Electron Holography of Semiconductor Devices

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Semiconducting devices are indispensable for a wide range of modern-day technologies. Their field of application ranges from simple diodes, transistors and solar cells to very complex multi-terminal devices like microprocessors and since they are becoming even more sophisticated, materials science demands suitable methods for investigating their electric properties. The functionality of all these devices is strongly affected by their built-in electric potential. The most basic case is the pn-junction: due to the diffusion of the different carrier types in two differently doped regions a depletion region is formed at the interface. The generated electric field leads to a characteristic built-in potential profile V_{pn}, measureable with off-axis electron holography (EH) in a TEM.

EH was prospected to become a key technique for measuring potentials and dopant profiles in semiconductor devices since the works of e.g. Rau et al. [1]. In EH an electron wave passing through the object is interfered with a reference wave passing through vacuum alone. From the interference pattern, the hologram, the complete electron wave hence amplitude and phase can be reconstructed by Fourier analysis. The phase φ of the object wave provides access to the inner potential distribution V(x,y,z)

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

where z is the direction of the electron beam and C_E is the interaction constant, depending on the acceleration voltage of the microscope.
Finally, knowledge of the potential distribution allows computation of the dopant distribution within an appropriate model relating the potential with the dopant concentration (e.g. drift-diffusion model) [2]. Figure 1 illustrates the application of dopant profiling by EH on a n-FET: In the reconstructed phase image highly n-doped regions below source and drain are clearly visible against the substrate.

Combination of EH with tomography (EHT) allows reconstruction of entire 3D-potential distributions [3,4]. To this end, a series of holograms of the object is recorded at different tilt angles. Following the holographic reconstruction of the tilt series, the 3D potential is reconstructed tomographically. Figure 2 shows the reconstructed 3D potential of a n-type MOSFET. The great advantage of a tomogram is evident, because object potentials can be measured inside and independent of surface effects. Here, the measured built-in voltage between p-doped substrate and highly n-doped source/drain regions is determined to 0.8V.

In addition to electric fields, EH is also capable of mapping strain fields by dark-field off-axis electron holography (DFH) [5,6]. Strain is of growing importance in modern semiconductor devices since it can be used to increase the charge carrier mobility. DFH uses a reference wave passing through an unstrained crystal to detect geometric phase differences inside the crystal, delivering the lattice strain in two dimensions. Figure 3 shows the strain in [110] direction of the substrate below three MOSFETs. The linscans in [110] and [001] direction reveal a compressive strain of -0.5% in the channel region below the transistor.

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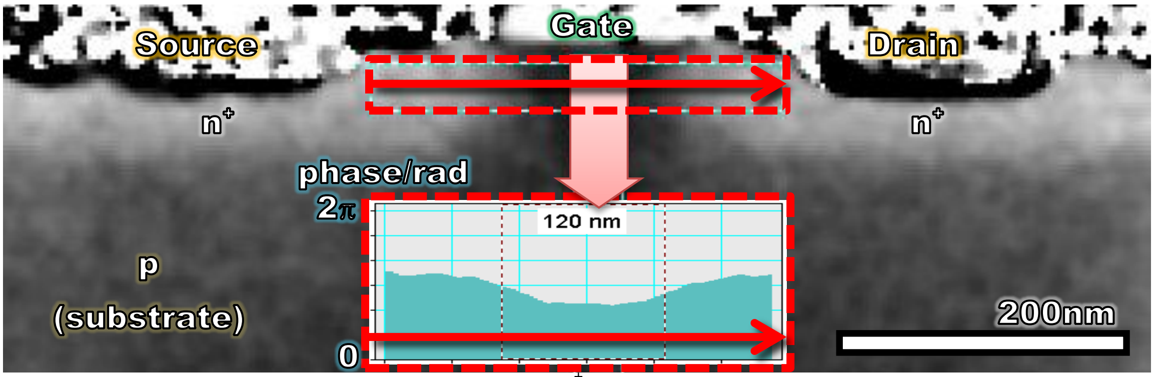

Figure 1. EH: phase image of a n-FET. The bright n[+]-doped areas below source and drain contacts are clearly visible against the bulk. The graph shows the profile from source to drain area indicated by the red dotted rectangle in the image.

