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InGa\mbox{/GaN} tunnel junctions for hole injection in GaN light emitting diodes

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InGa\mbox{/GaN} tunnel junction contacts were grown using plasma assisted molecular beam epitaxy (MBE) on top of a metal-organic chemical vapor deposition (MOCVD)-grown InGa\mbox{/GaN} blue (450 nm) light emitting diode. A voltage drop of 5.3 V at 100 mA, forward resistance of $2 \times 10^{-2}$ $\Omega$ cm$^2$, and a higher light output power compared to the reference light emitting diodes (LED) with semi-transparent p-contacts were measured in the tunnel junction LED (TJLED). A forward resistance of $5 \times 10^{-4}$ $\Omega$ cm$^2$ was measured in a GaN PN junction with the identical tunnel junction contact as the TJLED, grown completely by MBE. The depletion region due to the impurities at the regrowth interface between the MBE tunnel junction and the MOCVD-grown LED was hence found to limit the forward resistance measured in the TJLED. © 2014 AIP Publishing LLC. [http://dx.doi.org/10.1063/1.4897342]

This paper describes the incorporation of tunnel junctions (TJs) on blue light emitting diodes (LEDs) with minimal electrical loss introduced by the tunnel junction. Tunnel junctions$^1$ in the gallium nitride material system enable n-type tunneling contacts to p-GaN, multi-junction devices (multiple wavelength LEDs connected in series, multi-junction solar cells), and reverse polarization structures$^2$ (p-down LEDs). Tunnel junctions also provide a pathway to circumvent efficiency droop in LEDs using a cascaded LED design run at low current density.$^3$ However, low tunneling resistance is a prerequisite for the incorporation of TJs in commercial devices. Recently, tunnel junction device designs exploiting polarization in nitrides and embedded rare earth nitride nanoislands resulted in low resistance GaN tunnel junctions with resistivity as low as $10^{-4}$ $\Omega$ cm$^2$.$^4$–$^7$ In the case of the polarization-based approach, a $p^+$/GaInGaN/n$^+$ GaN structure is used where the depletion field of the $p^+$/n$^+$ GaN junction is aligned with the polarization field due to the sheet charge at InGaN/GaN interfaces. Even with a thin InGa\mbox{/N} layer (4 nm In$_{0.25}$Ga$_{0.75}$N), the band edges can be aligned to enable inter-band tunneling.$^1$ GdN nanoislands embedded in GaN $p^+$/n$^+$ junction provide intermediate states for tunneling across the depletion region.$^7$ With reduced tunnel barrier width for each of the two tunneling steps, a resistance of $5 \times 10^{-4} - 1 \times 10^{-3}$ $\Omega$ cm$^2$ was reported. Realization of such low resistance GaN-based tunnel junctions has generated interest in tunnel junction enabled devices such as tunnel junction LEDs,$^1$–$^4$ tunnel junction laser diodes,$^5$ and multi-junction solar cells.$^6$–$^8$

One of the immediate applications of a GaN-based tunnel junction is to replace the high resistance $p$-GaN layer in commercial LEDs with an $n$-type top contact. Since the $n$-type layer has low spreading resistance, the metal electrode coverage can be greatly minimized on the top surface and the light can be extracted from the top surface. Such an approach would have the advantage of avoiding the free carrier absorption losses in ITO current spreading layers in the case of top-emitting thin film LEDs and the complex fabrication processes involved in the case of flip-chip LEDs. A tunnel junction draws electrons from the valance band of the $p$-type material into the $n$-type material through inter-band tunneling, and holes in the valance band on the $p$-side are in turn injected into the active region.

Previous reports on tunnel junction LEDs have demonstrated the advantage in using a low spreading resistance $n$-type top contact layer. These tunnel junctions were primarily based on degenerately doped PN junctions ($p^+$/n$^+$ tunnel junctions),$^9$–$^{14}$ current spreading by two dimensional electron gas,$^{15}$ strained layer super lattices,$^{16}$ and transparent conducting ZnO nanoelectrodes.$^{17}$ Recently, polarization-based GaN/InGaN/GaN tunnel junctions on LEDs have also been demonstrated using metal organic chemical vapor deposition (MOCVD) technique.$^{18}$–$^{20}$ Although a higher output power was measured in all the aforementioned devices, voltage drop across the tunnel junction was high, and lead to high losses in LEDs. This was mainly due to the issues with the activation of the buried $p$-type layers grown by MOCVD. An ideal tunnel junction device should conduct with minimal bias (voltage drop) across it, while the LED is in forward operation. The on-resistance of the tunnel junction should also be minimal. Tunnel junctions satisfying this criteria, with a resistance of $10^{-3}$–$10^{-4}$ $\Omega$ cm$^2$ were recently demonstrated by using molecular beam epitaxy (MBE) technique.$^2$–$^4$ In this work, we demonstrate MBE grown tunnel junctions on commercial LED wafers with a low forward voltage compared to the tunnel junction LEDs reported in the literature.$^{12}$–$^{15}$ Furthermore, previous demonstrations of MBE-grown InGa\mbox{/GaN} TJs focused on structures along the N-polar orientation.$^{1}$–$^4$, 6–$^8$ In this work, polarization engineered InGa\mbox{/GaN} TJ with a low tunneling resistance ($5 \times 10^{-4}$ $\Omega$ cm$^2$) is reported on the technologically more important Ga-polar orientation.

