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Current crowding effect on light extraction efficiency of thin-film LEDs

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Using coupled 3D modelling of electrical, thermal, and optical processes, we consider operation of a blue LED with advanced thin-film flip-chip design. Significant effect of current crowing on light extraction from the LED die is predicted theoretically. As a result, the light extraction efficiency is found to decrease remarkably with the operation current. The nature of the effect is identified, and some ways for improvement of the high-current extraction efficiency are suggested and examined by simulations.

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1 Introduction Thin-film flip-chip (ThinGaN™) design of III-nitride LEDs has been suggested for substantial improvement of light extraction efficiency (LEE) due to the use of highly reflective p-electrode and texturing free n-contact layer surface after the substrate separation from the grown LED structure [1,2]. A record LEE of ~70-75% and excellent scalability of the LED dice were demonstrated for such LEDs. However, factors and physical mechanisms limiting performance of the thin-film LEDs are not yet identified so far. This paper reports on the impact of current crowding on LEE of the thin-film LEDs, which is considered, to our knowledge, for the first time. Using simulations, we will show that the LEE reduction with current is one more non-thermal mechanism of the efficiency droop commonly observed in III-nitride LEDs. Modifications of the chip design aimed at suppression of the current crowding effect on the LED efficiency are discussed in the paper as well.

2 Heterostructure and chip design We consider here a blue LED structure consisting of a 3 μm n-GaN contact layer (electron concentration $n = 3\times10^{18}$ cm^{-3}), a multiple quantum-well (MQW) active region, and a 40 nm p-$Al_{0.2}Ga_{0.8}N$ electron blocking layer ([Mg] = 1.5×10^{19} cm^{-3}), followed by a p-GaN contact layer ([Mg] = 2.5×10^{19} cm^{-3}) 200 nm thick. The active region includes four undoped 3 nm $In_{0.2}Ga_{0.8}N$ QWs separated by 10 nm n-GaN barriers ($n = 5\times10^{16}$ cm^{-3}), providing the emission spectrum with the peak wavelength at 450 nm. No special layer is placed between the top QW and AlGaN blocking layer. The heterostructure is assumed to be of Ga-polarity and completely strained with respect to the n-GaN contact layer.

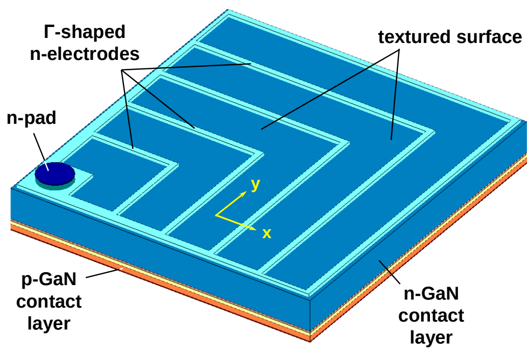

Fig. 2 Schematic LED chip design (highly reflective p-electrode deposited on p-contact layer is not shown in the picture).

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Design of a 815×875 μm^2 LED chip is shown schematically in Fig.1. Electrons are injected in the n-contact layer through a number of Γ-shaped metallic electrodes 15 μm wide. The spacing between the electrodes is 120 and 130 μm in the *x*- and *y*-direction, respectively (see Fig.1). An n-pad 90 μm in diameter is formed in the corner of the die. The substrate is assumed to be removed after growing of the LED structure, and free surface of the n-contact layer between the electrodes is textured to enhance the light extraction from the LED die. A continuous highly reflective p-electrode is deposited on top of the p-contact layer, and the LED die is assumed to be mounted on a heat-sink with p-layers down.

Modelling of the LED operation was performed with commercial SimuLED package [3] providing coupled 3D analysis of electrical, thermal, and optical processes in the LED die (see [4] for more detail). Auger recombination in the InGaN QWs was accounted for as an important mechanism limiting the internal quantum efficiency (IQE) of the LED structure at high-current operation [5-8]. Only the processes involving two electrons and one hole were considered, according to the results of Ref.[8] predicting dominant transitions of the second electron from the lower to upper conduction band of nitride semiconductors. The texturing of the n-contact layer surface was simulated via close-packed array of hexagonal pyramids with the period of 500 nm and height-to-base ratio of four. Optical properties of gold and silver were used in the 3D ray-tracing analysis for the n- and p-electrodes, respectively. The thermal resistance of 8 K/W was used to simulate the heat removal from the LED die mounted on the heat-sink.

