246 nm AlN-delta-GaN Quantum Well Ultraviolet Light-Emitting Diode

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Abstract: The 246 nm AlN-delta-GaN quantum well ultraviolet light-emitting diode was proposed and realized experimentally, with the dominant transverse electric-polarized emission been verified by both the ***k·p*** simulation and the room-temperature polarization-dependent electroluminescence measurements.

OCIS codes: (230.3670) Light-emitting diodes; (230.5590) Quantum-well, -wire and -dot devices

High-efficiency deep ultraviolet (UV) light emitting diodes (LEDs) operating at wavelengths (λ) below 300 nm are required for a wide variety of important applications such as sterilization, medical diagnostics and water purification. High Al-content AlGaN quantum wells (QWs) are employed to pursue such deep-UV LEDs and have been widely studied and reported for 220-280 nm spectral regimes [1-3]. Nevertheless, UV LEDs with AlGaN active regions usually suffer from low external quantum efficiencies (<10%), especially at shorter emission wavelengths [3]. The efficiency in such deep-UV LEDs is limited by the poor carrier injection efficiency caused by the low electrical conductivity in p- and n-types AlGaN layers; low internal quantum efficiency (η_{IQE}) resulted from reduced optical matrix element; and the low light extraction efficiency. Furthermore, the valence subband crossover in conventional AlGaN QWs and their role in determining the direction of optical emission is of crucial importance [2, 4]. Thus, it is important to explore novel QW active regions which can suppress the challenges and lead to improved quantum efficiencies.

Our previous work has proposed the use of the AlN-delta-GaN QW structure with 3-4 monolayers of the delta-GaN layer for 298 nm UV LEDs to reduce degradation due to the Quantum Confined Stark Effect, when compared to conventional AlGaN QWs that emit at a similar wavelength [5]. Pushing to shorter wavelengths such as ~250 nm, the use of conventional AlGaN QWs suffer from significant band-mixing effect as the Al-content is near the crossover point beyond which the energy separation between heavy hole (HH) and crystal-field split-off hole (CH) leads to both low transverse electric (TE)- and transverse magnetic (TM)-polarized optical emission [4]. Thus, in this work, we propose the use of the AlN-delta-GaN QW with thinner delta-GaN thickness in order to address the band-mixing effect with λ~250 nm. The valence band structure and corresponding polarization-dependent spontaneous emission of the proposed AlN-delta-GaN QW was investigated by the 6-band ***k·p*** simulations [4, 8-9]. The AlN-delta-GaN QW-like UV LEDs with 2-3 monolayers of delta-GaN layer were grown on the AlN/sapphire template by plasma-assisted molecular beam epitaxy (MBE) [6-7]. The angle-dependent and polarization-dependent electroluminescence (EL) measurements were conducted to validate the physics from the proposed QW design.

A schematic layer structure of the AlN-delta-GaN QW is shown in figure 1 which includes the 2-nm AlN sub-QW region with 4-Å delta-GaN layer to aim for ~250 nm peak emission. Here, the AlN sub-QW and the AlN barrier regions are clearly separated into the ***k·p*** simulations. From the calculated valence band structure, we identify two major advantages of using the AlN-delta-GaN QW: 1) the HH subband has been flipped into the topmost position, and 2) there exists a large separation between the HH1 and CH1 subbands which successfully resolves the band mixing issue. Thus, it is expected that the dominant conduction band (C) - HH1 transition will be endured by the AlN-delta-GaN QW active region. As a result, from the spontaneous emission spectra in figure 1, dominant TE-polarized spontaneous emission is obtained with λ = 243 nm.

To verify the polarization properties and the physics of the proposed AlN-delta-GaN QWs, the MBE-grown UV LED with such active region was investigated in this study. As shown in figure 2, the active region consists of 2-3 monolayers delta-GaN layer embedded in 1.75 nm AlN layer with graded AlGaN p- and n-polarization-induced-doped cladding layers. More MBE growth and device fabrication details can be found in *Refs.* 6-7. Room temperature EL measurement was first carried out, showing that the peak emission wavelength is 246 nm with current density (*j*) of 16.67 A/cm^2 from the AlN-delta-GaN QW with 2-3 monolayers delta-GaN layer.