Three structures are compared in this work—a reference MOCVD-grown LED (Fig. 1(a)) (REFLED), a MOCVD-grown LED with a MBE-grown tunneling $p$-contact (MOCVD LED + MBE TJ) (Fig. 1(b)) (TJLED), and a MBE-grown PN junction with a tunneling $p$-contact (MBE PN junction + MBE TJ) (Fig. 1(c)) (TJPN). REFLED consists of a commercial blue (450 nm) InGa\mbox{/GaN} LED wafer with thin semi-transparent Ni/Au $p$-type contacts. For the TJLED

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GaInN/GaN TJ-based contacts were grown by MBE on the same commercial InGaN/GaN-based blue LED as the reference LED. MBE regrowth on MOCVD LED leads to interfacial impurity effects. To understand the effects of the regrowth interface, the TJPN sample was grown completely by MBE without any interruption or regrowth. REFLED and TJLED share the same MOCVD active region, while the tunnel junction in TJLED and TJPN was identical.

The TJLED and TJPN samples were grown by MBE using standard effusion cells for In, Ga, Si, and Mg, with Veeco UNI-Bulb nitrogen plasma source. RF plasma power of 350 W, corresponding to a nitrogen-limited growth rate of 260 nm/h, was used in this study. In the case of the TJLED sample, magnesium delta doping was carried out to partially compensate the positive charge (O, C, and Si impurities) at the regrowth interface (Fig. 1(b)). This was followed by a heavily doped p⁺-GaN layer using nitrogen shutter pulsing technique with a duty cycle of 33%. The p⁺-GaN layer was grown in Ga-rich condition to avoid polarity inversion, and Ga polarity was confirmed through the absence of 3\/C212 reconstructions in the post-growth RHEED spectrum. Excess droplets were thermally desorbed after the p⁺-GaN layer to ensure a dry surface before InGaN growth. InGaN was grown in In-rich conditions using Ga flux less than the stoichiometric flux. By pulsing the nitrogen shutter with a duty cycle of 50%, high doping was achieved in the n⁺-GaN (1.2 × 10²⁰ cm⁻³) layer. The structure was terminated with an n-type GaN (260 nm, 2.5 × 10¹⁹ cm⁻³) current spreading layer grown in Ga-rich conditions. Identical growth conditions were used in TJPN diode growth, to achieve identical tunnel junction structures in both the cases. Figure 2 shows the atomic force microscopy (AFM) image of the surface of the InGaN/GaN TJLED, showing smooth surface morphology with rms roughness in the range of 0.4–0.5 nm. Al (20 nm)/Ni (20 nm)/Au (200 nm) top contact metal was deposited on n⁺-GaN by e-beam evaporation on the TJPN diode and TJLED samples. Mesa isolation was done using BCl₃/Cl₂ chemistry to reach the n-type GaN bottom contact layer. Al (20 nm)/Ni (20 nm)/Au(200 nm) contacts were deposited on the bottom n-GaN contact layer by e-beam evaporation. The reference LED (Fig. 1(a)) was fabricated using semi-transparent Ni (4 nm)/Au (6 nm) contacts on p-GaN and Al (20 nm)/Ni (20 nm)/Au (200 nm) contacts on n-type GaN. Electrical characterization was done using a B1500 Agilent Semiconductor Device Analyzer. Electroluminescence and on-wafer light output power measurements were obtained using a calibrated Ocean Optics USB 2000 spectrometer with a coupled fiber optic cable without an integrating sphere.

