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Nanometer-scale Resolved Cathodoluminescence Imaging: New Insights into GaAs/AlGaAs Core-shell Nanowire Lasers

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The one-dimensional geometry of GaAs-based nanowires (NWs) enables the possibility to achieve silicon-integrated nanoscale coherent light sources, i.e., NW lasers, attractive for future optical interconnects in on-chip data communication. Attributed to the ultra-small dimension of these novel device structures, also new challenges in metrology arise to probe individual NWs with highest possible resolution. In this study, we present a direct one-by-one correlation of the optical properties with the crystalline structure of single GaAs-AlGaAs core-multi-shell NW laser structures, using low temperature cathodoluminescence spectroscopy (CL) directly performed in a scanning transmission electron microscope (STEM)[1].

The GaAs/AlGaAs core-shell NW laser structures under investigation were fabricated by molecular beam epitaxy on Si (111) substrates (Fig. 1). Using a catalyst-free growth, GaAs cores were grown along the [111]-direction with a nominal diameter of about 50 nm. Subsequently, a 75 nm thick $Al_{0.3}Ga_{0.7}As$ shell layer was deposited, followed by a 5 nm thick GaAs single quantum well (QW). The coaxial GaAs QW, representing the active laser gain medium[2], was buried by another 75 nm thick $Al_{0.3}Ga_{0.7}As$ outer shell layer and a 5 nm thick GaAs cap to avoid oxidation. Single-mode lasing from these types of NWs was recently demonstrated[2], while here our focus is to highlight the local transport properties of excited charge carriers within the unique coaxial NW laser heterostructure.

Given the complex radial structure of the as-grown NWs, an optimized, low damage focused ion beam process was developed to prepare the core-shell NWs in radial cross-section geometry and to maintain the optical and structural integrity for low temperature STEM-CL.

STEM analysis of a single NW in Fig. 1(b) reveals the hexagonal symmetry defined by the major {110} crystal facets of the core-shell layers. The $Al_{0.3}Ga_{0.7}As$ shell exhibits clearly bright contrast stripes corresponding to Al-rich regions that emanate from the corners of the GaAs hexagon and extend towards the <112> direction. The QW appears in brighter contrast, illustrating relatively homogeneous thickness on all facets around the entire wire.

The corresponding low temperature / low-excitation power density CL spectrum of the same NW shows the highest CL intensity from the GaAs QW at 785 nm. Furthermore, the GaAs near band-edge (NBE) emission at 819 nm is observed as well as indirect excitonic emission from zincblende / wurtzite defects at 837 nm. In addition, we also find emission at about 663 nm which is attributed to local alloy fluctuations in the $Al_{0.3}Ga_{0.7}As$ shell[3]. To further identify the nature of the local distribution of the individual emissions, nanometer-scale spatially resolved CL imaging was applied. The GaAs NBE emission (Fig. 2(a)) appears most intense in the GaAs core. Due to transport processes, also excess carriers generated in the inner $Al_{0.3}Ga_{0.7}As$ shell are able to diffuse to the core and recombine radiatively. In contrast, CL from the GaAs QW (Fig. 2(b)) is circularly distributed within the shell layers at the expected position. Here, the generated electron-hole pairs in the inner and outer $Al_{0.3}Ga_{0.7}As$ shell are able to diffuse to the QW resulting in an intense emission. Thus, CL imaging enables a direct insight into the radial transport processes and allow determination of the diffusion length in the $Al_{0.3}Ga_{0.7}As$ shell which amounts to ~190 nm.

