High Internal Quantum Efficiency from AlGaN-delta-GaN Quantum Well at 260 nm

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Abstract: High internal quantum efficiency (85%) was realized from the AlGaN-delta-GaN quantum well (QW) structure grown on a conventional AlN/sapphire template by Molecular Beam Epitaxy. The peak emission wavelength is observed at 260 nm.

The maximum absorption spectrum through DNA is found at a wavelength (λ) around 260 nm [1-2]. Therefore, ultraviolet (UV) light-emitting diodes (LEDs) with peak emission wavelength of 260 nm is preferred for applications such as water purification and environment disinfection. However, the AlGaN-based UV LEDs around λ~260 nm are not developed enough to meet the commercial requirements since they suffer from the low external quantum efficiency (EQE) [2]. One of the direct reasons for limited EQE is the low internal quantum efficiency (IQE) caused by (i) large dislocation density induced non-radiative recombination; and (ii) quantum confined stark effect (QCSE) from those conventional AlGaN quantum wells (QWs) which will strongly limit the radiative recombination efficiency. To reduce the dislocation density due to the lack of native substrate, several groups have put a lot of efforts on substrate engineering and epitaxy optimization. Specifically, by using the patterned sapphire substrate, the dislocation density is significantly reduced from 1×10^{10} cm^{-2} to 5×10^{8} cm^{-2}, which leads to a large IQE boost from 1% to 60% [2].

Instead of limiting the non-radiative recombination, an alternative method to increase IQE for UV LEDs is to improve the electron-hole wave function overlap in the active region [3-4]. Our previous work proposed the idea of using the AlGaN-delta-GaN QW to replace the conventional AlGaN QW. The insertion of the ultra-thin delta-GaN layer provides a local minimum in the active region, which pushes both the electron and hole wave functions to the center of the QW. As a result, the wave function overlap and therefore the spontaneous emission rate are largely enhanced. For example, the use of $Al_{0.9}Ga_{0.1}N$-delta-GaN QW with 2 monolayer (ML) delta-GaN showed ~30 times enhancement in the spontaneous recombination rate, as compared to the conventional AlGaN QW at 260 nm [5]. Although promising results were realized theoretically, the epitaxial structures of the AlGaN-delta-GaN QW have not been demonstrated. Therefore, this study developed a growth technique for AlGaN-delta-GaN QW epitaxy and investigated the IQE performance from the structure.

In this work, the heterostructure was grown on a conventional AlN/sapphire template with dislocation density of $\sim1\times10^{10}$ cm^{-2} by using Veeco Gen10 Plasma-Assisted Molecular Beam Epitaxy (PAMBE). As shown in the inset of figure 1, the AlN buffer layer is grown prior to the active region epitaxy at a temperature of 800 °C with plasma power of 200W. The growth rate is calibrated as 5 nm/min under this growth condition. For the active region, the superlattice cycle started with a 2 ML GaN, followed by two 1.5-nm $Al_{0.9}Ga_{0.1}N$ sub-QW layers with a 3-nm AlN layer in the middle. There were two interruptions added after each AlGaN layer growth to desorb the excess Gallium and avoid unintentional GaN formation. The 5-period $Al_{0.9}Ga_{0.1}N$-delta-GaN/AlN QW was chosen to have a strong luminescence intensity. During the growth, long and streaky RHEED patterns were observed, which indicates a smooth surface was achieved.

Several characterization techniques were employed to confirm the incorporation of the 2ML GaN. For example, the high resolution X-ray diffraction ω-2θ scans were performed on the $Al_{0.9}Ga_{0.1}N$-delta-GaN QWs to investigate its structural properties. There is a strong shoulder next to the AlN substrate peak, which corresponds to the 90% AlGaN[5]. Besides, a clear secondary peak from GaN is observed from the scan as well, which indicates the existence of GaN layer. In addition, cross-sectional scanning transmission electron microscope (STEM) images of $Al_{0.9}Ga_{0.1}N$-delta-GaN QWs were collected and compared to that of $Al_{0.9}Ga_{0.1}N$ QWs without the GaN layer. Due to the strong Z-contrast of the STEM images, the AlN and AlGaN layers can be easily distinguished. Meanwhile, a thin bright layer is observed in between of the AlGaN sub-QW regions for $Al_{0.9}Ga_{0.1}N$-delta-GaN QWs but absent in the $Al_{0.9}Ga_{0.1}N$ QWs, which again demonstrates the formation of ultra-thin GaN layer in the $Al_{0.9}Ga_{0.1}N$-delta-GaN QWs.

