High-Temperature p-Type Polarization Doped AlGaN Cladding for sub-250 nm deep-UV Quantum Well LEDs by MBE

Shyam Bharadwaj[1*], SM Islam[1*], Kevin Lee[1], Andrew Devine[1], Vladimir Protasenko[1], Sergei Rouvimov[2], Huili (Grace) Xing[1] and Debdeep Jena[1]

[1]*Cornell University, Ithaca, NY 14853, USA*

[2]*University of Notre Dame, Notre Dame, IN 46556, USA*

**Contributed equally to this work, Email: sb2347@cornell.edu / Phone: (856) 761 4002*

Deep UV (DUV) light-emitting diodes (LEDs) are finding increased application in many areas including water purification and sterilization. Sub-270 nm emission is ideal for these applications since bacterial DNA absorbs strongly in this wavelength regime. To extract high energy photons (~5 eV), the LED cladding regions must be transparent and therefore consist of high Aluminum content (>60%) n- and p-AlGaN. Ensuring high electrical conductivity in such cladding regions becomes increasingly difficult with increasing Al content due to the large dopant activation energies, especially for the acceptor dopant, Magnesium (Mg) [1]. To maximize Mg incorporation by MBE, a commonly utilized approach is to grow the p-cladding region at a low temperature (~630 °C [2]). A low growth temperature causes defects and undesired compositional inhomogeneity, leading to inferior vertical hole transport (**Fig. 1**). To address these issues, a combination of high temperature MBE growth of the p-AlGaN cladding and polarization-induced doping is employed. While high growth temperature ensures good crystal quality and compositional uniformity for the Al-rich p-AlGaN, the polarization-induced doping compensates for the reduced Mg incorporation at high temperature. A sub-250 nm DUV LED is demonstrated *for the first time* using MBE-grown p-AlGaN layers at a high temperature of 730 °C. SIMS analysis (**Fig. 2**) showed that Mg incorporation decreases by ~5 times over the temperature range from 650-730°C for 75% AlGaN, and that Mg incorporation decreases at high Al content, consistent with thermodynamic principles [3]. Based on the observations from Fig. 1 and 2, a substrate temperature of 730 °C was chosen for the p-cladding layer for a sub-250 nm DUV LED structure.

Fig. 4(a) shows the cross-section layer structure of the DUV LED. Plasma-MBE growth was performed on AlN-on-sapphire templates at a substrate temperature of 730 °C, except for the p+ GaN cap layer, which was grown at 650°C at a growth rate of 100 nm/hr. Standard Al, Ga, Si, and Mg solid source effusion cells and a N_2 RF plasma source were used. An AlN nucleation layer was grown first followed by a compositionally graded down AlGaN buffer layer. Then, a 100 nm graded up ($Al_{0.65}Ga_{0.35}N$ to $Al_{0.95}Ga_{0.05}N$) layer was grown as the polarization-induced n-cladding layer. 4 periods of 2.5 nm AlN barriers/2 monolayers of GaN quantum discs (QDs) were used as the active region [4] to provide DUV interband photon emission by extreme quantum confinement. A 50 nm linearly graded down ($Al_{0.95}Ga_{0.05}N$ to $Al_{0.65}Ga_{0.35}N$) layer p-cladding region capable of providing $\sim 3.6\times10^{18}/cm^3$ hole density through polarization induced doping [5] was used. Finally, a p+ GaN cap was grown as a contact layer.

To test the LED structure, Transmission line method (TLM) structures and 100×100 μm^2 LED mesas were fabricated using ICP-RIE and lift off. A Ti/Al/Ni/Au = 20/100/40/50 nm metal contact stack was deposited on the n-layer and annealed at 880 °C for 30 seconds for improved n-type ohmics. A semi-transparent current spreading metal stack was deposited (Ni/Au = 5/5 nm) on the p-layer, followed by a thick contact for probing (Ti/Au = 20/100 nm). TLM structures shown in **Fig. 3** yielded contact resistances of n-contact: $R_{cn}\sim 3.065\times10^{-3}\ \Omega cm^2$, p-contact: $R_{cp}\sim 5.94\times10^{-1}\ \Omega cm^2$, and low individual layer resistances (n-layer: 4.34 kΩ/□, p-layer: 11.1 kΩ/□) confirming that the improved epitaxial crystalline quality from the high temperature p-layer growth and polarization-induced doping offset any decreased Mg incorporation. This p-layer resistance is amongst the best reported to date for a high-Al-content AlGaN layer [6,7]. For device characterization, current-voltage (J-V) measurements and room temperature electroluminescence (EL) measurements were performed. **Figs. 4(b)** and **4(c)** show the LED turn-on near the bandgap energy ~6V with low leakage and an emission wavelength of ~248 nm. The broad low-intensity peak around 350 nm likely stems from absorption and reemission by the p-GaN cap layer. Emission beyond 400 nm is probably due to deep-level defects in the AlN.

Future work will comprise of scaling down device area to lower leakage current, temperature dependent EL measurements to extract dopant activation energies and the effectiveness of polarization-induced doping, and angle-dependent EL measurements to investigate TE vs TM light emission. This device demonstration will enable further optimization of DUV LED design, leading to an enhancement of external quantum efficiency of sub-250 nm LEDs.