Electroluminescence measurements of the TJLED and REFLED samples (pulsed measurement with a duty cycle of 0.1% to avoid joule heating effects) are shown in Figure 3. As the current increased from 20 mA to 100 mA, a blue shift in the peak emission wavelength from 443.8 nm to 442.4 nm was measured in the REFLED (Fig. 3(a)). Electroluminescence characteristics of the TJLED (Fig. 3(b)) were found to be similar to that of the REFLED, with a blue shift in the peak wavelength from 447.4 nm to 444.9 nm, corresponding to an increase in the current from 20 mA to 100 mA. It should be noted that the band gap of the InGaN layer used in the TJLED
would suggest absorption of blue photons. However, the photo-generated electron-hole pair would experience a very high electric field in the InGaN layer. As a result, the generated hole is swept back to the p-GaN layer. The photo-generated electron is swept to the top contact, and is injected back into the n-GaN layer through the power supply. Thus, if the internal quantum efficiency of the device is high, which is the case for blue LEDs, the photo-generated carriers are re-injected into the active region and absorption losses due to the low bandgap InGaN tunnel barrier is not expected to be an appreciable loss mechanism. Hence, in spite of the low bandgap of the InGaN barrier, the electroluminescence spectrum of the TJLED does not show additional peaks compared to the REFLED, indicating that there is no measurable absorption/re-emission due to the tunnel junction.

On-wafer pulsed output power measurements (0.1% duty cycle) show an increased power output from the TJLED compared to the REFLED (Fig. 4(a)). This is simply because of less electrode coverage on the top surface of the TJLED. Optical micrograph (Fig. 4(b)) shows excellent current spreading in the n-GaN layer. These results are consistent with the previous reports of higher output power in TJ LEDs. The main metric for a TJLED is the forward voltage and the forward resistance. Current-voltage characteristics of the TJ LED device and the reference LED (350 μm × 350 μm) are shown in Figure 5. Forward voltage measured in the TJLED at 100 μA (500 μA) current is 2.625 V (2.9 V), which is slightly larger compared to 2.5 V (2.675 V) in the REFLED. However, after the device turn-on the forward resistance of the TJLED is comparable to that of the REFLED. 20 mA (100 mA) current drive, relevant for LED device operation, is achieved at 3.9 V (5.35 V) in InGaN/GaN TJLED compared to 3.775 V (5.975 V) in the REFLED. Forward resistance of the TJ LED device was extracted to be 2 × 10⁻² Ω cm².

Electrical characteristics of the TJPN diode device (50 μm × 50 μm) are shown in Figure 6. The TJPN sample showed rectification, with a forward voltage of 2.85 V measured at a current density of 20 A/cm², compared to 3 V measured in a GaN PN junction reported in the literature. This indicates that there is no significant voltage drop across the tunnel junction. A total forward resistance of 5 × 10⁻⁴ Ω cm² was measured in the linear region, with the top and bottom contact resistances measured to be 1 × 10⁻⁶ Ω cm² and 2 × 10⁻⁶ Ω cm², respectively. Hence, a tunnel junction resistance of 5 × 10⁻⁴ Ω cm² was extracted, which is the difference between the total resistance and the contact resistances.

The forward voltage in the TJLED structure is the sum of the voltage drop across the active region, the regrowth interface, and the tunnel junction. The TJLED and the TJPN samples had the identical tunnel junction structure. TJPN diode was grown completely by MBE, and hence the regrowth interface effects were eliminated. TJPN diode showed low tunneling resistance as well as no significant voltage drop across the tunnel junction; hence, the voltage drop measured in the TJ LED structure can be attributed to the regrowth interface depletion, which acts as a barrier for hole injection.

The regrowth interface (Fig. 1(b)) is generally found to contain oxygen, carbon, and silicon impurities, which act as n-type dopants on the surface. Although chemical treatment can reduce the amount of impurities, complete removal has been a challenge, as reported previously for high electron mobility transistors (HEMT). The positive impurity sheet

![FIG. 4. (a) On-wafer output power of TJLED and REFLED, showing higher output from TJLED due to less metal footprint on the top contact surface. (b) Optical micrograph showing uniform light emission at high current density (100 mA) due to low spreading resistance n-type top layer enabled by the tunnel junction.](image)

![FIG. 5. Linear I-V characteristics of the TJLED and the REFLED (350 μm × 350 μm). Forward resistance of the TJLED was measured to be 2 × 10⁻² Ω cm². TJLED shows lowest reported voltage drop of 5.3 V at 100 mA current drive. Inset: Log I-V characteristics of TJ LED and REFLED.](image)

![FIG. 6. Linear current voltage characteristics of Ga-polar GaN TJPN diode showing a low tunnel junction resistance of 5 × 10⁻⁴ Ω cm². Inset: Log J-V characteristics of TJPN diode.](image)
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