Study of current crowding effect in different LED die structures

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GaN/InGaN light emitting diodes (LEDs) grown on sapphire substrates have mesa structure with current transport along the lateral direction due to the insulating nature of the substrate. Due to this geometry, the finite resistance of the n-type material of the GaN buffer and lower confinement layer causes the current to "crowd" near the edge of the contact. This problem give rises to unequal heating and unequal light emission from LED dice. Study on different die geometry shows current crowding problem can be reduced by using multi-finger design.

1. Introduction

Continuous progress and research works made III nitride semiconductors the basic materials for visible and ultraviolet optoelectronics. LED heterostructures are conventionally grown on commercial sapphire substrates. Cheap sapphire substrates are quite suitable for large-scale production of blue/green LEDs operating at low and intermediate current densities. As a compromise between the materials properties and cost, silicon substrates have recently been applied to fabricate visible LEDs. The substrate material largely determines the choice of the LED chip design: planar for sapphire and vertical for SiC. A vertical chip with an n-electrode formed to the back side of the SiC substrate provides a highly uniform current density distribution in the active region. In contrast, a planar LED chip with on-one-side n- and p-electrodes exhibits considerable current crowding near the electrode edges and, as a result, an in-plane non-uniformity of the electroluminescence (EL) intensity [1]. In addition, the non-uniform current spreading in the LED die is predicted to induce local overheating of the heterostructure, lowering the light emission efficiency and affecting the series resistance of the diode [2]. In turn, the heat generation in an LED depends on the fraction of light absorbed inside the heterostructure. Therefore, adequate modeling of the LED operation generally requires a coupled analysis of the current spreading, heat transfer, light emission in the active region, and its extraction from the die. Earlier studies of current crowding in LED dice were primarily based on analytical quasi-2D models. They largely focused on the role of the n-contact layer and the semi transparent p-electrode in the current spreading over the dice and on searching the electrode configurations that

would produce a uniform current density distribution in the active region [3–6]. Being recognized as an important factor limiting the LED performance, the current crowding in III-nitride light emitters was in the focus of numerous studies. However, there is still lack of understanding of factors controlling the LED self-heating and its effect on the device characteristics, including current-voltage (I-V) characteristic, output power, external and wall-plug efficiency (WPE), series resistance of the diode, and emission spectra.

Here we study a self-consistent modeling analysis of the isothermal current spreading in blue LED dice at 300K. For this purpose, three-dimensional simulation is performed by the SpeCLED and Ratro 2008 simulator.

2. Chip design

We consider here a blue MQW LED heterostructure. The Ga-faced structure consists of a GaN: Si contact layer 2 μm thick ([Si] = 5×10^{18} cm^{-3}), a multiple-quantum-well (MQW) active region, a 60 nm Al$_{0.15}$Ga$_{0.85}$N: Mg stopper layer ([Mg] = 2×10^{19} cm^{-3}), and a 0.1 μm GaN: Mg contact layer ([Mg] = 5×10^{18} cm^{-3}). The active region contains three unintentionally doped In$_{0.21}$Ga$_{0.79}$N quantum wells (QWs) 4 nm thick separated by 6 nm GaN: Si barriers. Every barrier is doped up to the typical Si concentration of 5×10^{18} cm^{-3}.

Here three different type of 300×300 μm^2 LED die structure is shown schematically in Fig. 1.

Structure (a)