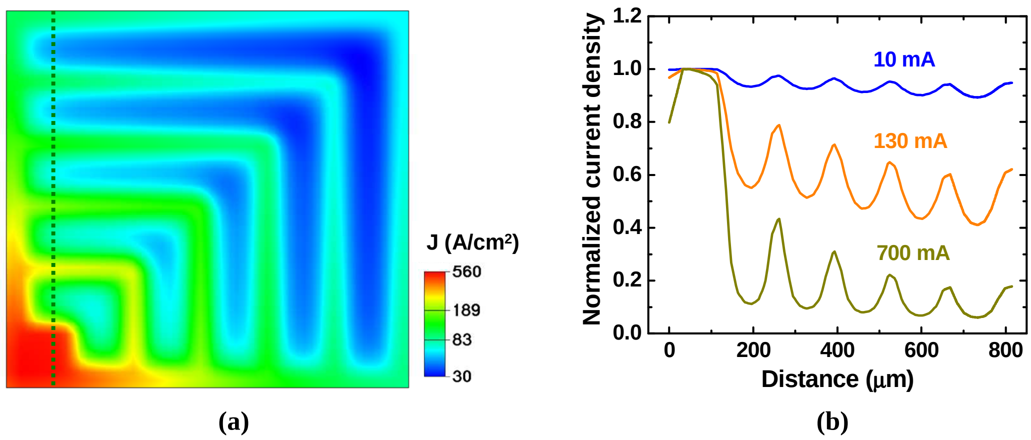

Fig. 2 Current density distribution in the active region at the current of 700 mA (a) and normalized current density profiles in the cross-section marked in (a) by dotted line computed for different total currents flowing through the LED (b).

3 Simulation results Coupled 3D modelling of current spreading, heat transfer, and light extraction from the LED die has been performed in a wide range of the forward current variation. Some of the most important results are discussed below.

Figure 2a shows 2D distribution of the vertical current density J_z in the active region of LED computed for the current of 700 mA. One can see considerable current crow-ding near/under metallic electrodes and especially under the n-pad. The current density non-uniformity is found to rise permanently with the forward current flowing through the LED, as demonstrated by Fig.2b. First, the ratio of maximum to minimum current density in the Γ-shaped electrode region increases with current. Second, the fraction of current localized under the n-pad also grows, as the total current in increased. The current crowding is accompanied by a local active region overheating (not shown here) that reduces the light emission efficiency in the areas of maximum current localization. The maximum overheating occurs under the n-pad and approaches ~25-40 K at the current I = 700-1000 mA.

To understand the effect of the current crowding on light extraction from the die, we computed the probability of photons emitted from a certain point of the active region to be extracted somewhere from the die. The 2D distribution of the extraction probability is displayed in Fig.3a. One can see that photons emitted under the n-pad have extremely low probability of extraction. Those emitted near the Γ-shaped electrodes have a higher but still insufficiently high extraction probability (see also Fig.3b). Such a behaviour is found to be practically independent of current. The reason for the above effect is the optical losses of the emitted light caused by its incomplete reflection from the n-electrodes. One can also see from comparison of Fig.2b and Fig.3b that the current flowing under the n-pad actually shunts the remaining area of the LED die giving a minor contribution to the light emission.

Additional negative effect of the current crowding is the IQE reduction in the areas of enhanced current localization (Fig.3b). This is caused by both the active region overheating and Auger recombination, as discussed above.

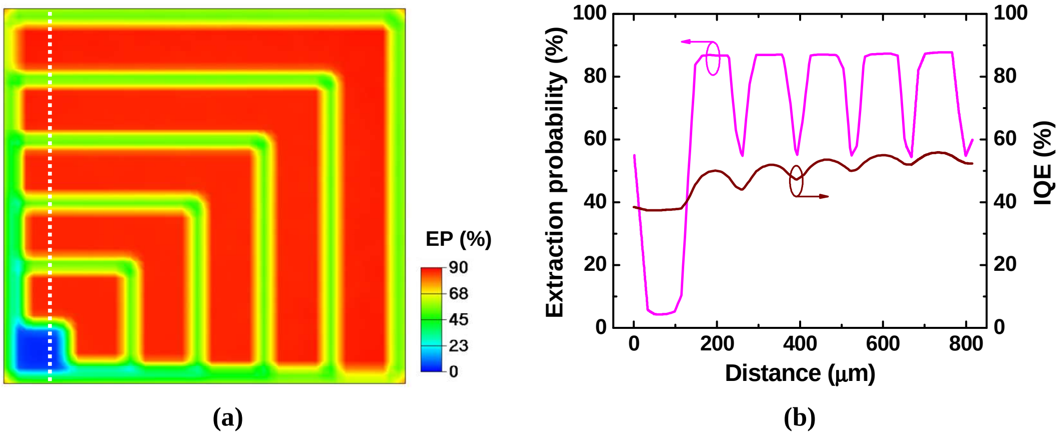

Fig. 3 Distribution of light extraction probability (EP) in the active region (a) and in the cross-section marked in (a) by dotted line (b). IQE profile in the selected cross-section is also plotted in (b).

