Graded P-AlGaN Superlattice for Reduced Electron Overflow in Tunneling Injected UVC LEDs

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We discuss the design of the p-AlGaN cladding layer for reduced electron overflow in tunneling injected III-Nitride ultraviolet light emitting diodes (UV LEDs). We report 282 nm tunneling injected UV LEDs by blocking electron overflow using graded p-AlGaN superlattice structure. III-Nitride ultra-violet light emitting diodes have a large variety of applications, however, the device performance is severely limited by the poor p-type conductivity and high p-type contact resistance. In this work, we show that non-equilibrium tunneling hole injection could be adopted for enhanced device performance. By introducing a graded p-AlGaN superlattice layer, electron overflow is greatly reduced, leading to enhanced device performance.

The tunneling injected UV LED structure reported in this work replaces conventional p-type contact with tunneling contact using an AlGaN/ InGaN interband tunnel junction. Polarization sheet charge with density higher than 10^{13} cm^{-2} at the AlGaN/ InGaN interfaces results in a high polarization field and sharp band bending in the InGaN layer, which in turn results in a reduced interband tunneling barrier width. However, the tunneling probability could be greatly reduced by the depletion barrier in p-AlGaN layer due to the difficulty in achieving degenerate p-type doping, and the large AlGaN/ InGaN valence band offset. The depletion barrier can be reduced by introducing three dimensional polarization charge from compositional grading in p-AlGaN layer. However, the electric field in the graded p-AlGaN layer could drive overflowing electrons to the top n-AlGaN layer, leading to severe electron overshoot. In this work, we combine the polarization grading and short period superlattice approaches to achieve both enhanced acceptor activation and reduced electron overflow.

The effect of the graded p-AlGaN superlattice in the tunneling injected UV LEDs was studied experimentally. The tunneling injected UV LEDs were grown by plasma assisted molecular beam epitaxy on metal polar $Al_{0.7}Ga_{0.3}N$ templates with threading dislocation density of 2.5×10^{9} cm^{-2}. The UV LEDs contain three 3 nm $Al_{0.58}Ga_{0.42}N$ quantum wells, 50 nm graded p-AlGaN layer, thin tunnel junction layer with 4 nm $In_{0.2}Ga_{0.8}N$, and 150 nm n-$Al_{0.7}Ga_{0.3}N$ top contact layer. Three samples were grown under similar growth conditions, but with different p-AlGaN structure. Sample A has continuous grading from 92% to 64% Al mole fraction in p-AlGaN, while Sample B and C have graded $Al_xGa_{1-x}N/Al_yGa_{1-y}N$ superlattice structures, with x grade from 92% to 64% and y grade from 100% to 75%. The widths of the SL barrier/ well are 0.5/ 0.5 nm and 1.8/ 1.8 nm for Sample B and C, respectively. 30×30 um^2 devices with ~ 25% top metal coverage were used for electrical and optical measurements. Sample A showed soft turn-on with a voltage drop of 3.96 V at 20 A/cm^2, while the current increases sharply at high current density, indicating severe electron overflow. In comparison, when short period superlattices are adopted, the electron overflow at high current is greatly reduced. Sample B and C showed similar electrical characteristics at high current levels, however, an increase of the voltage drop at 20 A/cm^2 from 4.58 V (B) to 6.87 V (C) was observed when the SL barrier/ well thicknesses are increased, which is attributed to better electron blocking and higher acceptor activation rate by using thicker barrier/ well SL.

On-wafer electroluminescence measurements confirmed non-equilibrium hole injection into the active regions for all the samples. The samples showed similar emission peak wavelength at 282 nm. However, Sample A showed minimal emission power, confirming severe electron overflow. The efficiency curves for Sample C peaked at approximately 250 A/cm^2, while Sample B showed much lower efficiencies at low current injection, and did not show droop till high current levels (1 kA/cm^2). The higher efficiency in sample C (1.8/1.8 nm SL) is attributed to lower electron overflow to top n-type contact compared to sample B (0.5/0.5 nm SL). The maximum on-wafer EQE and WPE are 0.076% and 0.035%, which are limited by low internal quantum efficiency and poor light extraction efficiency. Nevertheless, this demonstration shows that effective interband tunnel junction could be achieved for deep UV LEDs, and graded p-AlGaN superlattice structure is favorable for reducing electron overflow in tunneling injected UV LEDs. This provides a novel method for hole injection and carrier transport engineering in deep UV emitters.

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References:

[1] Y. Zhang, S. Krishnamoorthy, J. M. Johnson, F. Akyol, A. Allerman, M. W. Moseley, A. Armstrong, J. Hwang and S. Rajan, Appl. Phys. Lett. **106**, 141103 (2015).

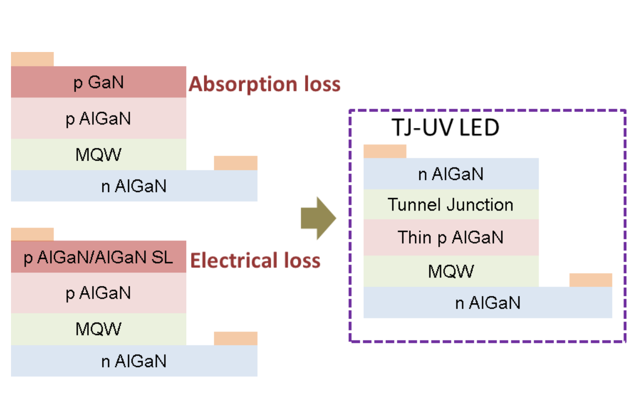

Fig. 1 Schematic design of a TJ-based UV LED.

