Fine Structural Studies of AlGaN Laser Heterostructures with Digitally Alloyed Quantum Wells Grown on c-Al$_2$O$_3$ by plasma-Assisted Molecular Beam Epitaxy

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The AlGaN QW heterostructures with high Al-content are promising for mid-ultraviolet optoelectronics, the fast growing area where molecular-beam epitaxy (MBE) became one of prospective epitaxial technologies [1]. Recently we have demonstrated reduction of the both lasing wavelength and threshold power density of optically-pumped AlGaN-based laser heterostrucures grown on standard c-Al$_2$O$_3$ substrates [2]. Accurately controlled metal-rich stoichiometic conditions were used to achieve atomically smooth morphology of the Al$_x$Ga$_{1-x}$N (x=0.4-1) layers with desired composition and strain level, whereas so called "digital alloying" technique was employed to fabricate the QW active regions. The paper reports on studies of atomic structure and composition of the AlGaN QW heterostructures by high resolution transmission electron microscopy (HRTEM) and high angle annular dark field (HAADF) scanning transmission electron microscopy (STEM).

The AlGaN-based heterostructures were grown on c-sapphire substrates by using a Compact 21T (Riber CA) PA MBE setup equipped with a nitrogen plasma activator H D25 (Oxford Applied Research). The structures were initiated with high-temperature (780°C) AlN nucleation layers grown by migration enhanced pitaxy for extending the lateral size of AlN nuclei to minimize generation of threading dislocations (TDs) [3]. The following (2-3) µm-thick AlN buffer as well as AlGaN cladding and waveguide layers were grown in a two-dimensional mode (rms<1nm) by using metal-rich conditions at relatively low growth temperatures (below 780 and 700°C), respectively. Modulation of average Al content in the QWs was adjusted precisely by varying the short-term durations of the open and closed Al cell [2]. HRTEM and HAADF STEM analysis was performed on FEIT it an 80-300 electron microscope operated at 300 keV and equipped with an Oxford Inca EDX detector. ATEM cross-section sample was prepared by Focus Ion Beam (FIB) using FEI Helios SEM/FIB dual beam equipment.

Fig. 1 shows a cross-section STEM images of the AlGaN single QW heterostructure grown on top of the 2µm-thick AlN buffer layer. TEM images demonstrate atomically smooth surface morphology and abrupt interfaces within the heterostructure, typical for metal-rich MBE growth. The chosen growth conditions are found to preserve a high level of elastic stress in the structures, which can be controllably affected by in setting ultrathin GaN and AlN interlayers in AlN buffer and AlGaN cladding layers, respectively. The abrupt stress variations seem to increase probabilities of TD's inclination and annihilation resulting in the reduced TD density of 10^8 -10^9 cm^{-2} in the top (active) part of (2-3)µm-thick heterostructures. The dislocation filtering effect can be enforced by intentionally and spontaneously formed AlGaN superlattices. The latter is clearly revealed by Z-contrast imaging in HAADF STEM (Figs. 1 (b) and 2 (b)) and confirmed by EDX analysis. Both HRTEM (Fig. 2 (a)) and HAADF STEM (Fig. 2 (b)) techniques enabled one to resolve the 2.26-nm-thick AlGaN SQW formed by the three-period sub-monolayer GaN/AlGaN digital alloying.

