## Spectroscopy in STEM/TEM

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## Characterization of cubic GaN/AlN multi-quantum wells using state-of-the-art analytical STEM

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Analytical transmission electron microscopy provides superior access to structural, chemical and electronic properties of quantum structures grown on locally nanopatterned semiconductor surfaces. Other thin film characterization techniques frequently fail to adequately reveal the properties of nanostructures, if these can be grown only locally, as is the case e.g. if electron beam lithography is used for substrate patterning, because of the small patterned substrate areas on which growth needs to be characterized. With the advent of $C_s$-probe corrected STEMs, improved electron sources and advanced detectors for both, EELS and EDS, the analytical performance of off-the-shelf electron microscopes has recently significantly improved and facilitates the characterization of such quantum structures. The aim of this contribution is to spread light on the performance and limits of an actual advanced electron microscope in the characterization of an electronic quantum structure.

To this end a multi-quantum well (MQW) structure consisting of a 20 layer stack of cubic AlN (2 nm) and cubic GaN layers (4 nm) were grown by plasma enhanced molecular beam epitaxy on a sub-µm patterned 3C-SiC(001) surface. Patterning of the SiC surface was achieved by electron beam lithography followed by reactive ion etching (RIE), resulting in square-shaped SiC posts of about 550 nm width and 700 nm height. Cross-sectional TEM-samples were fabricated from several posts using focused ion beam preparation and subsequent low-energy ion polishing to remove FIB-induced surface damage. A JEOL ARM200 (S)TEM equipped with a cold field emission gun, $C_s$-probe corrector, ultra-high-resolution pole piece, GIF Quantum imaging energy filter and a Centurion EDX silicon drift detector was used to characterize the sample. Mostly the STEM mode was employed at 200 kV acceleration voltage in order to benefit from the high lateral resolution available with both, the annular bright-field (ABF) and the high-angle annular dark-field (HAADF) detector. STEM-ABF images as in Fig. 1 (a) indicate that the MQW-structure has grown conformally around the mesas fabricated by RIE. The MQWs exhibit an undulating shape owing to the presence of (111) stacking faults, as can be clearly seen in atomic resolution ABF- (Fig. 1 b) and HAADF-STEM images (Fig. 1c-d). Low-loss EEL spectra were recorded in a spot mode from individual layers of the MQW structure in a region with almost perfectly planar layer sequence, displayed in the ADF-STEM image in Fig. 1 (e). The 0.3 eV energy resolution of the microscope allows to observe the band edges of the two wide band gap semiconductors as well as characteristic surface and bulk plasmon features of the two different MQW materials (Fig. 1 f). The depth profiles of the chemical elements C, N, O, Al, Si, and Ga were recorded in parallel using core-loss EELS and EDS line scans with an electron beam of < 0.2 nm diameter at a step size of 0.1 nm. Even though the overall agreement of depth profiles is impressive for most elements at first glance, some systematic deviations are observed between EDS and EELS profiles e.g. for nitrogen and gallium. The origin of these differences is analyzed and discussed.

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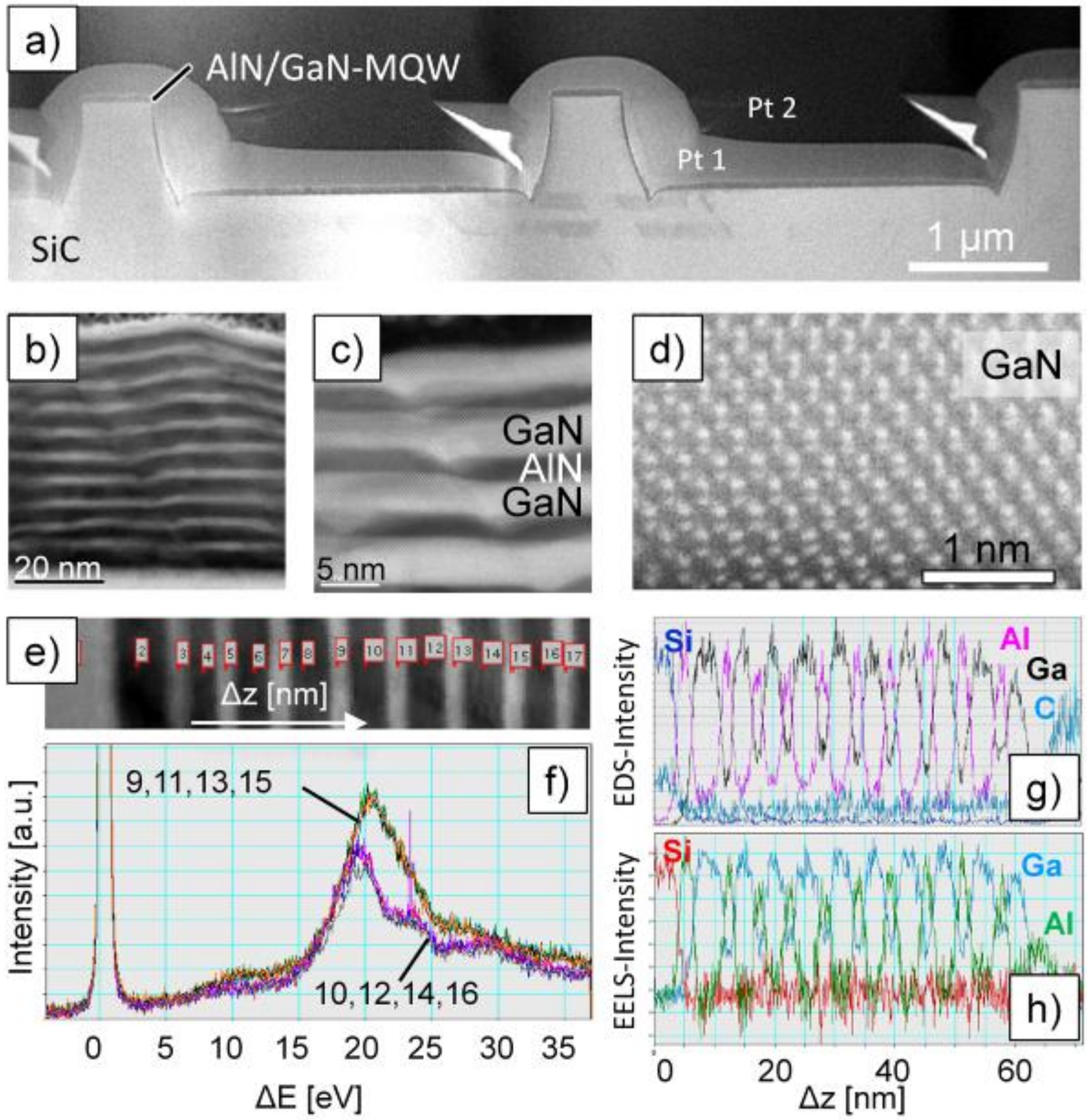


**Figure 1.** Analytical scanning transmission electron microscopy characterization of a cubic AlN/GaN multilayer quantum well structure (MQW) grown on a nanopatterned 3C-SiC(001) substrate. For details see text.