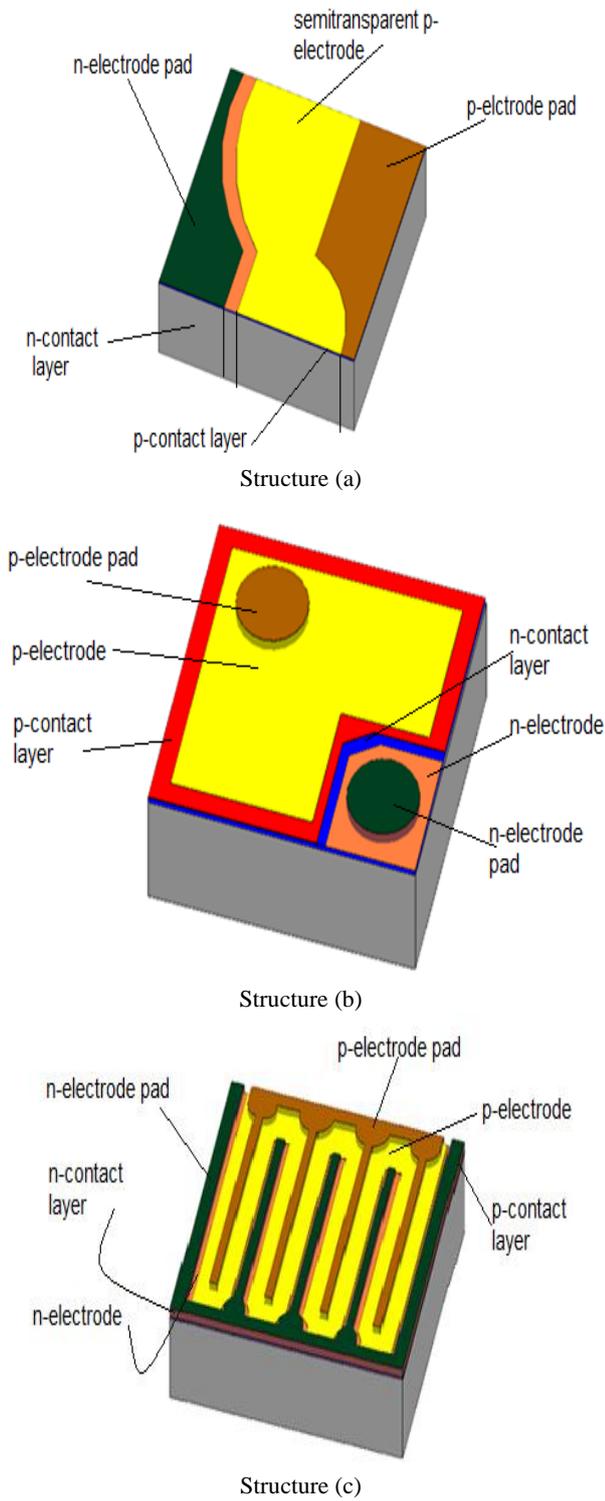Structure (b)

Structure (c)

Fig. 1. Different LED die structures considered in the simulation program.

The specific contact resistances of the n and p-contact electrodes is considered here to be of 10^{-5} and 10^{-4} $\Omega \cdot cm^2$, respectively

3. Results and discussion

Fig. 2 explained the distributions of the current density over the active region for three specified LED structures (a), (b) and (c).
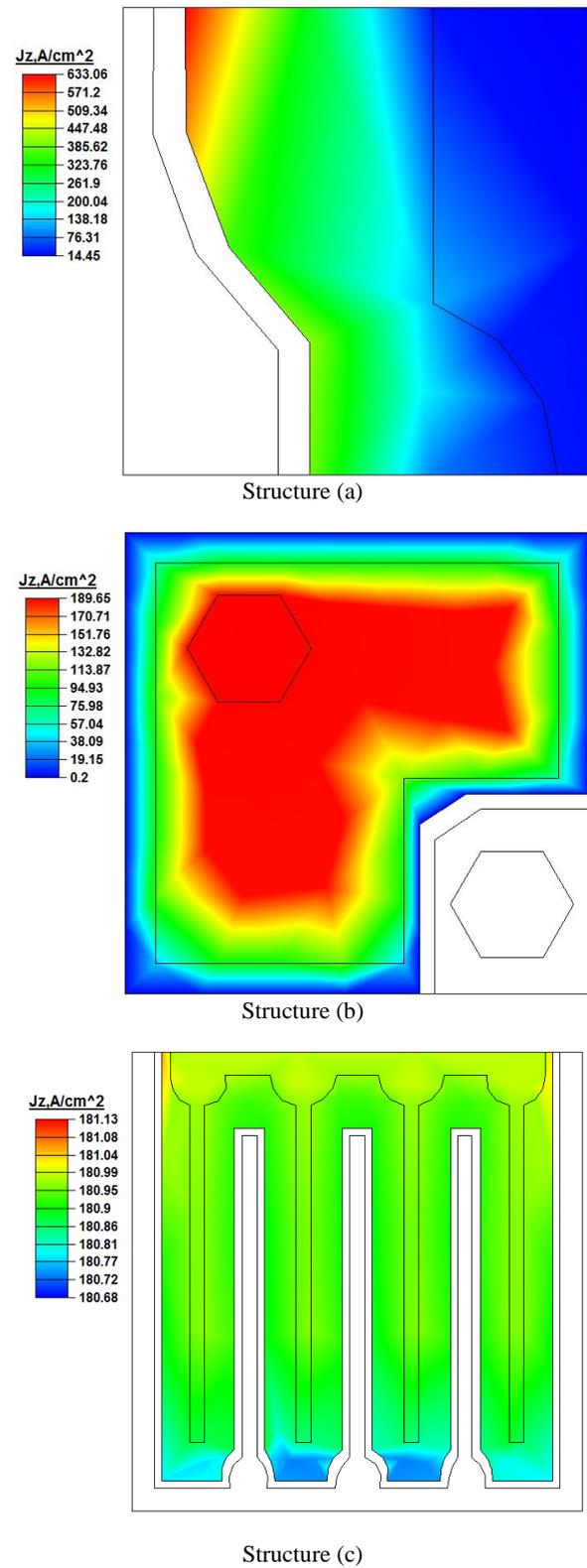

