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Invited Paper

III- Nitride Tunnel Junctions: Devices and Applications

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Availability of efficient inter-band tunnel junctions (TJ) could enhance a broad range of III-nitride devices such as multiple active region LEDs, lasers, UV emitters, and solar cells. A tunnel junction can be used as a tunneling contact to p-GaN in emitters, and also be used to cascade multiple active regions for multi-active region LEDs and multi-junction solar cells. While the large band gap of GaN is a challenge for tunneling devices, in this work, we show two approaches of using polarization [1-2] and midgap states [3] to enhance tunneling by orders of magnitude. We show device applications of these tunnel junctions junctions, and show that they could provide a solution to the challenge of efficiency droop in solid state lighting.

Polarization engineering [1-2] can be used to create large band-bending over nanoscale lengths to enhance tunneling by several orders of magnitude, overcoming fundamental limits of homojunction P-N tunnel diodes. The band diagram of a GaN/InGaN/GaN TJ, with the thickness of InGaN layer required for the TJ design, is shown in Fig.1. Such tunnel junctions were incorporated in a GaN P-N junction as a n-type tunneling contact to p-GaN, as shown in Fig. 2**.** 4 nm of 25% InGaN inserted between degenerately doped GaN aligns the conduction and valence bands of GaN, owing to the high polarization charge dipole at the GaN/InGaN interface, resulting in a high current density even close to zero bias across the tunnel junction. As the P-N junction is forward biased, the TJ gets reverse biased, tunnel injecting holes into p-GaN. The tunneling resistivity is extracted by subtracting the contact and series resistances from the overall forward bias resistance to be $1.2 \times 10^{-4}\ \Omega\text{cm}^2$. This is the lowest reported tunneling resistivity in GaN.

The second approach to enhance tunneling in III nitrides is to introduce mid gap states in a GaN p^+ n^+ junction, to reduce the tunneling barrier width. GdN nano-islands embedded in heavily doped GaN P-N junctions were used to inject holes into a GaN P-N junction, as shown in Fig. 3(a). Tunnel junction specific contact resistivity of GdN-based tunnel junction has been de-embedded from the overall device resistance to be $1.3 \times 10^{-3}\ \Omega\ \text{cm}^2$ [3]. Figure 4 shows the tunneling resistivity achieved in different material systems. Our work represents the lowest tunneling resistance achieved in GaN.

Low resistance tunnel junctions were also integrated into commercial blue LED (450 nm) structures enabling p-contact free LEDs. Excellent current spreading and enhanced light output power was observed in the TJ LED devices. The voltage drop in the TJ LED devices are the lowest reported till date (4 V @ 20 mA, 5.4 V @ 100mA).

Tunnel junctions can act as sites for carrier regeneration in cascaded p-n junction/ LED structures. Multiple (n= 1,2, 4) pn junctions were stacked epitaxially using TJ interconnects and the turn-on voltage was found to scale with the number of junctions. This low resistance TJ interconnects enable a cascaded LED device structure (Fig. 5). Such a device can be operated in the low current regime wherein there are minimal or no efficiency droop effects, while still achieving high brightness due to multiple photon emission from the multiple LEDs that are cascaded. Calculations indicate enhanced wall plug efficiency and lowered joule heating in high brightness cascaded LEDs when the tunnel junctions are efficient [5].

In conclusion, state-of-the-art polarization engineered GaN/InGaN/GaN tunnel junctions ($1.2 \times 10^{-4}\ \Omega\text{-cm}^2$) and GdN nanoislands embedded tunnel junctions ($1.3 \times 10^{-3}\ \Omega\text{-cm}^2$) have been demonstrated. Tunnel junctions were also integrated with commercial blue LED resulting in a p-contact free LED. Record low voltage drop is reported for TJ LED (450 nm) devices. Cascaded p-n junctions have been demonstrated. The proposed cascaded LED structure holds promise in circumventing the efficiency droop bottleneck.

