Semiconductor nanostructures seen by focused x-rays

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Semiconductor nanostructures are important building blocks for a large variety of present and future devices. Examples reach from electronic devices with typical dimensions of several 10 nm at least in one direction, over quantum dots for optical as well as electronic applications, semiconductor nanowires for solar cells or thermoelectric devices, regular nanostructure arrays for photonic applications, and many more.

In almost all cases, the properties of the nanostructures are determined by their size and shape via quantum confinement effects, and by the chemical composition and the strain distribution, influencing the band alignments and the splitting of degenerate energy levels. To understand nanostructure "behavior", e.g. their optical or electric response, obtaining very detailed information on those structural parameters is essential. Beside electron microscopy and scanning probe techniques, x-ray diffraction has proven a powerful tool, particularly for the precise determination of strain fields and chemical composition. Traditionally, x-ray scattering experiments illuminate comparatively large sample areas in the mm range down to few 10 µm, hence obtain good statistically averaged data. While this is usually an asset, it can also turn into a considerable drawback in situations where very inhomogeneous ensembles of nanostructures are illuminated simultaneously. A similar problem arises if single nanostructures are embedded into complex device architectures and the area of interest is very small.

In order to cover also such cases, we have developed methods to investigate individual nanostructures using focused x-ray beams. The progress of focusing optics at synchrotron sources yields beam diameters in the 100 nm range, suitable to selectively illuminate individual objects. This enables the analysis of single nanowires or quantum dots, as in the case of a single buried SiGe island inside a MOS transistor shown in Fig. 1 [1]. In addition, the small beams at synchrotron sources are often highly coherent, allowing to address an old problem of x-ray diffraction, namely to retrieve the unknown phase of the scattered beam so that the real-space structure can be calculated directly from the scattering data [2].

We will review recent developments and progress in the field of x-ray diffraction using focused beams, and present examples using conventional analysis as well as concepts like phase retrieval and diffraction holography [3]. We will also discuss the strengths, limitations, and problems of focused x-ray beam experiments in comparison to electron and scanning probe microscopy.

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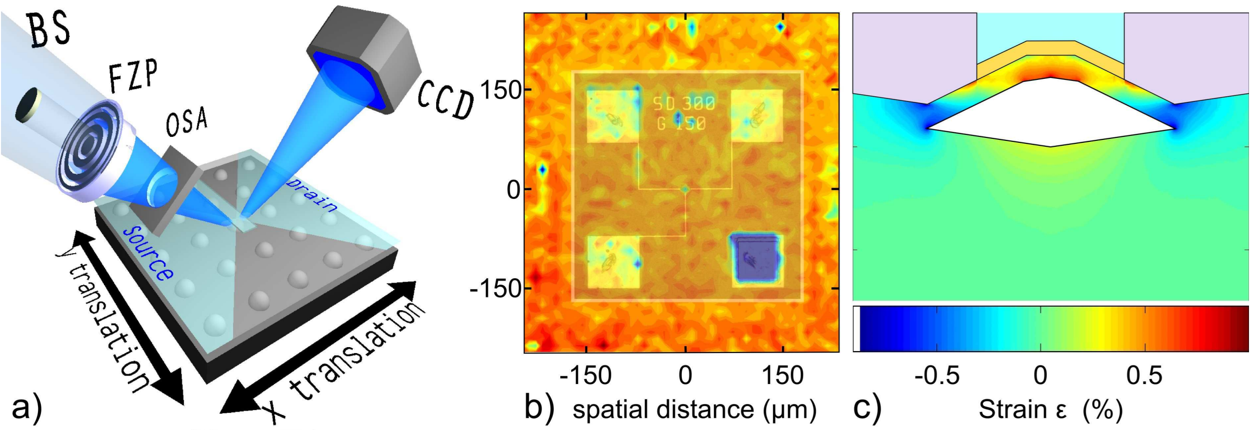

Fig. 1: (a) Experimental x-ray nanobeam setup: beamstop (BS), Fresnel zone plate (FZP) and an order sorting aperture (OSA) are used to focus the incoming X-ray beam. (b) scanning x-ray diffraction map reveals the real-space structure of the sample for a certain diffraction vector (colormap). Overlaid is an optical microscope image of the sam region. (c) strain distribution obtained for the Si cap above a single buried SiGe island inside a transistor structure.