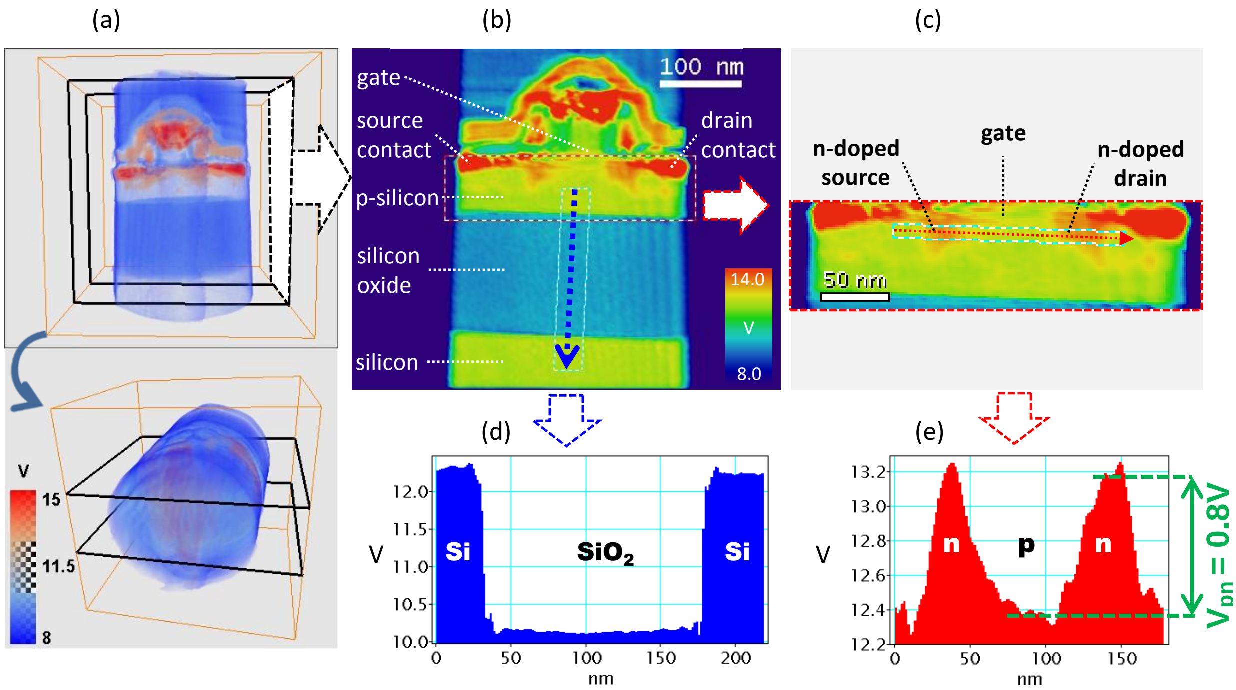

Figure 2. EHT: 3D reconstruction of a FIB-prepared sample of a n-type MOSFET (AMD 90nm technology).
(a) Volume rendering of the 3D potential distribution.
(b) 2D potential map obtained by averaging over the region between the two planes indicated in (a).
(c) Detailed view of the p-doped substrate with highly n-doped regions below source and drain (red).
(d) Line profile showing the mean inner potentials of Si (12.2 V) and SiO2 (10.1 V)
(e) Line profile showing the built-in voltage V_{pn} between p- and n-doped silicon (0.8 V).
(Sample courtesy of H. J. Engelmann, GLOBALFOUNDRIES, Dresden)

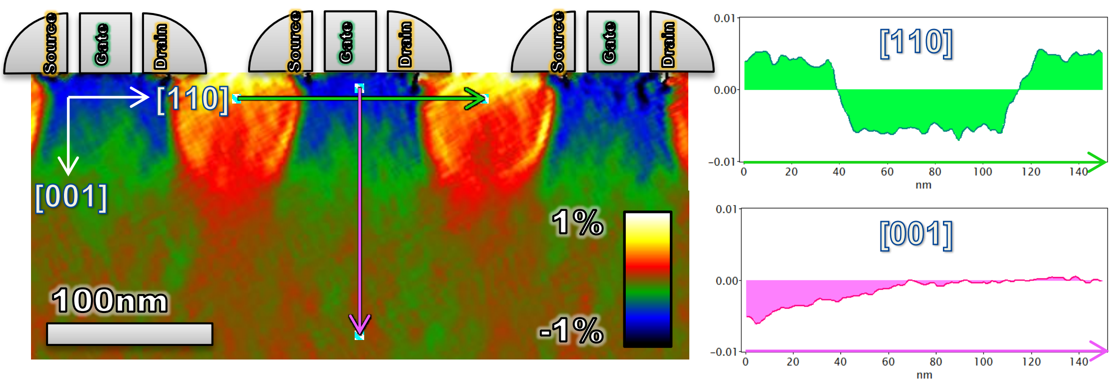

Figure 3. DFH: Map of the (110) lattice strain below three MOSFETs. Arrows indicate the position of the two linescans in [110]-direction (green) and [001]-direction (red).
(Sample courtesy of H. J. Engelmann, GLOBALFOUNDRIES, Dresden)