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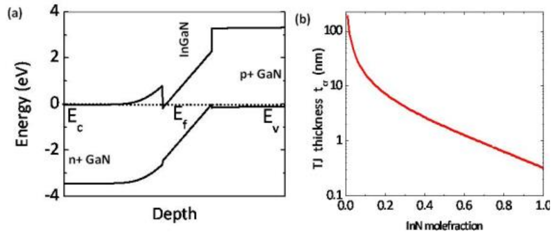

FIG.1. (a) Band diagram of a GaN/InGaN/GaN tunnel junction (TJ) (b) Design thickness of InGaN barrier thickness for band alignment.

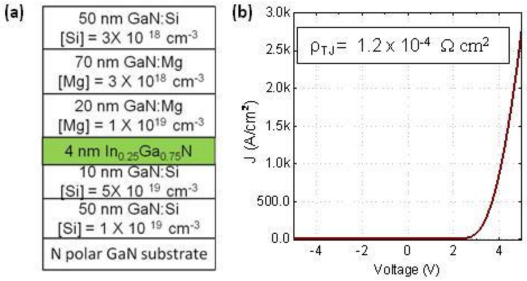

FIG.2: (a) Epitaxial stack of a *p-contact free PN junction*. TJ makes a tunneling contact to p-GaN. (b) IV characteristics of the device (specific tunnel resistivity of 1.2 X 10^{-4} Ω-cm^2) .

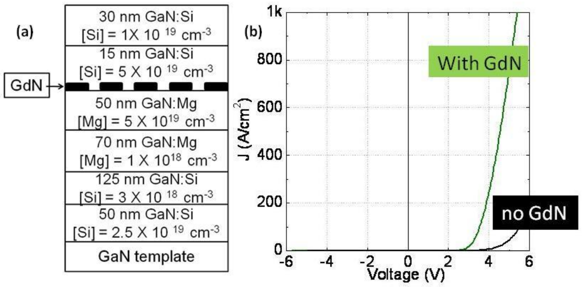

Fig. 3: (a) Epitaxial stack of *p-contact free PN junction* with GaN/GdN TJ (b) IV characteristics of the device. A specific tunnel resistivity of 1.3 X 10^{-3} Ω-cm^2 is extracted.

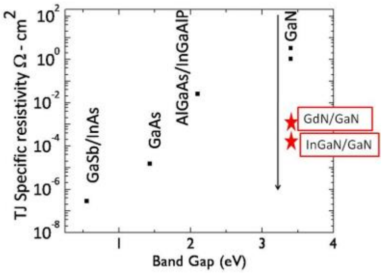

Fig. 4: Tunnel junction resistivity achieved in different material systems. Our results represent the state-of-the-art GaN tunnel junctions.

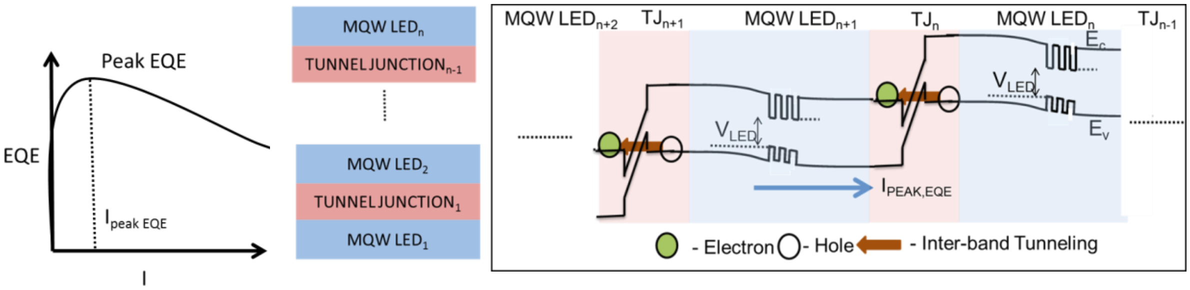

Fig. 5: (a) Efficiency droop in a single LED with peak EQE at $I_{\text{peak EQE}}$ (b) Epitaxially cascaded LED structure with carrier regeneration at the tunnel junction. The cascaded LED structure can be run at low current regime for high brightness.