Characterization of semiconductor nanostructures using ultra-high resolution STEM-CL

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For a comprehensive understanding of complex semiconductor heterostructures and the physics of devices based on them, a systematic determination and correlation of the structural, chemical, electronic, and optical properties on a nanometer scale is essential. Luminescence techniques belong to the most sensitive, non-destructive methods of semiconductor research. The combination of luminescence spectroscopy – in particular at liquid He temperatures – with the high spatial resolution of a scanning transmission electron microscope (STEM) as realized by the technique of low temperature cathodoluminescence microscopy in a STEM (STEM-CL), provides a unique, extremely powerful tool for the optical nano-characterization of quantum structures.

Typical results, which will be presented, include the nm-scale analysis of group III-V semiconductor nanostructures visualizing the enormous capability of STEM-CL characterization.

The direct identification of the emission of a two-dimensional electron gas (2DEG) in a lateral GaN/AlN/AlGaN heterostructure field-effect transistor (HFET) will be shown. The characteristic emission of the 2DEG channel is observed on the low-energy side of the dominating donor-bound exciton luminescence. Beside this spectral fingerprint, the exact local origin of the 2DEG CL is verified to be close to the GaN/AlN interface. Due to the superposition of several possible recombination channels in the near-band-edge spectral region, this local verification is essential for the unambiguous identification of the 2DEG luminescence. The transport of the generated excess minority carriers (i.e. holes) into the 2DEG region leads to an intensity onset of the 2DEG emission already 60 nm below the GaN/AlN interface (already in the GaN drift region). Vertical transport measurements of the active region are easily accessible in STEM-CL in this way directly visualizing the vertical capture of excess carriers into the 2DEG.

Single dot spectroscopy by means of low temperature STEM-CL provides a detailed insight into the energy structure of individual quantum dots (QDs) and directly correlates those properties with the real structure on a nanoscale. We characterize the vertical and lateral transfer of carriers within a 7-fold layer stack with high-density InP quantum dots grown via Stranski-Krastanov mode. We observe a characteristic change of the excitonic emission lines during scanning across an individual InP QD in a lateral CL linescan. This reveals the change of the numbers of excess carriers reaching the dot - i.e. altering the quantum dot population. The shift of emission energies visualize the renormalization of the ground-state energy of the single dot and the intensity ratio of the excitonic recombinations verifies this change in occupation.