Structure (a)

Structure (b)

Structure (c)

Fig. 2. Displays the computed distributions of the current density over the active region for three specified LED structures.

Fig. 2 displays the computed distributions of the current density over the active region of square LED at the forward current of 100 mA. One can see that the current crowding occurs near the gap between the n- and p electrodes. The current density decays nearly exponentially with the distance measured from the p-electrode edge. The current crowding next to the inter electrode gap is clearly seen in the structure (a & b) but in structure (c) is shows almost uniform distribution. In fact, the current density at the p-electrode edge may be about 2-3 orders of magnitude higher than in the other regions. The current crowding produces remarkable temperature non-uniformity in the die which, in turn, affects the conductivity of the contact layers.

Fig. 3 describes the output optical power as a function of forward current. The optical output power of the LED computed on the assumption of the light extraction efficiency from the die to be of 4%.
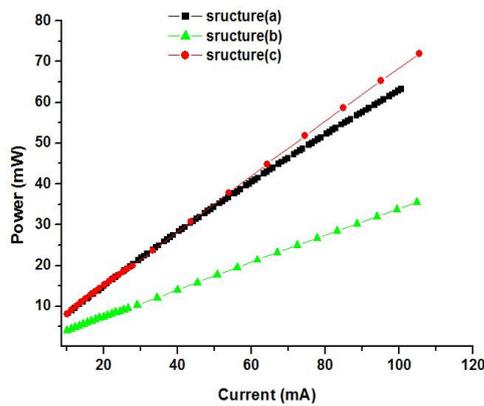

Fig. 3. Output power variation with forward current for structure (a), (b) and (c).

The output power of light emitted from the back side of the sapphire substrate computed for the different LED structure operated at different currents reproduces well the rollover observed at currents greater than 60 mA (Fig. 3). This effect is primarily related to the device self-heating. Therefore, the current crowding is a main mechanism responsible for the LED efficiency degradation at high currents.
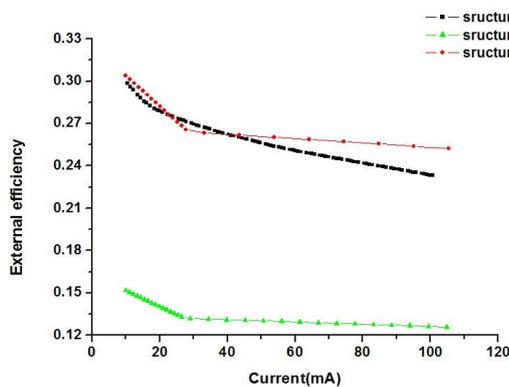

Fig. 4. Comparisons of External efficiency as a function of forward current for structure (a), (b) and (c).
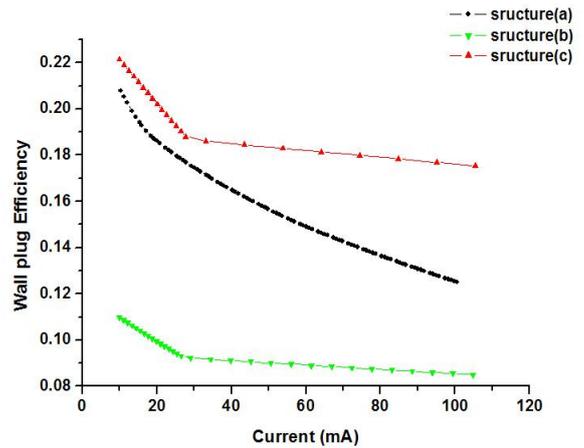

Fig. 5. Variations of Wallplug efficiency as function of forward current for structure (a), (b) and (c).

