All-MOCVD Tunnel Junctions for Reduced-Droop High-Power Multi-Junction Cascaded LEDs

Brendan P. Gunning[1], Syed M. N. Hassan[2], Zane J.-Eddine[2], Hareesh Chandrasekar[2], Hyemin Jung[2], Mary H. Crawford[1], Andrew A. Armstrong[1], Siddharth Rajan[2], and Shamsul Arafin[2]

[1]Sandia National Laboratories, Albuquerque, NM 87185, U.S.A.
[2]Department of Electrical and Computer Engineering, The Ohio State University, Columbus, OH 43210, U.S.A.

While III-Nitride based LEDs have seen phenomenal commercial success, they nonetheless suffer from several significant drawbacks. These include efficiency droop, where the LED efficiency drops off at high injection current, as well as poor p-type conductivity and high p-type contact resistance. In the past few years, III-Nitride tunnel junctions have seen significant research interest as a way to work around some of the p-type issues but can also be used as a way to work around efficiency droop. Instead of a single LED operating at high current (i.e. far from peak efficiency), one could run 3 cascaded LEDs series-connected by tunnel junctions at low current (i.e. nearer peak efficiency) but higher voltage. Remarkable progress to-date has been made to demonstrate the viability of these tunnel junctions for UV and visible LEDs, lasers, and VCSELs. A wide variety of tunnel junctions have been shown, including GaN homojunction and InGaN-interlayer tunnel junctions, and have been grown by both MBE and MOCVD, as well as hybrid growth techniques involving both. Many of the best results to-date have been made using all-MBE and hybrid approaches, while MOCVD tunnel junctions have generally lagged behind due to Mg memory effects, delayed Mg turn-on, and trade-offs related to high Si-doping.

In this work, we demonstrate commercially-relevant all-MOCVD continuously-grown (i.e. without interruption) tunnel junctions with state-of-the-art voltage penalties (i.e. excess voltage compared to baseline pn junction diode). The growth was performed at atmospheric pressure in a Taiyo Nippon Sanso SR4000HT MOCVD reactor. Buried p-type activation is performed during device processing after the mesa etch under relatively standard activation conditions. Using a baseline pn junction diode structure, we demonstrate both GaN homojunction and graded InGaN interlayer tunnel junctions. For the GaN homojunction, we apply Mg and/or δ-doping of 2-5×10^{13} cm^{-2} (calculated dose) prior to initiating the thin p^{++} tunnel junction layer, achieving voltage penalties of ~0.14, 0.29, and 0.47 V at 1, 10, and 100 A/cm^2, respectively. We have also demonstrated an approach using δ-doped graded InGaN interlayers (0% to 10% indium fraction) inside the tunnel junction, with which we have achieved voltage penalties of 0.09, 0.13, and 0.19 V at 1, 10, and 100 A/cm^2, respectively. The pn junction diodes with homojunction and graded InGaN tunnel junctions both exhibit minimum differential resistance that is lower than the baseline p-contacted pn junction diode. Finally, we demonstrate linear EQE scaling for 2x and 3x cascaded blue LEDs, even when series-connected with preliminary non-optimized GaN homojunction tunnel junctions. Newer cascaded LEDs with various tunnel junctions will be presented and discussed at the conference.

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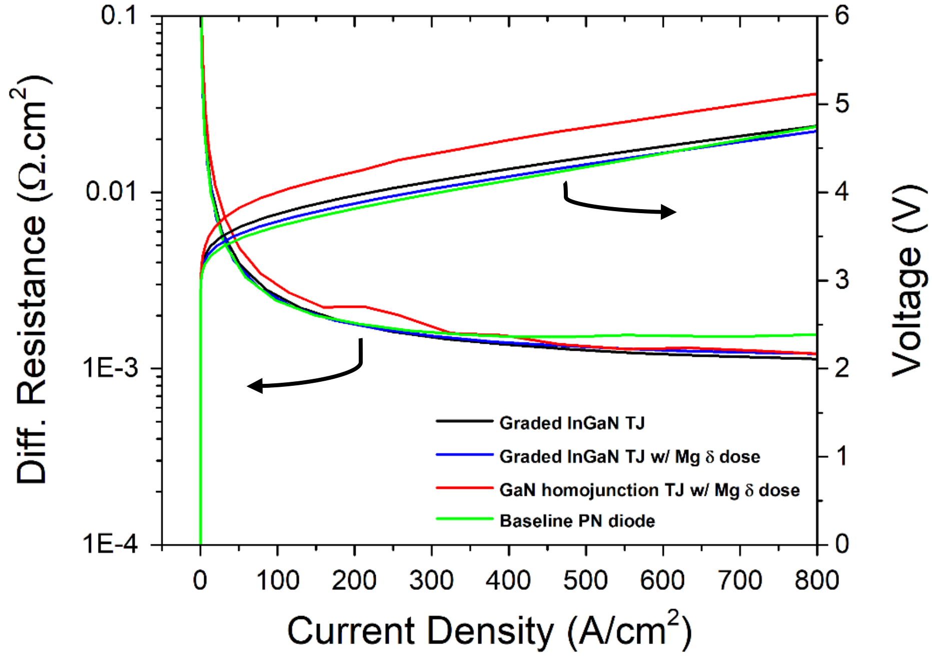

Figure 1. Differential resistance (left axis) and voltage (right axis) vs. current density for various types of tunnel junctions compared with baseline PN diode.

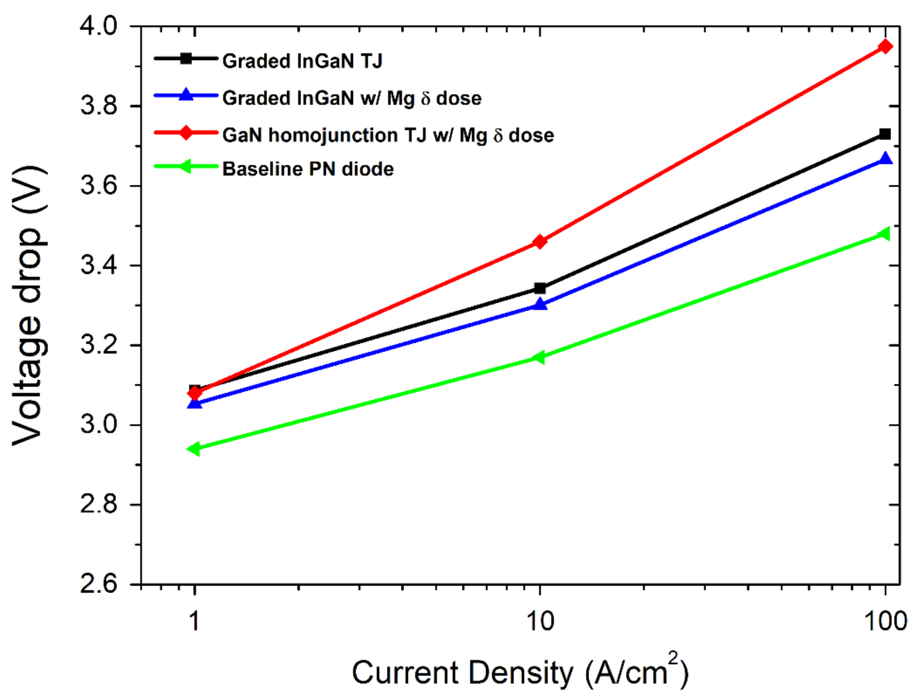

Figure 2. Voltage drop vs. current density for various tunnel junctions compared with baseline PN diode.