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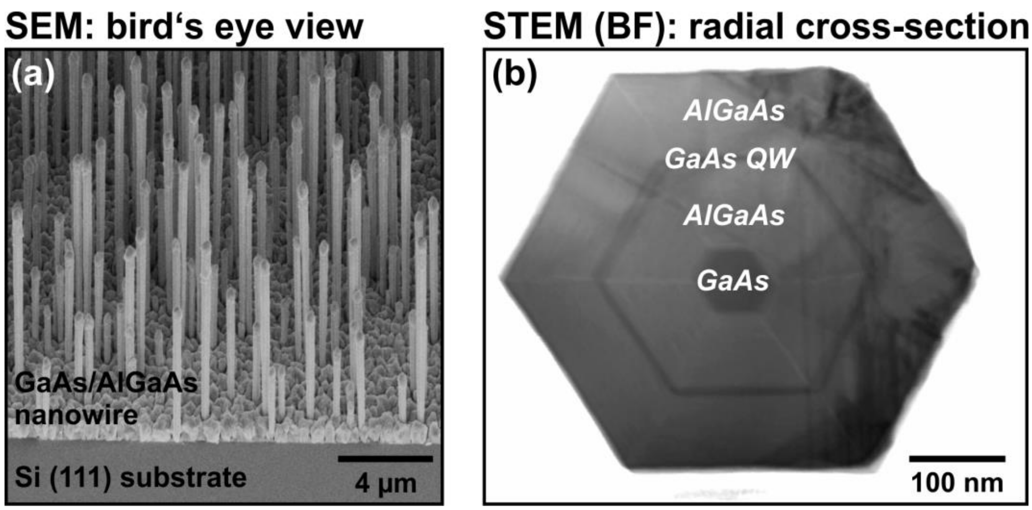

Figure 1. (a) Overview SEM image of the GaAs/AlGaAs NWs grown by molecular beam epitaxy on Si (111) substrate, (b) radial cross-section STEM image in bright-field contrast of the core-shell nanowire.

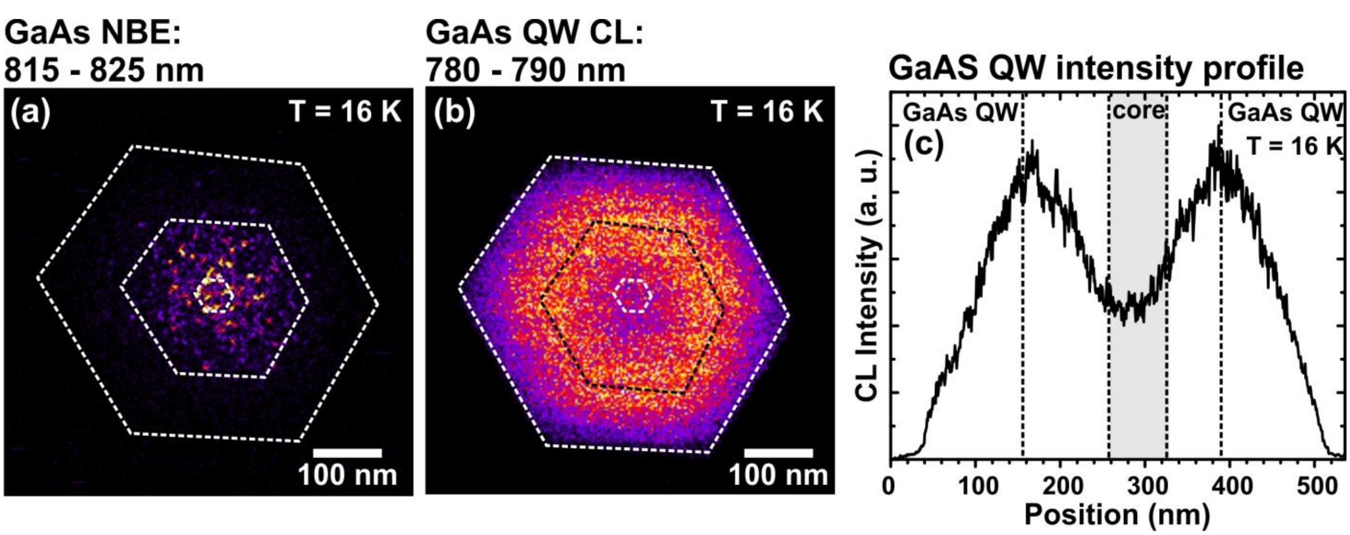

Figure 2. Nanometer-scale resolved monochromatic mappings at the spectral position of (a) the GaAs near band edge emission at 820 nm and (b) the quantum well luminescence between 785 nm, (c) CL intensity profile of the quantum well luminescence.

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