Figs. 4 and 5 show the simulated external quantum efficiencies and wall plug efficiency of the three structures of LEDs as a function of the forward current. These two plots clearly demonstrate the advantages of the multi finger (structure (c)) chip design over the structure (a) and structure (b). Due to suppressed current crowding, in turn it reduces the overheating problem. From Fig. 5 it was clear that the multi finger structure is capable of high-current operation without considerable droop of the external efficiency at currents from 10 to 120 mA.
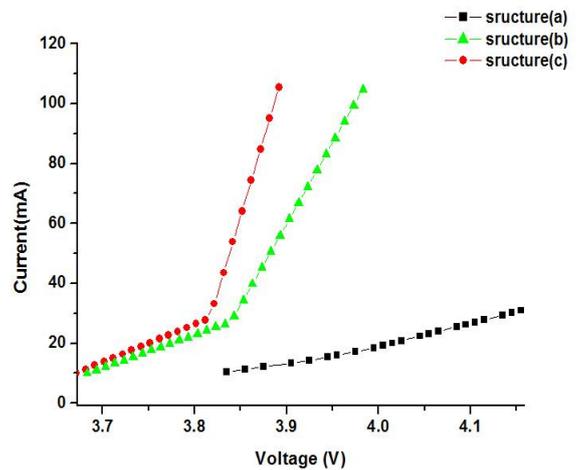

Fig. 6. I-V characteristics for three different structures.

A comparison of simulated current – voltage characteristics of the three different LED structure is given in Fig. 6. The series resistance is observed to be low for the LED structure (c).
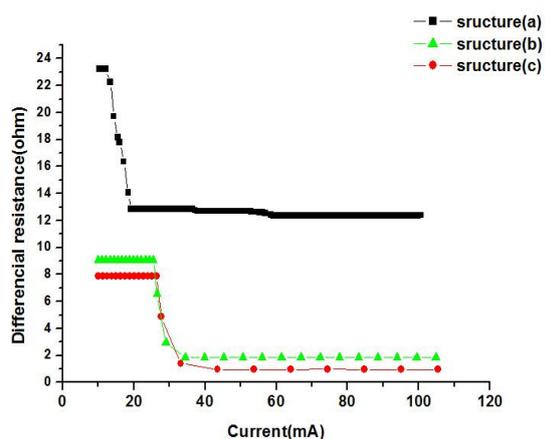
*Fig. 7. Differential resistance versus forward current curve
for three different LED die structure.*

The simulations results show that the observable reduction of the LED differential resistance with current density for three structures (Fig. 7). For structure (a) it varies from 24 ohm to 13 ohm, for structure (b) it founds to be varying from 9 to 1.98 ohm and for structure (c) it was 7.86 to .96 ohm respectively.

The series resistances of three structures of LED dice considered here differ significantly. The structure (a) chip, it has an approximately two times higher resistance than the structure (b) and (c). The detailed analysis has shown that this effect can be attributed to a larger inter electrode gap in the structure (a). Indeed, the width of the gap nearly corresponds to an effective length of the current spread region in the die. The larger the length, the higher is the distributed series resistance of the diode. Therefore, the width of the inter-electrode gap is a crucial factor controlling the series resistance of LEDs.

4. Conclusion

Using simulations results, we have analyzed the current spreading effects on the characteristics of blue LED dice. Current crowding which leads self-heating of the device, as well as the chip design, is found to affect remarkably the characteristic of the structure. The finger structure (structure (c)) shows the advantages over other conventional considered structures for the high current LED. A crucial factor determining the series resistance is the width of the inter-electrode gap that can be controlled by the die processing technology. Current crowding of an LED is found to result in remarkable degradation of its external efficiency under high-current operation conditions and is one of the mechanisms responsible for the commonly observed efficiency decreasing with current.

References

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