n-GaN region have been generated, the NPNPN-GaN junctions increase the layer resistivity vertically, which is beneficial for better current spreading [15–17]. Figures 6(a) and 6(b) depict the simplified equivalent circuits of the reference device and the NPNPN-GaN device. In the reference device grown on the insulating substrates with the lateral current-injection scheme, the current flows both vertically and laterally from the p-GaN region to the n-GaN region. However, the current preferably flows vertically due to the much smaller sheet resistance of the n-GaN region compared to the p-GaN region. This leads to the non-uniform current distribution (i.e., $I_1 > I_2 > I_3 > I_4 > ..... > I_n$), which is root reason for the current crowding effect [12]. This detrimental current crowding effect can be suppressed by incorporating the NPNPN-GaN junctions in the LED structure. In the case of the NPNPN-GaN device, we divide the total current into a vertical portion ($J_1$) and a horizontal portion ($J_2$). Based on the equivalent circuits in Figs. 6(a) and 6(b), the simplified equations, Eq. (1) and Eq. (2), are obtained.

$$\frac{J_1}{J_2} = \frac{w_{CSL} t_{CSL}}{lw} + \frac{1}{\frac{\rho_{p-GaN}}{\rho_{CSL}} t_p + \frac{N\rho_{npn}}{\rho_{CSL}}} \quad (1)$$

$$\frac{J_1}{J_2} \cong \frac{1}{\frac{\rho_{p-GaN}}{\rho_{CSL}} t_p + \frac{N\rho_{npn}}{\rho_{CSL}}} \quad (2)$$

where $w_{CSL}$ is the width of the current spreading layer and $t_{CSL}$ is the thickness of the current spreading layer, $w$ is the width of the device mesa, $l$ is the length of the device mesa, $t_p$ is the thickness of the p-GaN region, $\rho_{p-GaN}$ and $\rho_{CSL}$ are the resistivities for the p-GaN region and the current spreading layer, respectively, and $\rho_{npn}$ is the specific interfacial resistivity induced by the barrier height in each NPN-GaN junction [17]. N is the total number of NPN-GaN junctions. From Eq. (2), obviously the lateral current (i.e., $J_2$) can be improved by a higher ratio of $N \times \rho_{npn} / \rho_{CSL}$, which can be achieved through either increasing $N \times \rho_{npn}$ or reducing $\rho_{CSL}$. Therefore, the current crowding effect can be suppressed by incorporating the NPNPN-GaN junctions in the LED structure. It is noted that the current spreading effect will also be enhanced by properly increasing the p-GaN region thickness $t_p$ as shown in Eq. (2).

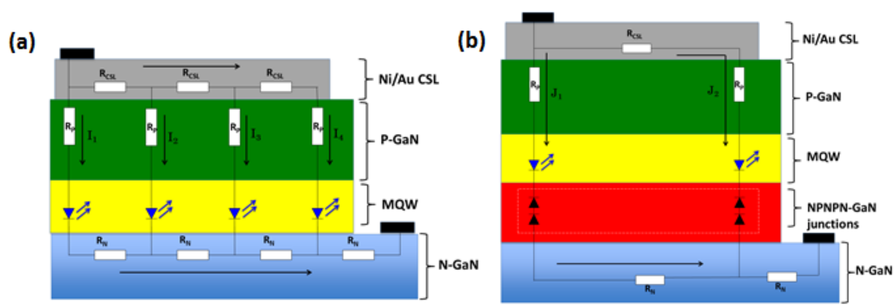


Fig. 6. (a) Equivalent circuit of an InGaN/GaN LED grown on an insulating substrate (e.g., sapphire) using Ni/Au current spreading layer with lateral current-injection scheme ($I_1 > I_2 > I_3 > I_4 > ..... > I_n$) [17], and (b) simplified equivalent circuit of the InGaN/GaN LED with possible current paths ($J_1$ and $J_2$) when the NPNPN-GaN junctions is embedded, using Ni/Au as the current spreading layer on the top [17].

The improved current spreading effect by incorporating the NPNPN-GaN junctions brings about another benefit of higher efficiency of hole injection into the MQWs, which is confirmed by the simulated hole concentration distribution as shown in Fig. 7(a). The combined effects of the electron overflow reduction, the current crowding suppression, and

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the hole injection enhancement with the application of the NPNPN-GaN junctions therefore enhance the radiative recombination rate, as shown in Fig. 7(b), which explains the enhancements of the optical output power and the EQE in the NPNPN-GaN device.

