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Mapping strain fields in semiconductor nanodevices by dark-field off-axis electron holography and nano-beam diffraction

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Strained silicon has already become a standard technology in advanced semiconductor device engineering to boost performance and efficiency in modern transistor devices [1]. Therefore, the determination of the exact two-dimensional strain distribution at nanometre scale is of major interest in semiconductor device characterization [2]. For instance, GLOBALFOUNDRIES demands an accuracy better than $\Delta\varepsilon$=0.1% for the strain $\varepsilon\pm\Delta\varepsilon$ measured in the transistor channel. Lateral resolution should at least reach 5 nm.

Dark-field off-axis electron holography (DFH) and nano-beam diffraction (NBD) are TEM-based techniques that are able to match these requirements. In DFH, diffracted waves from adjacent sample areas are interfered using the dark-field off-axis holography configuration [3]. The superposition of one part of the diffracted wave emanating from strained Si and the other part emanating from adjacent strain-free Si substrate forms a dark-field hologram, from which differences in amplitude and phase of the diffracted wave can be reconstructed. The gradient of the phase parallel to the diffraction vector yields the lattice strain in this direction [4]. In NBD, a series of diffraction patterns is acquired along a line profile of interest and compared to a reference diffraction pattern from an unstrained region in the Si substrate. A line profile of the local strain is then calculated from the relative displacement of the diffraction spots in the nanodiffraction patterns [5,6].

Figure 1 illustrates a successful strain measurement in a state-of-the-art transistor structure manufactured by GLOBALFOUNDRIES Dresden. Recessed SiGe at source and drain induces compressive strain in the transistor channel. Our experiments allow reconstruction of a (110) lattice strain map at 800 nm and 200 nm field of view, and lateral resolution of 10 nm and 4 nm, respectively. A statistical evaluation of multiple line profiles from a series of holograms leads to a sensitivity of $\Delta\varepsilon$=0.1% at 10 nm resolution and $\Delta\varepsilon$=0.2% at 4 nm resolution, were noise poses the most severe problem. However, since the strain values are retrieved by means of the derivative of the reconstructed (220) phase along the [110] direction, strain profiles along the channel are more affected by noise than perpendicular profiles.

For the purpose of comparison, NBD patterns have been recorded along the channel of transistor B and C; a parallel NBD scan inside the substrate is needed to receive the reference spot positions. Peak fitting software is used to determine the positions of the <-440> and <440> diffraction spots; their relative displacement to the reference position then yields (110) lattice strain profiles. The FWHM of the diffraction peaks coincides with the scanning probe, and hence can be used to define the resolution in our NBD experiments to around 6 nm. From a statistical evaluation of the NBD reference scans in the substrate, the accuracy in the strain measurement estimates as $\Delta\varepsilon$=0.1%.

A comparison of the line profiles at transistor B and C illustrates that DFH and NBD yield consistent results in the transistor channel. NBD measures ε_{xx}=-(0.7±0.1)% compressive strain in the centre of channel B and C, while DFH experiments yield ε_{xx}=-(0.6±0.1)% or ε_{xx}=-(0.6±0.2)%.

Our results demonstrate that DFH and NBD are two complementary, well suited techniques for strain metrology in state of the art transistor devices at nm-scale resolution. Whereas NBD is a quite simple technique easy to perform, DFH needs more sophisticated equipment and evaluation. However, DFH provides the two-dimensional strain distribution within one single acquisition. Although sensitivity of both techniques is comparable, we will provide further examples of sole DFH experiments on other devices proving a sensitivity better than $\Delta\varepsilon$=0.1%.

