°C for 120 s. In these devices, the deposited Ti/Au (30 nm/150 nm) contacts were used as the p-electrode and n-electrode, respectively.

Figures 7(a) and 7(b) depict the simplified equivalent circuit of InGaN/GaN LEDs. In the case of PNPNP-GaN incorporated as the current spreading layer, we divide the total current into the vertical portion (J_1) and the horizontal portion (J_2). Similar to the devices without transparent current spreading layer, the total voltage drop consists of those between ITO and Ti/Au in the p-contact, p-GaN, MQW region, n-GaN as well as the n-contact. Based on the equivalent circuit in Fig. 7(b), Eq. (6) (for current path 1) and Eq. (7) (for current path 2) are obtained.

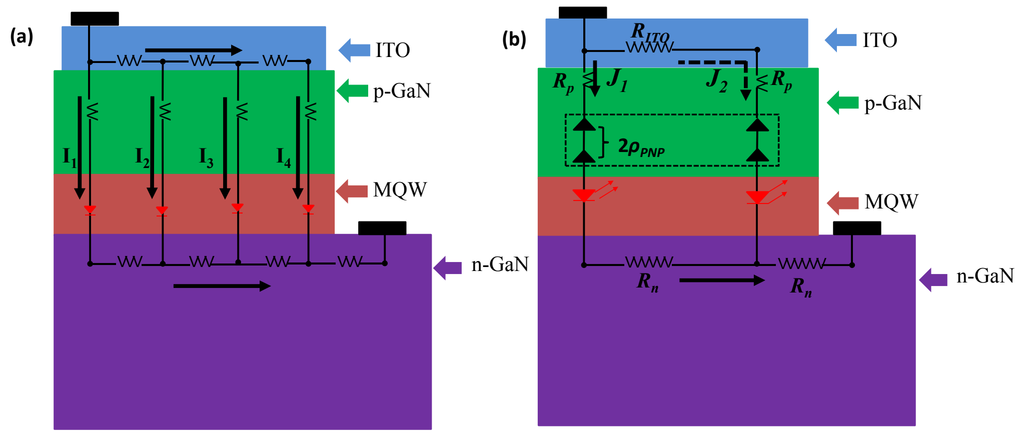

Fig. 7. (a) Equivalent circuit of an InGaN/GaN LED grown on an insulating substrate (e.g., sapphire) using ITO top coating with lateral current-injection scheme ($I_1 > I_2 > I_3 > I_4 > ..... > I_n$), and (b) a simplified equivalent circuit of this InGaN/GaN LED with possible current paths (J_1 and J_2) when a PNPNP-GaN current spreading layer is embedded, along with additional ITO film used as the transparent current spreading layer on the top.

$$J_1 lw\frac{\rho_{p-GaN}t_p}{lw}+J_1 lw\frac{N\cdot\rho_{PNP}}{lw}+V_{pn}+V_{p-contact}+V_{n-contact}+J_1 lw\frac{\rho_{n-GaN}l}{wt_n}+ \left(J_1 lw+J_2 w_{ITO}t_{ITO}\right)\frac{\rho_{n-GaN}l_0}{wt_n}=U \tag{6}$$

$$J_2 w_{ITO}t_{ITO}\frac{\rho_{ITO}l}{t_{ITO}w_{ITO}}+J_2 w_{ITO}t_{ITO}\frac{\rho_{p-GaN}t_p}{lw}+J_2 w_{ITO}t_{ITO}\frac{N\cdot\rho_{PNP}}{lw}+V_{pn}+V_{p-contact}+V_{n-contact}+ \left(J_1 lw+J_2 w_{ITO}t_{ITO}\right)\frac{\rho_{n-GaN}l_0}{wt_n}=U \tag{7}$$

where l represents the length of the lateral current path, l_0 is the distance from the mesa edge to the center of the n-contact, and w is the width of the device mesa. t_{ITO} and w_{ITO} is the thickness and width of the ITO film (in our case, w = 350 µm and w_{ITO} = 330 µm), respectively, and ρ_{ITO} is the ITO resistivity. The thickness of p-GaN and n-GaN is t_p and t_n, respectively; $\rho_{p\text{-}GaN}$ and $\rho_{n\text{-}GaN}$ is the resistivity for p-GaN and n-GaN, respectively; V_{pn} denotes the junction voltage drop of multiple quantum wells in InGaN/GaN LED; and $V_{p\text{-}contact}$ and $V_{n\text{-}contact}$ are the voltage drops across the p-contact (Ti/Au on ITO) and n-contact, respectively. ρ_{PNP} is the specific interfacial resistivity induced by the barrier height in each PNP-GaN junction. N is the total number of PNP-GaN junction, and in our device, we have two PNP-GaN junctions (i.e., PNPNP-GaN), and thus N is 2 (i.e., the total interfacial specific resistivity is 2 × ρ_{PNP}).

By equating Eq. (6) and Eq. (7), Eq. (8) is derived. However, l, w and w_{ITO} are in the order of the device mesa size, which is 350 μm × 350 μm, while t_{ITO} is 200 nm ($t_{ITO} << l$), then Eq. (8) can be simplified into Eq. (9).

$$\frac{J_1}{J_2} = \frac{w_{ITO} t_{ITO}}{lw} + \frac{l}{\frac{\rho_{P-GaN}}{\rho_{TCL}} t_p + \frac{N \cdot \rho_{PNP}}{\rho_{TCL}}} \tag{8}$$

$$\frac{J_1}{J_2} \cong \frac{l}{\frac{\rho_{P-GaN}}{\rho_{TCL}} t_p + \frac{N \cdot \rho_{PNP}}{\rho_{TCL}}} \tag{9}$$

Equation (9) shows that a higher ratio of $N \cdot \rho_{PNP} / \rho_{TCL}$ helps to enhance the lateral current (i.e., J_2). Therefore, either $N \cdot \rho_{PNP}$ has to be increased or ρ_{TCL} has to be reduced for an increased ratio of $N \cdot \rho_{PNP} / \rho_{TCL}$. Meanwhile, the current spreading effect will also be improved by properly increasing the p-GaN thickness (t_p).

Acknowledgments

This work is supported by the Singapore National Research Foundation under Grant No. NRF-RF-2009-09 and NRF-CRP-6-2010-2 and the Singapore Agency for Science, Technology and Research (A*STAR) SERC under Grant No. 112 120 2009. The work is also supported by the National Natural Science Foundation of China (NSFC) (Project Nos. 61006037, 61177014 and 61076015), and Tianjin Natural Science foundation (Project Nos. 11JCZDJC21900 and 11JCYDJC25800).

#178005 - $15.00 USD Received 12 Oct 2012; revised 5 Feb 2013; accepted 7 Feb 2013; published 21 Feb 2013