

Waveguide vs Quantum Well Emission in AlGa_N-Based Deep-Ultraviolet LEDs on Bulk AlN Substrate

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Principal Investigator(s): Debdeep Jena (primary); and Huili (Grace) Xing

User(s): Sheena (Hsin Wei) Huang

Affiliation(s): Electrical and Computer Engineering, Cornell University

Primary Source(s) of Research Funding: DARPA

Contact: djena@cornell.edu, hh494@cornell.edu

Research Group Website: <https://jena-xing.engineering.cornell.edu/>

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Abstract:

Deep-ultraviolet (DUV) laser diodes (LDs) emitting in the UV-C wavelengths of 100–280 nm have the potential to enable applications such as bio/chemical sensing, disinfection, and medical treatment. While electrically injected AlGa_N UVC laser diodes have been recently reported with a quantum well active region grown by metal-organic chemical vapor deposition (MOCVD) [1] and nanowires by molecular beam epitaxy (MBE) [2], laser diodes with AlGa_N quantum wells grown by MBE on bulk AlN substrates in the wavelength range below 280 nm have not yet been reported. Here, we report an MBE-grown AlGa_N laser-diode heterostructure on bulk AlN that sustains continuous-wave current densities exceeding 4 kA/cm² and exhibits a transition of spontaneous emission from the waveguide (~265 nm) to the quantum well (~281 nm). We also investigate the mechanism responsible for QW population and radiative recombination transition using simulation. This study is a step towards realizing low-threshold current density AlGa_N-based DUV laser diodes by MBE.

Summary of Research:

Fig. 1(a) shows the device heterostructure grown by nitrogen plasma-assisted MBE. The AlGa_N epilayers on the bulk AlN substrate along the (0001) direction. Fig. 1 (b)-(c) summarize the characterization of the as-grown MBE films including X-ray diffraction symmetric and asymmetric scans. Quasi-vertical circular diodes from the heterostructure were fabricated on the sample, with a schematic shown in Fig. 2(a). The devices sustain continuous-wave current densities up to 3 kA/cm² at ~15 V without observable degradation, as shown in Fig. 2(b).

The room temperature electroluminescence spectra show that at low current density, the emission is dominated

by a waveguide peak near 265 nm. With increasing injection, a longer-wavelength quantum well emission near 281 nm emerges and progressively dominates. Spectral deconvolution in Fig. 3(b) shows that the quantum well peak wavelength remains nearly constant with current, while the waveguide peak exhibits only a small redshift, indicating minimal self-heating. The integrated intensities in Fig. 3(c) reveal a clear crossover from waveguide to quantum well-dominated emission at ~3.1 kA/cm², indicating current-driven carrier redistribution into the quantum well. The corresponding light–current–voltage characteristics in Fig. 3(d) show a monotonic increase in optical output without rollover up to 4.2 kA/cm², confirming stable high-current operation required for UVC laser diodes [1,3].

To identify the mechanism limiting waveguide-quantum well carrier redistribution, self-consistent drift diffusion simulations using SiLENSe were performed. The radiative recombination profile in Fig. 4(a) shows that in the low-injection regime for 4.4–4.8 V bias voltages, the dominant recombination region shifts from the waveguide to the quantum well with increasing bias. The corresponding hole distribution in Fig. 4(b) reveals that this transition is driven by increased hole population in the quantum well, enabled by carrier pile-up near the polarization-induced barriers and gradual quantum well filling. In contrast, the electron concentration in Fig. 4(c) is already high and weakly bias dependent. This identifies hole-limited transport as the bottleneck for efficient quantum well recombination.

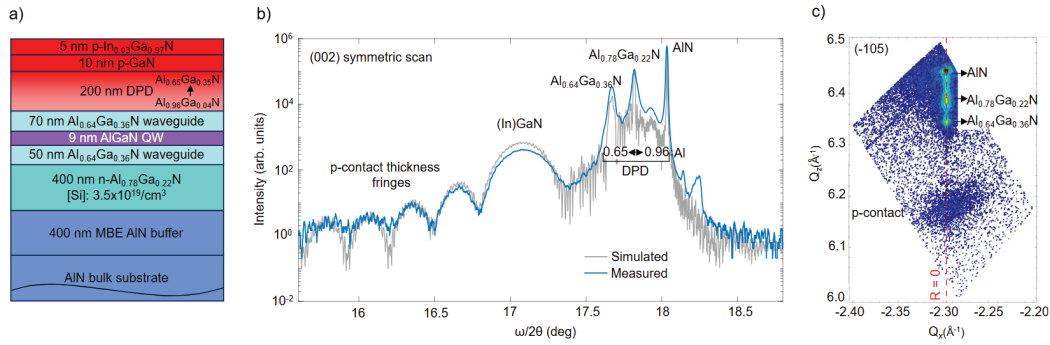


Figure 1: a) Layer structure of the AlGaIn heterostructure grown by MBE on metal polar bulk AlN substrate. b) Symmetric X-ray diffraction scan used to determine the AlGaIn composition in the structure. c) Asymmetric reciprocal space map (RSM) to confirm the AlGaIn layers are pseudomorphically grown on the substrate.