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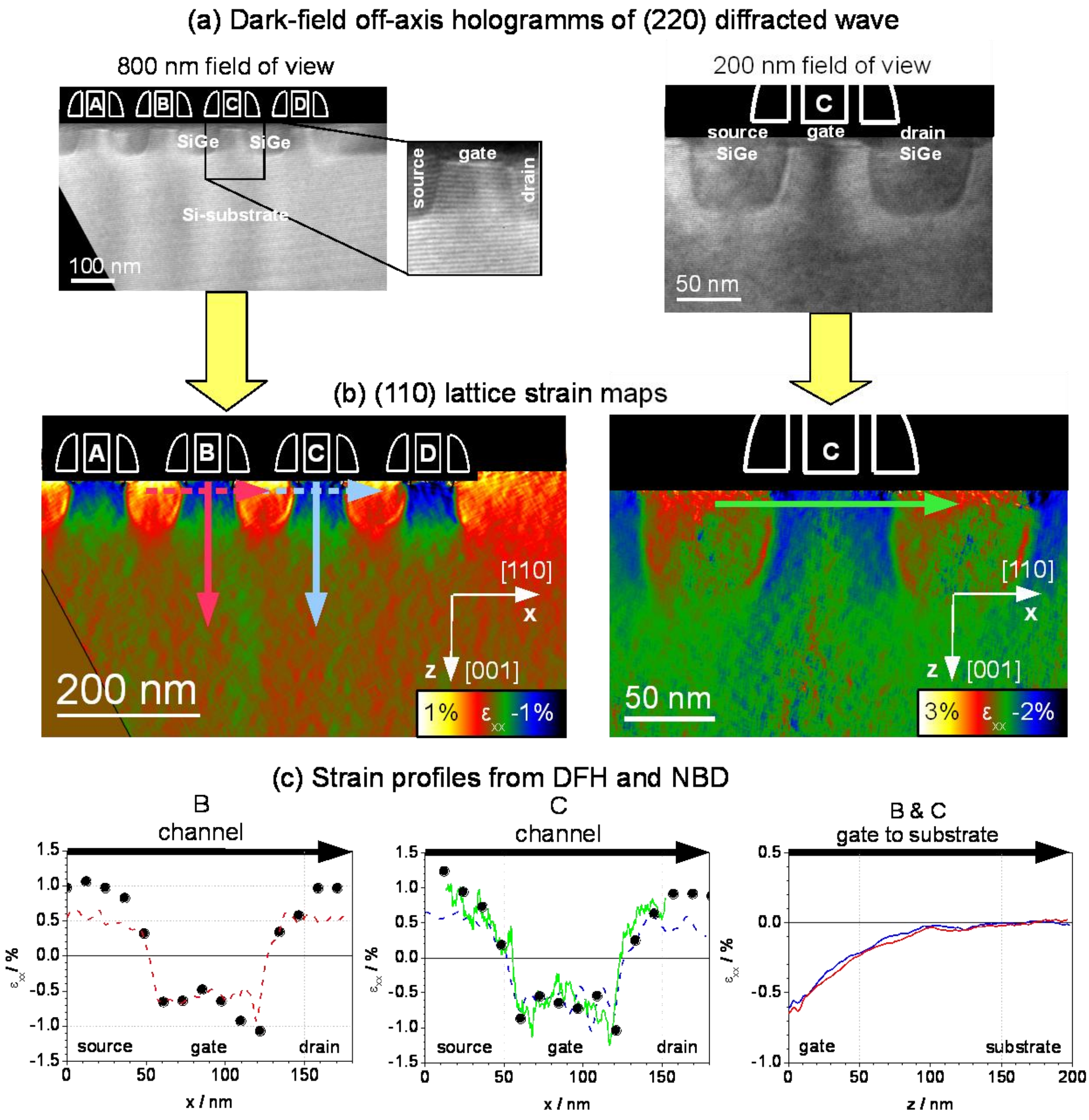

Figure 1. (a) Dark-field off-axis holograms of the (220) diffracted wave: 800 nm field of view is sufficient to cover the 4 MOS transistors (A, B, C, D) with recessed SiGe at source and drain. The bending of the interference fringes indicates strong lattice strain in the transistor channel. 200 nm field of view can cover only transistor C (b) Maps of the (110) lattice strain reconstructed from the holograms: The left strain map provides 10 nm, the right strain map even provides 4 nm lateral resolution. (c) The strain profiles taken from the maps (solid and dashed lines) are compared to the NBD scans (dots). Within the wide error bars, DFH and NBD yield consistent results. Regardless of the method used, compressive strain in the center of the transistor channel can be estimated to ε_{xx}=0.6%.