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Current spreading and thermal effects in blue LED dice

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We have applied simulations to study current the spreading and heat transfer in blue III-nitride light-emitting diodes (LEDs) with the focus on self-heating and its effect on the device characteristics. A conventional planar design of an LED die is considered for the heat sink through a sapphire substrate. The computations predict a great current crowding at the contact electrode edges, resulting in a non-uniform temperature distribution over the die. The thermal effect on the current-voltage characteristic, output optical power, and series resistance of the diode is analyzed and the theoretical predictions are compared with available observations.

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1 Introduction Planar chip design with on-one-side *n*- and *p*-contact electrodes is commonly employed in most III-nitride LEDs. Such a chip configuration leads to a considerable current crowding near the electrode edges and, as a result, to in-plane non-uniformity of the electroluminescence intensity. In addition, the non-uniform current spreading over an LED die induces a local overheating of the device heterostructure, lowering its internal quantum efficiency (IQE). 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 (see, e.g., [1] and references therein). 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.

This paper reports on a self-consistent modeling analysis of the current spreading and heat transfer in blue LED dice. For this purpose, coupled three-dimensional simulation is performed based on the hybrid approach suggested in [1].

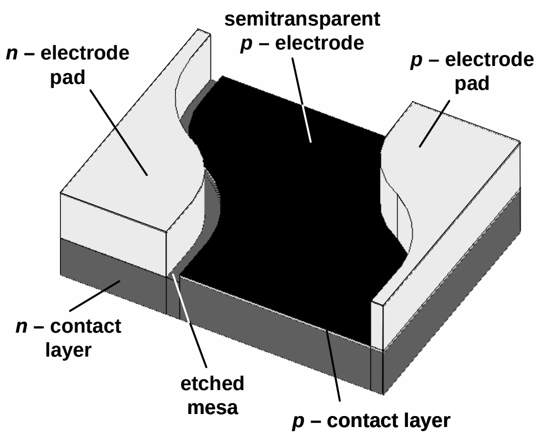

Fig.1 Schematic of the LED die. The thicknesses of both pads are increased for clearness.

2 Heterostructure and chip design We consider here a blue MQW LED heterostructure similar to that studied in [2]. The Ga-faced structure consists of a GaN:Si contact layer 4 μm thick ([Si] = 4×10^{18} cm^{-3}), a multiple-quantum-well (MQW) active region, a 60 nm $Al_{0.15}Ga_{0.85}N$:Mg stopper

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layer ([Mg] = 1.5×10^{19} cm^{-3}), and a 0.5 μm GaN:Mg contact layer ([Mg] = 2×10^{19} cm^{-3}). The active region contains four unintentionally doped $In_{0.13}Ga_{0.87}N$ quantum wells (QWs) 3 nm thick separated by 12 nm GaN:Si barriers. Every barrier is doped up to the typical Si concentration of 2-5×10^{18} cm^{-3}.

A 190×250 μm^2 LED die is shown schematically in Fig1. The die design is similar to that reported in [3]. There are an *n*-electrode formed in the mesa etched in the LED heterostructure, a semitransparent *p*-electrode through which the light emission is partly extracted, and a *p*-electrode pad formed in a corner of the die. The mesa depth is assumed to be of 0.7 μm. The heat sink through a 300 μm sapphire substrate is implied, which corresponds to the chip thermal resistance of ~150 K/W. The temperature dependence of both electron and hole density of states and carrier mobilities is accounted for in the simulations, according to the data of [4]. We assume also the specific contact resistances of the *n*- and *p*-contact electrodes to be of 10^{-5} and 10^{-4} Ω·cm^2, respectively.