References:
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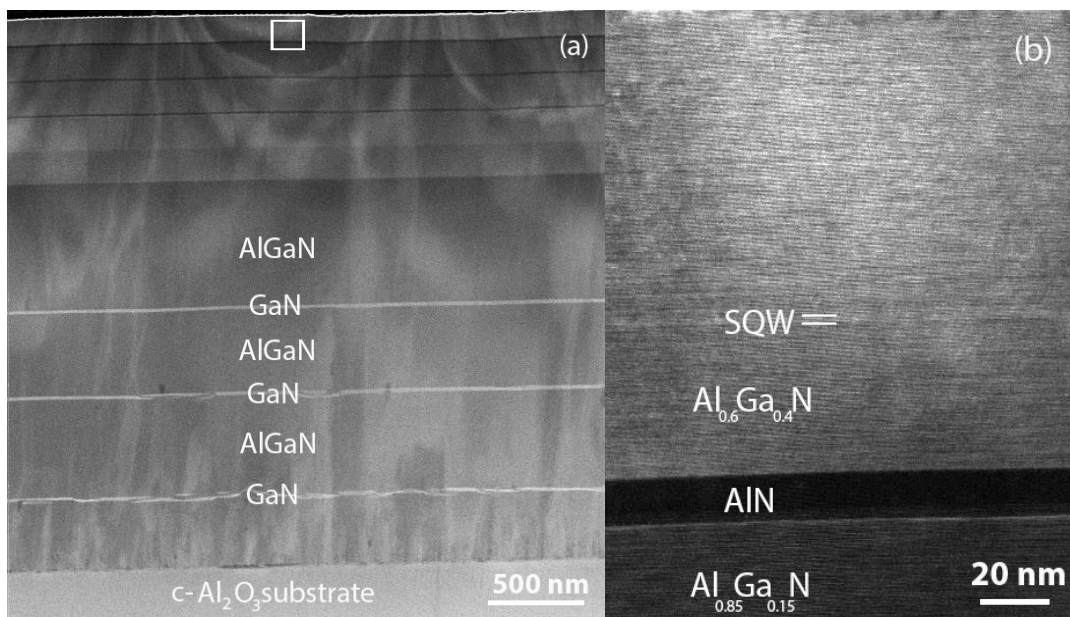
Figure 1. HAADF STEM images of AlGaN-based laser heterostructure on c-Al_2O_3 substrate(a), and magnified image (see rectangular area in Fig. 1a) of its active region with 2.26-nm-thick single QW $Al_{0.5}Ga_{0.5}N$ / $Al_{0.6}Ga_{0.4}N$ (b). Image (a) includes AlN buffer layer with six 3-nm-thick GaN insertions.
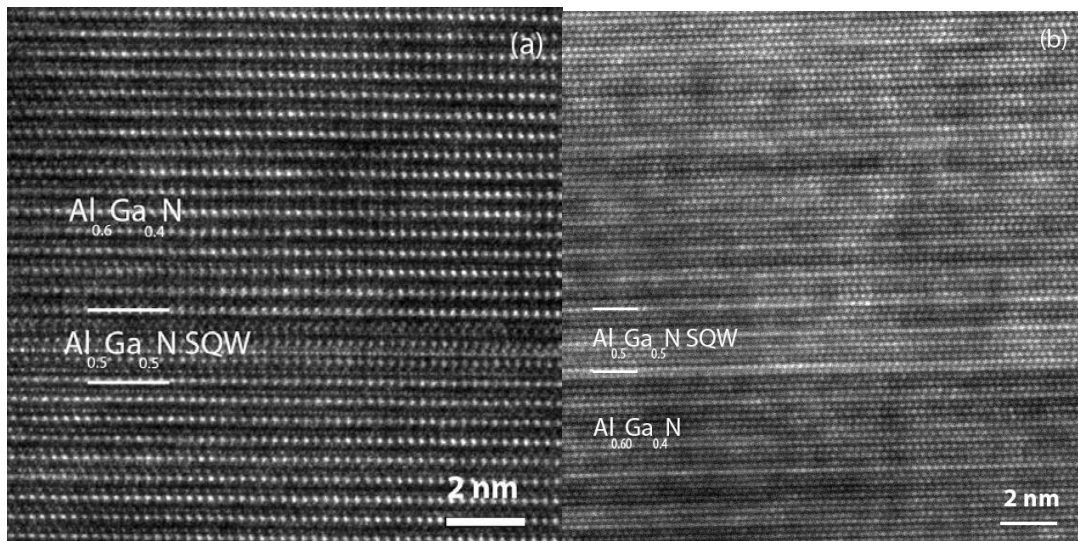
Figure 2. HRTEM (a) and HAADF STEM (b) images of $Al_{0.5}Ga_{0.5}N$ SQW in a $Al_{0.6}Ga_{0.4}N$ waveguide layer. Note: The variations of Al content are visible within $Al_xGa_{1-x}N$ layers (due to Z-contrast imaging) and were also confirmed by EDX analysis.