To investigate the optical properties from the $Al_{0.9}Ga_{0.1}N$-delta-GaN QWs, low temperature (4K) and room temperature photoluminescence (PL) were performed on the epitaxial structure. A pulsed Excimer laser (λ = 193 nm, 5 ns pulse duration, 1 µJ/pulse energy, 20 Hz repetition rate) was used for PL excitation. As shown in figure 1, the peak emission wavelength is observed at 255 nm at room temperature and its intensity does not increase significantly at low temperature. In this study, we used the temperature-dependent integrated PL spectra (I_{300K}/I_{4K}) to estimate device internal quantum efficiency. Specifically, for $Al_{0.9}Ga_{0.1}N$-delta-GaN QWs, the IQE is calculated as 85%, which is an extremely high value for the heterostructure grown on a conventional AlGaN template (dislocation density of ~1×10^{10} cm^{-2}) near 260 nm. The improved IQE value, which corresponds to the enhancement of the spontaneous emission rate, is attributed to the improvement of the electron and hole wave function overlap by using the delta-GaN QW design.

Figure 1(b) summarized the IQE values reported in the literature over the range of 200 – 300 nm [6-15]. In general, the IQE values show a decreasing trend as λ decreases. Specifically, at λ ~ 260 nm, the IQE value is typically in the range of 40% - 60%, with only one value up to 90% by engineering the substrate and limiting the non-radiative recombinations[14]. The 85% IQE from our $Al_{0.9}Ga_{0.1}N$-delta-GaN QW in this study almost reaches the record of the experimental data at same emission wavelength regime. Moreover, it is worthy to point out that the heterostructure in this study was grown on the substrate with higher dislocation density as compared with Ref. 14. We believe that by using the improved template, the IQE can be further improved by the use of $Al_{0.9}Ga_{0.1}N$-delta-GaN QW design, which indicates that this active region is very promising for DUV LED applications.

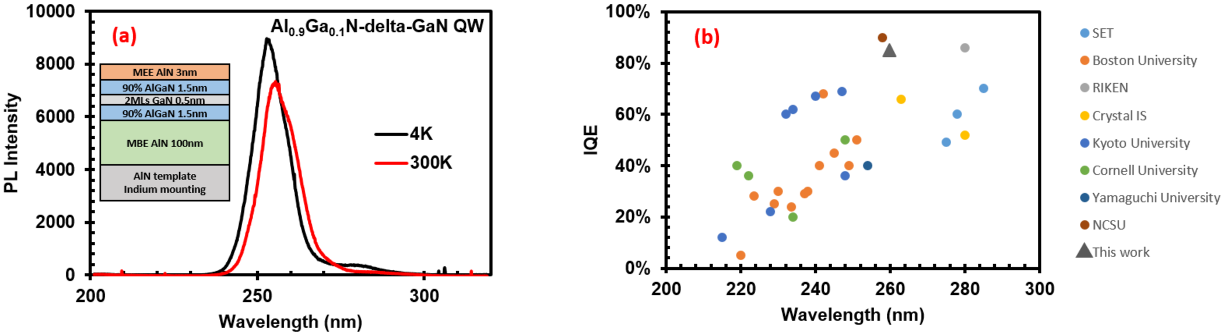

Figure 1: Inset: Schematic of the $Al_{0.9}Ga_{0.1}N$-delta-GaN QW structure (a) photoluminescence spectra of $Al_{0.9}Ga_{0.1}N$-delta-GaN QW structure at room temperature (red) and low temperature (black); (b) Reported IQE values for deep-UV LEDs.

In summary, the AlGaN-delta-GaN QW was successfully grown by MBE for 255 nm emission. The insertion of 2ML GaN was confirmed by both XRD and STEM images. By using temperature-dependent PL measurements, the IQE from the $Al_{0.9}Ga_{0.1}N$-delta-GaN QWs is estimated as 85%, which is a very high value for DUV emission. The extraordinary IQE result is attributed to the improved electron-hole wave function overlap. Thus, it is expected that AlGaN-delta-GaN QW is a promising alternative for 260 nm UV LEDs.

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