Nanobeam Beam Diffraction (NBD) in the TEM for Drift-corrected Strain Mapping in Semiconductor Devices

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To increase the carrier mobility in modern silicon devices, strain of the order of 1-2 % is introduced into the channel. Several experimental methods have been developed to measure the strain, among them Convergent Beam Electron Diffraction (CBED), Dark Field Electron Holography (DFEH)[1], Scanning TEM High Angle Annular Dark Field Imaging (STEM-HAADF), and Nano-Beam Diffraction (NBD) [2]. Arguably, NBD is the most straight forward and conceptually most simple method: A parallel beam with small diameter (~5nm) is formed in the TEM and scanned across the sample, and diffraction patterns (at a zone axis) are recorded and analyzed for each location. However, finding the exact location of the diffraction spots with sub-pixel resolution and the huge data files are a challenge.

We developed an in-house software package called F-Strain, which reads and fits NBD maps and profiles in standard format (.dm3 or .ser-files). The program is written in a third party industry standard scripting language. Data analysis is performed in three steps: First, each diffraction pattern is filtered using an auto-correlation algorithm. This step reduces noise and converts the diffraction disks to spikes [3]. Then, an algorithm locates the 30 most inner reflections in the diffraction pattern [4]. These reflections are fitted individually with a background-corrected 2D-Gaussian. Lastly, a two dimensional grid is fitted to all 30 spot locations, using the confidence level of each individual spot location (σ_x, σ_y) as weight in the fit of the grid. This ensures that spots with high location confidence (small σ) contribute strongly to the final fit, while spots with a less well defined location in the pattern contribute only marginally. The base vectors of the grid, i. g. g_{220} and g_{004} for the $Si_{[110]}$ diffraction pattern, are then compared to vectors imported from unstrained material, and the strain is determined as $\varepsilon = (g_{ref} - g_{strain})/g_{strain}$. A special filtering feature used in the analysis makes it possible to measure strain in silicon devices even in the presence of other crystalline materials covering the probed area, which is important for the characterization of the next generation of devices (Fin-FETs) [5].

The precision of the program is determined by analyzing the variability of 50 patterns acquired in nominally unstrained material. For diffraction patterns with 2kx2k pixel size the program reaches a reproducibility, and thus precision, of 0.035% in [004]-direction, and 0.055% in [220]. Interestingly, the full resolution of the CCD camera is not needed to achieve this precision, since the uncertainty only increases slightly even if the number of pixels in the pattern is reduced dramatically. Fig. 1 shows the measurement error for the two directions as a function of pixel size in the diffraction pattern, showing measurement errors of less that 0.07% for patterns with only 512x512 pixels.

The fact that high fidelity is given even at small pattern sizes allows the recording of drift corrected strain maps using standard acquisition tools: The diffraction patterns are recorded using a CCD camera, while NBD scanning dark field images is recorded for the drift correction using an annular dark field detector above the viewing chamber. Fig 2 shows the strain maps for strain in [220] and [004] direction for a 22 nm pFET, using a 5 nm beam in a 200kV microscope. The acquisition time for the map (50x37 points) was 35 minutes, analysis time using F-Strain was 20 minutes on a laptop computer.

In conclusion, we developed a diffraction pattern fitting program which analyses diffraction patterns by (1) fitting each individual spot, and (2) fit a grid to the spots, using the confidence level from the spot fit as a weight. The precision of this method is comparable to holographic methods, and high enough to confine the acquisition to the center area of the CCD, thus allowing drift-corrected acquisition of strain maps of up to 3000 points without any sample tilt.

References:

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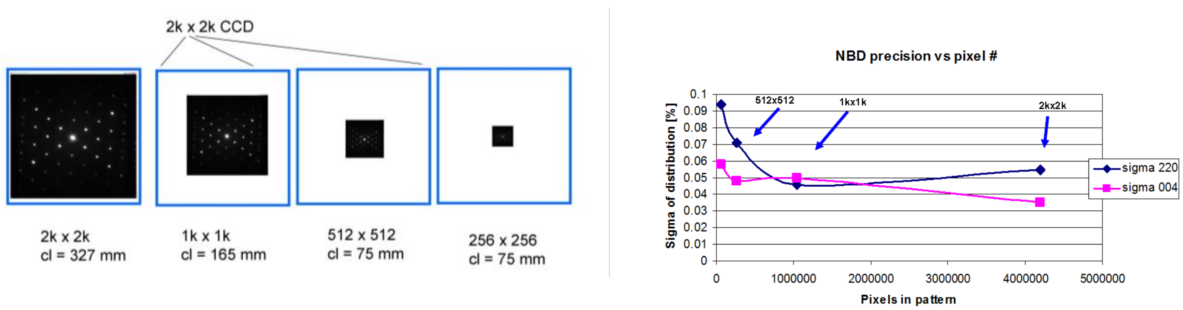

Figure 1. Reducing the area of the CCD used to acquire the diffraction patterns results in a decrease of precision only for patterns smaller than 512x512 pixels

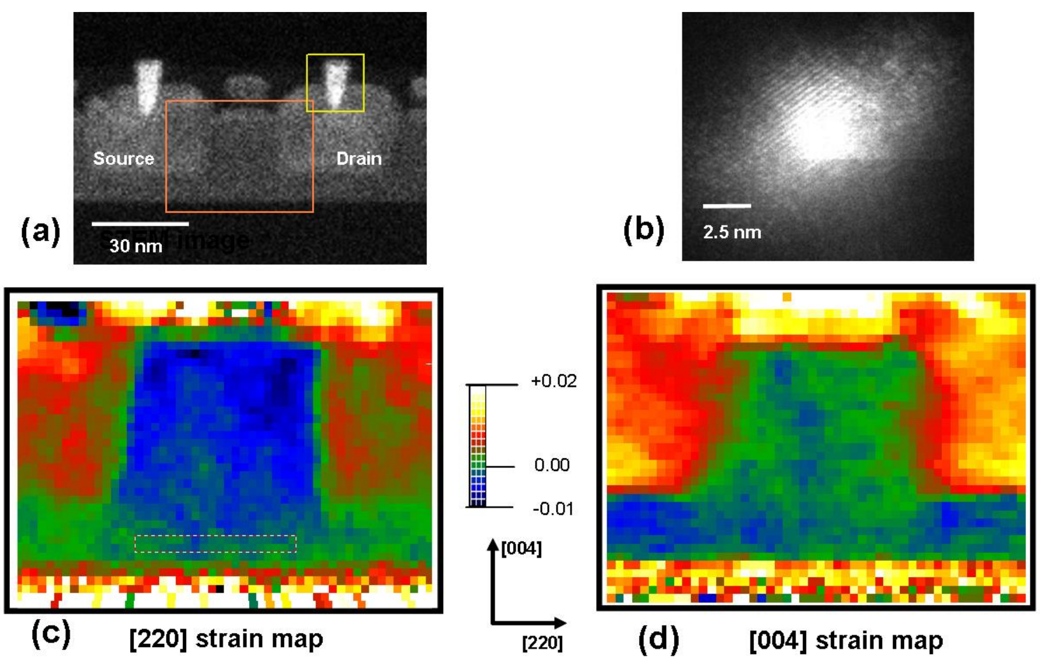

Figure 2. (a) Scanning NBD dark field image of strained pFET with acquisition area (orange) and drift correction area(yellow).(b) Image of 5 nm NBD probe. (c) and (d) Strain maps of [220] and [004] strain showing 0.7% compressive strain in [220] between source and drain, and only minimal strain in [004] direction.