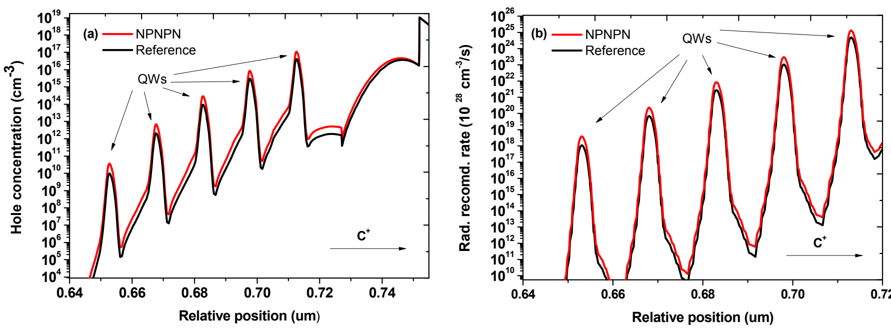


Fig. 7. Simulated (a) hole concentration and (b) radiative recombination rates at 20 A/cm$^2$ across the InGaN/GaN MQW region for the reference device and the NPNPN-GaN device, respectively.

Figure 8 shows the current-voltage (I-V) characteristics of the two devices. Clearly we can see that the NPNPN-GaN device exhibits an increased forward voltage when compared to the reference device. The forward voltages of the reference device and the NPNPN-GaN device at 20 mA are 4.8 and 5.4 V, respectively. The increased forward voltage is likely due to the voltage drop across the NPNPN-GaN junctions as shown below. Due to the small thickness of each layer in the N-P-N junction, an abrupt junction model can be applied and the built-in potential in the P-GaN/N-GaN junction can be calculated to be 3.28 V using Eq. (3)

$$V_{bi} = \frac{kT}{e}\ln\left(\frac{N_a N_d}{N_i^2}\right) \tag{3}$$

where $e$ is the elementary electron charge and $N_i = 1.9 \times 10^{-10}$ cm$^{-3}$ for GaN. Therefore, the total depletion region width is 93.39 nm according to the Eq. (4)

$$W_t = \sqrt{\frac{2\varepsilon_r\varepsilon_0\left(1/N_a + 1/N_d\right)V_{bi}}{e}} \tag{4}$$

where $\varepsilon_r = 8.9$ for GaN and $\varepsilon_o$ is the absolute dielectric constant [23]. This depletion region consists of the depletion region width in P-GaN of 86.47 nm and the depletion region width in N-GaN layer of 6.91 nm, respectively, with the assumption that P-GaN and N-GaN layers have infinite lengths. However, the P-GaN layer has the actual thickness of only 40 nm; so, the depletion region extends through the whole P-GaN layer. It is also worthy to note that ionization ratio of the Mg dopants at room temperature is 1% in GaN [24]. According to the charge neutrality principle in the depletion region of a homojunction, the actual depletion width in N-GaN of NPN-GaN junction is only about 2.95 nm. Hence, the current can flow through the reversely biased junction when it was in reach through breakdown situation. The reach through breakdown voltage for the reversely biased junction is calculated according to Eq. (5)

$$BV_{RT} = \frac{eN_a W_p^2}{2\varepsilon_r\varepsilon_0} \tag{5}$$

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where $W_p$ is the width of P-GaN [25]. A value of 0.65 V is obtained, which is found close to the increment of the forward voltage in the NPNPN-GaN device. The NPNPN-GaN junctions can be further optimized by tuning the thickness, doping concentrations and the periods of NPN-GaN junctions, so that the improved current spreading can overwhelm the increased forward voltage, and thus an improved electrical performance can be realized.

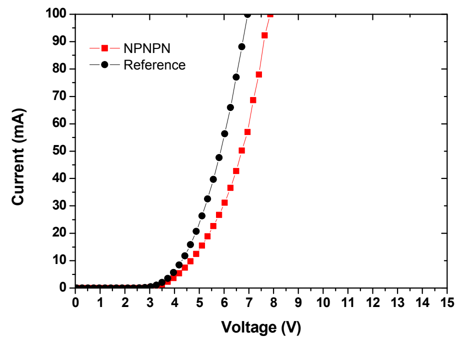


Fig. 8. Measured I-V characteristics of the reference device and the NPNPN-GaN device.

## 4. Conclusion

In conclusion, the InGaN/GaN LED with a new design architecture of NPNPN-GaN junctions inserted between the n-GaN and the InGaN/GaN MQWs has been proposed and studied in this work. The experimental and theoretical findings indicate that the NPNPN-GaN junctions mitigate the electron overflow and reduce the current crowding effect. As the result, the optical power and EQE can be significantly improved. This work offers an alternative way to improve the carrier balancing and, thus, the LED performance.

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