Local Strain in Indented Silicon Wafers Investigated by Full-field X-ray Micro Diffraction Imaging

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Damage in silicon wafers from handling and processing is a severe problem in device production. Microcracks may grow catastrophically shattering the wafer while dislocation and slip bands reduce the yield of the electronic devices. X-ray diffraction imaging, XRDI, (topography) is capable of imaging the dislocations, slip bands and microcracks with a very high strain sensitivity [1] but no quantitative information about residual strain or tilt is available from topograms. Full field X-ray Micro Diffraction Imaging (XMDI), also known as rocking curve imaging (RCI) is a high resolution X-ray method to characterize and to quantify the damage in crystals [2]. XMDI provides more structure information on lattice parameter and deformation, crystal misorientation and grain size, etc. by fitting rocking curves. For the experiments, a series of silicon (001) wafers treated with various loads of nanoindentation (from 200 mN to 2 N) to produce well defined artificial damage similar to the real damaged observed in wafers from production process. We have first time successfully measured XMDI at the W2 beamline, HASYLAB. For one 200mN-load indented sample we used 25 keV photons and measured the 004, 117 and 220 reflections, in both Bragg reflection and Laue transmission modes. A second sample was annealed with dislocations and slip bands along <111> planes. The 220 reflection was used in transmission mode.

The diffractometer at the W2 beamline with the heavy loading 2-theta arm with a 10-300 mm translation stage allowed us to mount our own high-resolution CCD camera with effective pixel size of 0.36 µm and to record the diffraction images at different distances but not close enough for unblurred maps. A code for data analysis allows the extraction of diffraction and scattering maps from the collected XMDI data for 2D or 3D evaluations and visualizations. The Bragg peak integrated intensity or area, peak broadening or width, peak-position shift and diffuse scattering component at each pixel in the image data are extracted and mapped out. It was possible with the actual setup to find detailed information on micro-structural defects and local strain field in the indented Si samples [3]. The 200 mN indentation in the silicon wafer has generated an accumulation of structural defects under the indenter, and these defects are accompanied with lattice defects which may result in strain fields.

The strain field, visible in the shift of peak position, around the 200 mN loaded indent is shown in Fig.1 as one example. In the 004 reflection, the integrated intensity map presents a real-space 2D projection of the strain fields into the {110} plane. The maps show lateral symmetric, “bowl shape” distributed strain fields induced by the 200 mN indent, extending to a spatial domain of ~80×80 µm² around the indent. The peak-position shift around the strain field is about -0.015~0.015°. The shifts drop down along the four {111} planes which are the typical cleavage planes for Si. A special feature it could be measured, that the strain changes from compressive (red) to tensile (blue) into depth.

The strain field and defect distribution, as revealed by the two or three-dimensional maps at 004 and 220 diffractions, are strongly dependent on the indentation load, crystal anisotropy and annealing treatment. The indentations generate strain fields extending to a domain much larger and deeper than the plastically deformed zones around the indenter impression.
Figure 1: Maps of peak position shift in degree in the 200 mN loaded indent in Si wafer (sample Dr1). The maps were extracted from the XMDI data collected at 004 reflection and at azimuthal angle 0°. The top and side views of the Berkovich indenter employed for indentation are illustrated. The marked positions 1-6 are typical sites in the strain field.

XMDI data from the 004 reflection contains mostly the depth information of strain field induced by the indent. Distinct from the 004 reflection, the XMDI at the 220 measures the crystal planes which are perpendicular to the crystal surface (001), hence it provides mostly the information on (001) plane projection. It could be shown from the 220 measurements that the indentation may cause some convex and concave curvatures on surface parallel (001) planes, and thus, releases the lattice strain accumulated near the surface. It can also be noticed that in this reflection, the tilting of the crystal planes along <110> is dominant. The tilting zones are alternatively distributed around the indent with a maximum tilt angle of ~0.008°.

In summary the experiments showed in detail and quantitatively the complex strain and tilt distribution in damaged Si. Further works will focus on the samples with higher indent loads of 5 N - 50 N and various annealing methods which are found to be critical for wafer breakage during industrial processes. From a technological point of view the setup should be optimized for further XMDI mesurements at W2. The blurring of the maps can be avoided by narrowing the slits to minimize the virtual source point for higher resolution. This would cause a loss of intensity and longer measuring times. The better choice would be the construction of an adapter, which allows the positioning of the camera as near to the sample as posible.

References