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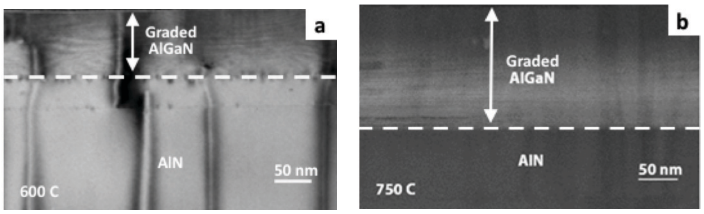

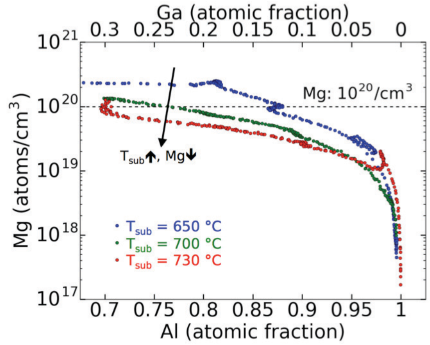

Fig. 1. TEM images of linearly graded AlGaN grown on AlN template substrates at (a) 600 °C and (b) 750 °C. At 600 °C, many striations can be seen indicating undesired Al-content fluctuation. The higher temperature growth shows absence of striations and Al-content fluctuation.

Fig. 2. SIMS data showing Magnesium incorporation in AlGaN as a function of substrate temperature and Aluminum content. As Aluminum content and substrate temperature rise, Magnesium incorporation decreases.

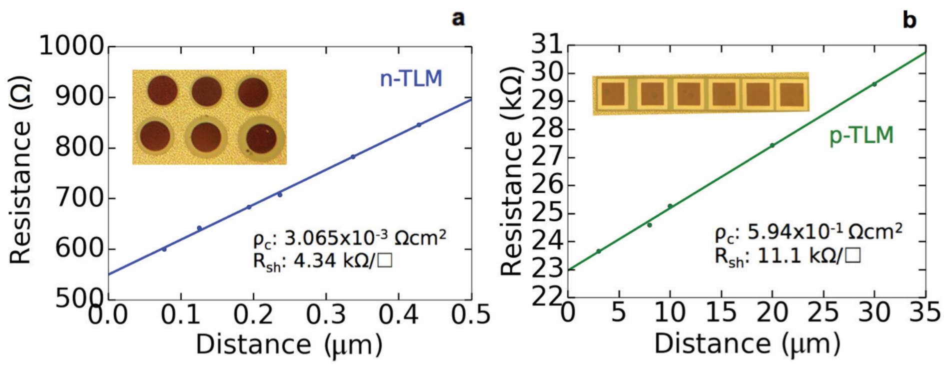

Fig. 3. TLM measurements for the (a) n-contact and, (b) p-contact of the LED structure. Extracted specific contact resistivities and sheet resistances are shown on the bottom right.

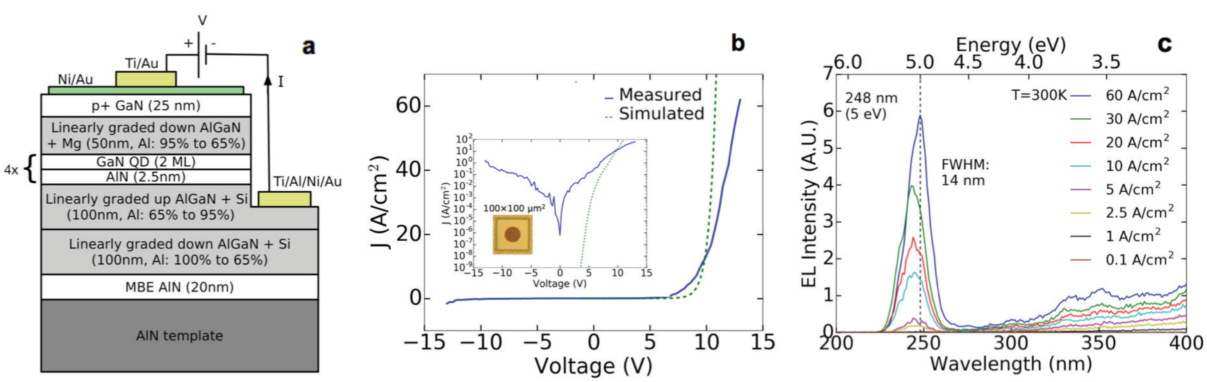

Fig. 4. (a) Schematic layer structure of the MBE grown extreme quantum-confinement active region DUV LED showing thicknesses and compositions, (b) measured and simulated linear scale JV characteristic with log scale in inset for a 100×100 µm^2 device showing turn on around 6 V, and (c) room temperature electroluminescence spectrum for the same 100×100 µm^2 device at various current injection levels showing peak emission around 248 nm. The broad emission around 350 nm in (c) is likely from the p-GaN cap layer.

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