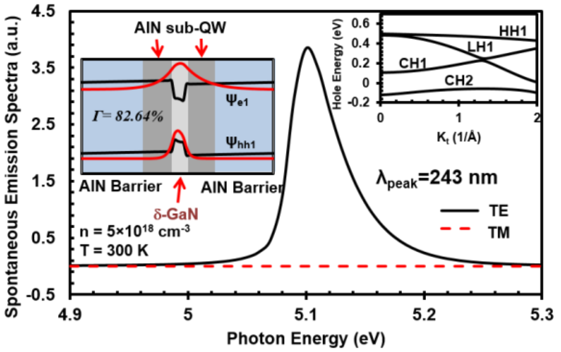

Figure 1: TE- and TM-polarized spontaneous emission spectra at n = 5 ×10^{18} cm^{-3}. Inset left: band structure of AlN-delta-GaN QW structure with electron and hole wavefunctions; inset right: valence band structure.

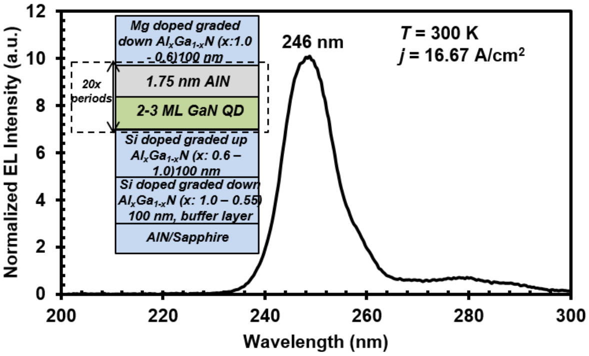

Figure 2: EL spectrum of MBE-grown AlN-delta-GaN QW-like LED with peak emission wavelength of 246 nm at j=16.67 A/cm^2. Inset: schematic of MBE-grown AlN-delta-GaN QW LED.

The polarization-dependent EL measurements were performed with the setup plotted in figure 3(a), similar with *Refs.* 2, 5, 10. A Glan-Taylor polarizer is placed between the stationary stage and the optical fiber and can be rotated to resolve the $I_{//}$ (electric field parallel to the incident plane) and $I_{\perp}$ (electric field perpendicular to the incident plane). At a particular detection angle (θ), TE and TM components can be derived by the equations $I_{//} = I_{TEy}\cos^2\theta + I_{TM}\sin^2\theta$ and $I_{\perp} = I_{TEx}$. Figure 3(b) presents the polarization-dependent EL spectra at θ = 30° for the AlN-delta-GaN QW LED. The results show that the $I_{\perp}/I_{//}$ ratio is 1.18 for θ = 30° with the corresponding TE/TM ratio calculated as 17.731. Thus, dominant TE-polarized emission is demonstrated from the AlN-delta-GaN QW structure which can be attributed to the dominant C-HH transition from the proposed design.

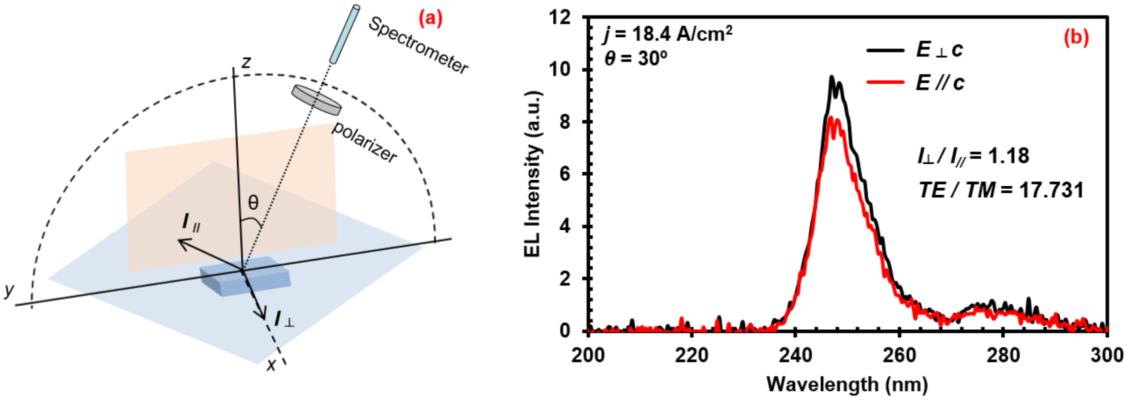

Figure 3: (a) Schematic of polarization-dependent EL measurement setup; (b) Polarization-dependent EL measurement at θ = 30º.

In summary, the AlN-delta-GaN QW is proposed, and experimentally demonstrated for 246 nm UV LED, and the polarization properties are investigated for the first time. The use of the AlN-delta-GaN QW with 2-3 monolayers delta-GaN layer addresses the band mixing problem, and leads to dominant C-HH transition. As a result, dominant TE-polarized emission is demonstrated by polarization-dependent EL measurements. Thus, it is expected that the use of the AlN-delta-GaN QW will serve as a promising alternative for 250 nm UV LEDs.

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