), leading to a strong bending only within the n-doped regions.

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8. This work has been presented at the MC2013 and a paper with the title "Tomographic Investigation of Fermi Level Pinning at Focussed Ion Beam Milled Semiconductor Surfaces" by D. Wolf et al. is currently submitted at APL.
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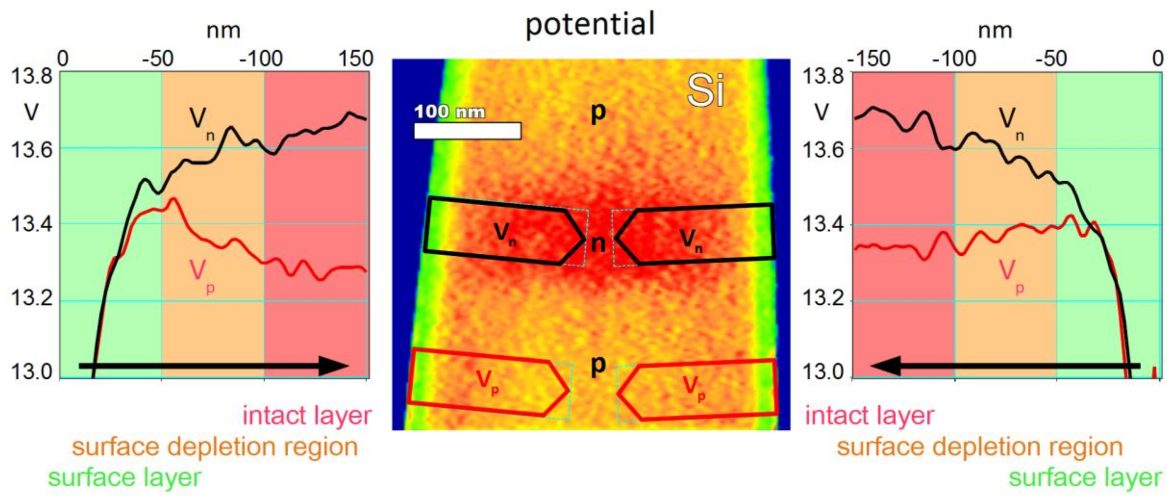


**Figure 1.** Slice through 3D potential of a Si-Needle with pnp-structure, arrows indicating the direction of the profiles. Adjacent profiles show the potential distribution from the FIB-affected surface, which pins the Fermi-level to the intact region in the n-doped area (black) and in the p-doped area (red), respectively.

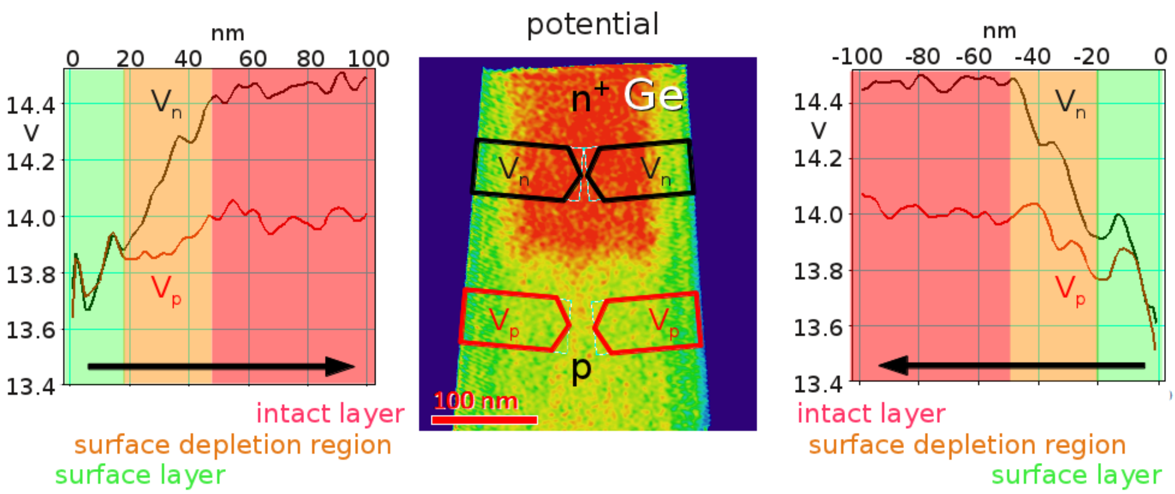


**Figure 2.** Slice through 3D potential of a Ge-Needle with pn-junction, arrows indicating the direction of the profiles. Adjacent profiles show the potential distribution from the FIB-affected surface, which pins the Fermi-level to the intact region in the n-doped area (black) and in the p-doped area (red), respectively.