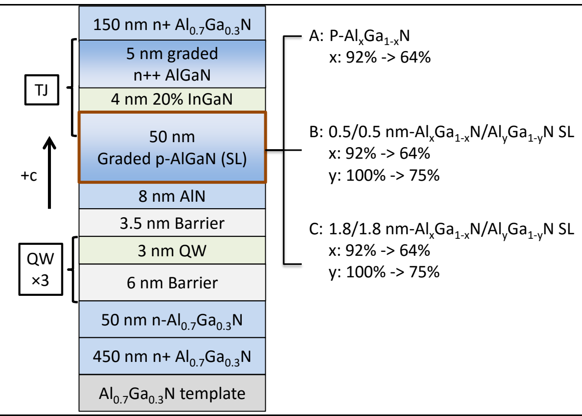

Fig. 2 Growth stack of the tunneling injected UV LEDs

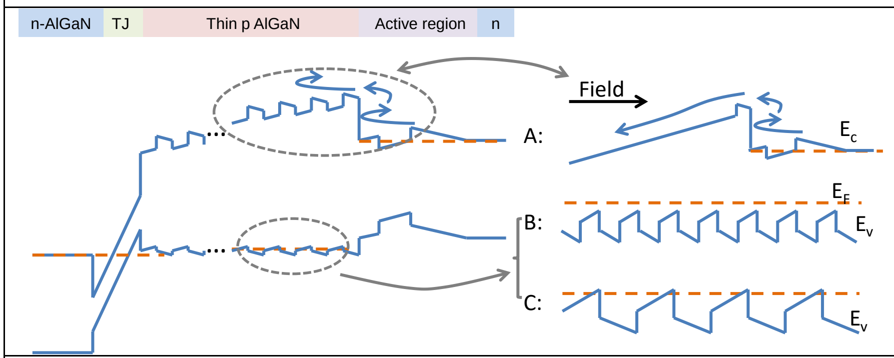

Fig. 3 Schematic band diagram under operation for the samples

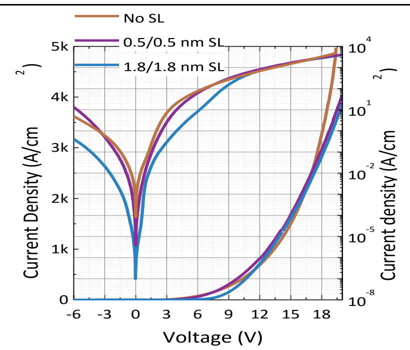

Fig. 4 Current-Voltage curves of 30 × 30 um² devices.

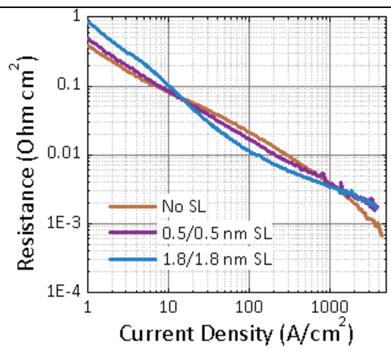

Fig. 5 Differential resistances

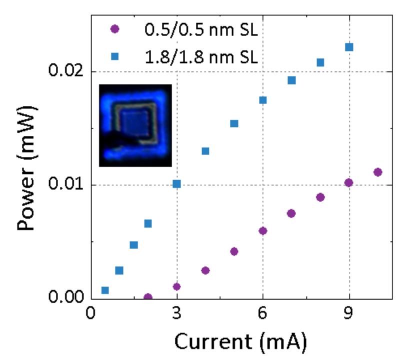

Fig. 6 Output power of 30 × 30 um² devices

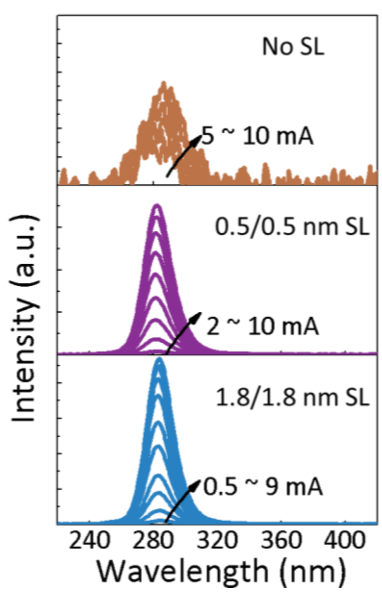

Fig. 7 Comparison of emission spectrums of the devices

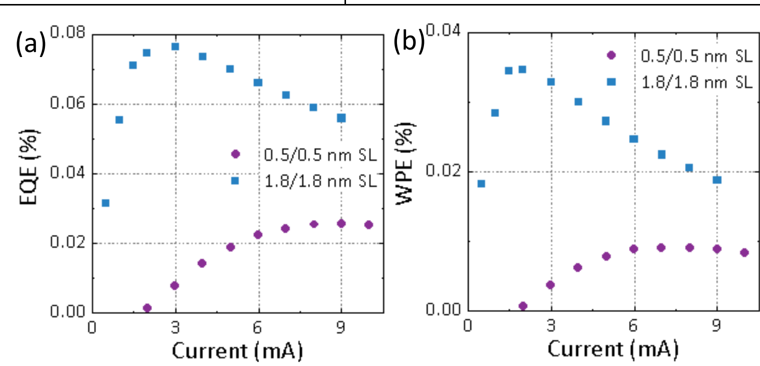

Fig. 8 EQE and WPE of the devices