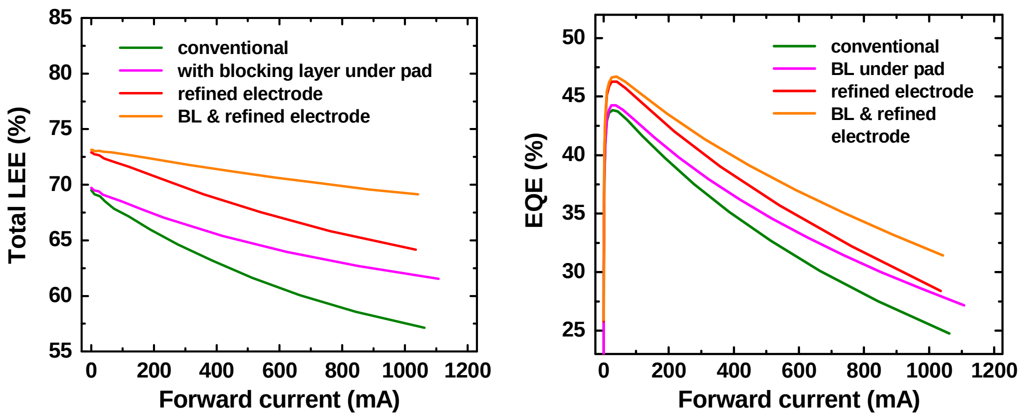

Fig. 4 Total LEE and EQE as a function of forward current computed for LEDs of various designs.

Both reduced extraction probability near/under metallic electrodes and pad and increase of the current crowding with the forward current result in a remarkable dependence of the total LEE upon the current (Fig.4a) in the chip of the considered design. Actually, the LEE is predicted to fall down from ~70% at low current to ~57% at the current as high, as 1000 mA. To diminish the negative effect of the current crowding on LEE, we examined two modifications of the chip design: (i) inserting of an insulating layer (IL) between the pad and n-contact layer, and (ii) using of a narrow, 5 μm wide, Γ-shaped metallic electrodes with the spacing reduced by a factor of two (NE&RS), as compared to that of the initial design. Both approaches result in an LEE improvement, as shown in Fig.4a. However, the most efficient turns out the combination of these approaches, providing much weaker LEE reduction, from ~73% to ~69% , at the current varied from zero to 1000 mA (see Fig.4a). This LEE improvement is found to provide increasing of the LED external quantum efficiency (EQE) by ~20-25% at the operation currents varied in the range of 700-1000 mA (Fig.4b).

The operation voltage V_f varies slightly upon changing the chip design. The use of the IL under the n-pad leads to increasing of differential resistance $R_d = dV_f/dI$ from 0.12 to 0.18 Ω at 700 mA, while utilization of the NE&RS chip design reduces R_d to 0.09 Ω at the same current. Utilization of both approaches provides nearly the same differential resistance as that of the LED with the initial chip design.

4 Conclusion Using simulations, we predict a significant effect of current crowding on the efficiency of light extraction from a thin-film flip-chip LED. This effect originates from the current localization near/under the low-reflective metallic electrodes and pad, which becomes ever stronger with the total current flowing through the diode. As a result, LEE tends to decrease with current. In addition to Auger recombination [5-8], the above effect actually represents a new non-thermal mechanism contributing to the efficiency droop of III-nitride LED that, to our knowledge, has not been yet considered to date.

Two approaches to improvement of the chip design are suggested and examined theoretically. One is based on inserting of an insulating film between the pad and n-contact layer aimed at avoiding the carrier injection in the area of maximum optical losses of emitted light. Another approach utilizes narrow metallic electrodes with reduced spacing, providing partial suppression of the current crowding and reduced optical losses of light reflected from the electrodes. Combination of both approaches is found to allow substantial improvement of LEE at high-current LED operation. The estimated improvement in the EQE of the LEDs due to the proposed modifications of the chip design is as high, as ~20-25% .

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