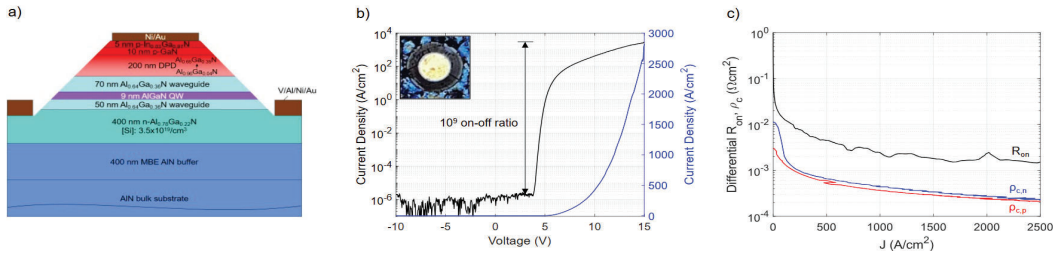


Figure 2: a) Schematic of the cross section of the fabricated circular LED. b) Linear and log-scale current density vs voltage of a 30 μm anode LED, shown in the inset. c) Differential ON-resistance of the same diode from (b), and p- and n-type specific contact resistances from rectangular TLM measurements.

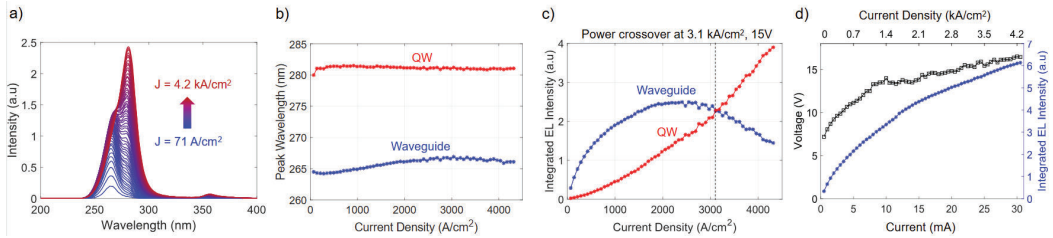


Figure 3: (a) CTLM-IV curves comparison of p-contact without undergoing n contact anneal, after undergoing n-contact anneal with SiO₂ cap, and after undergoing n-contact anneal without SiO₂ cap. IVs are plotted for 2 μm spacing. (b) Resistance vs metal electrode spacings for the data shown in (a).

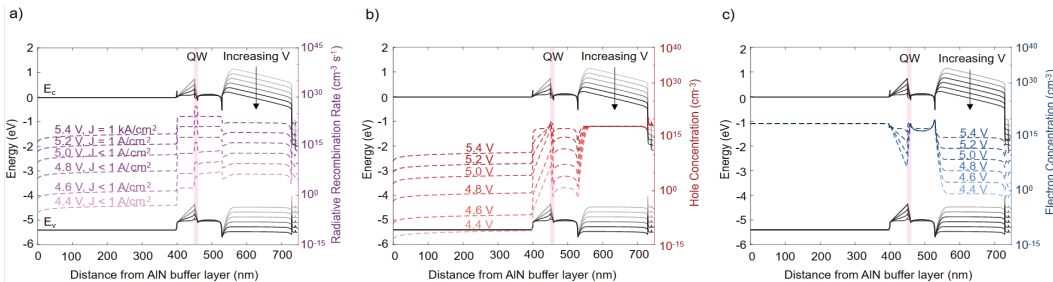


Figure 4: (a) Room temperature J-V characteristics of two LEDs, one with SiO₂ capping method and one without. The differential ON-resistance was extracted at 400 A/cm². (b) IV from batch test of LEDs with and without SiO₂ capping. (c) Room temperature electroluminescence of an LED with the SiO₂ capping method. Inset shows the microscopy image of a fabricated LED.

Conclusions and Future Steps:

To further reduce the current density needed to achieve population inversion and lasing in the device, further structure optimization to reduce the hole injection will be investigated.

References:

- [1] Z. Zhang et al., Appl. Phys. Expr. 12, 124003 (2019).
- [2] S. Zhao et al., Appl. Phys. Lett. 109, 191106 (2016).
- [3] Z. Zhang et al., Appl. Phys. Lett. 121, 222103 (2022).