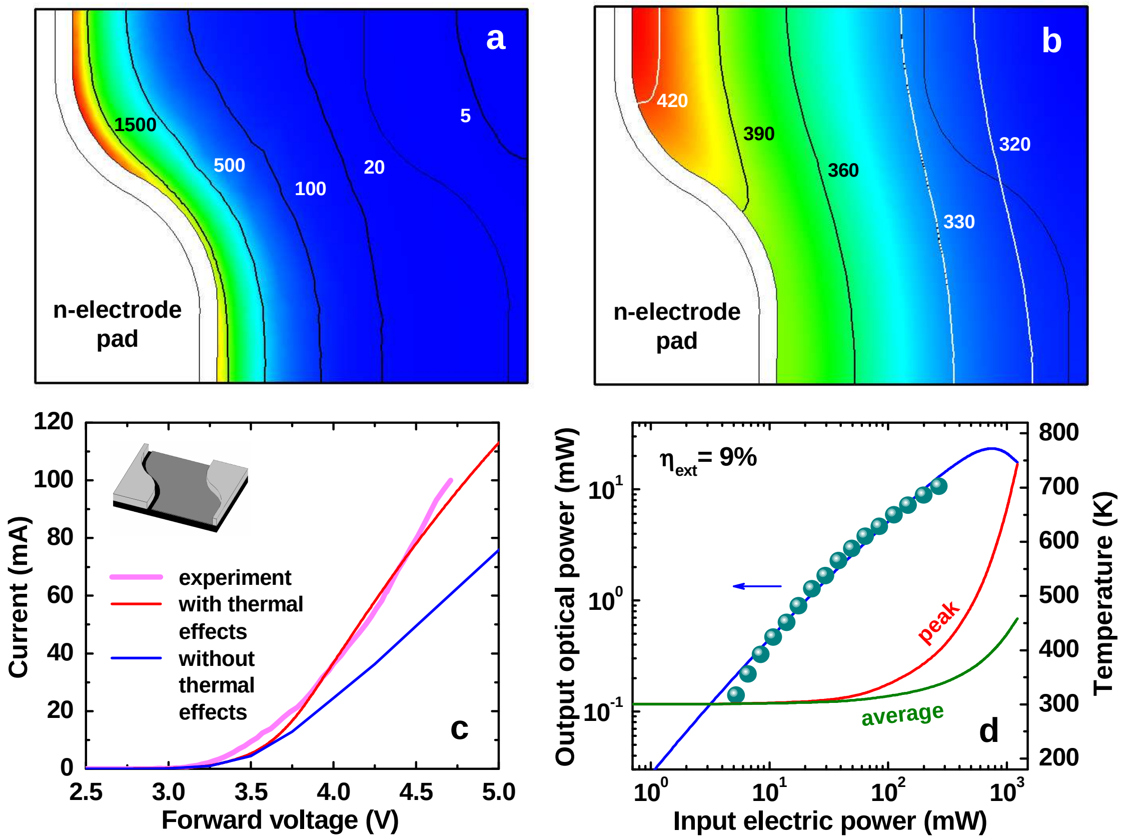

Fig. 2 In-plane distributions and isolines of the current density in A/cm^2 (a) and temperature in K (b) in the LED active region. The colour gradation from black to white indicates a variable increase. The I-V characteristic (c) and the optical output power *versus* the input electric power (d) of the LED. Gray line in (c) and open circles in (d) are experimental data borrowed from [2] and [3], respectively.

According to the hybrid approach suggested in [1], the operation of the LED heterostructure at different temperatures was simulated by the SiLENSe 2.0 package [5] based on a 1D drift-diffusion approach [6]. The results obtained were used to determine the non-linear resistance of the *p-n* junction region and then to perform 3D coupled simulations of the current spreading and heat transfer in the LED die by the SpeCLED 1.1 code [5]. In order to imitate the effect of In composition fluctuations on IQE, the effective threading dislocation density was lowered in the InGaN layers from 10^9 cm^{-2}, the value typical of heterostructures grown on mismatched sapphire substrates, to 10^8 cm^{-2} (see [6] for detail).

3 Results Fig.2a shows the in-plane current density distribution in the active region of the LED corresponding to the current of 80 mA and forward voltage of 4.5 V. The current crowding next to the inter-electrode gap is clearly seen in the figure. 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 (Fig2b), which, in turn, affects the conductivity of the contact layers. The maximum overheating is found to be ~ 120 K for this current.

Fig.2c compares the computed I-V characteristic with the experimental one reported in [2]. One can see that the theoretical curve, accounting for the device self-heating, fits well the measured characteristic. In contrast, the I-V curve ignoring thermal effects predicts a noticeably higher series resistance of the diode. This is primarily because of the neglected influence of temperature on the *n*-contact layer conductivity. The *p*-contact layer is found to provide a minor contribution to the LED series resistance due to its small thickness.

The optical output power of the LED computed on the assumption of the light extraction efficiency from the die to be of 9%, is compared with the experimental data of [3] in Fig.2d. It is seen that the theory reproduces well the sublinear output power dependence on the input electric power. Actually, this corresponds to the commonly observed WPE degradation with current. The detailed analysis of the carrier transport and recombination in the active region of the LED heterostructure has shown two principal reasons for the efficiency degradation: (i) reduction of IQE caused by different temperature dependence of the radiative and non-radiative recombination rates and (ii) the carrier leakage from the active region enhanced by the high current density and temperature. Fig.2d demonstrates, in particular, a correlation between the output power degradation and computed temperature rise in the LED die. Therefore, the current crowding combined with the local active region overheating is a mechanism responsible for the LED efficiency degradation at high currents. This conclusion is in line with the data reported in [7] where improvement of thermal management in the chip resulted in a three-fold efficiency improvement.

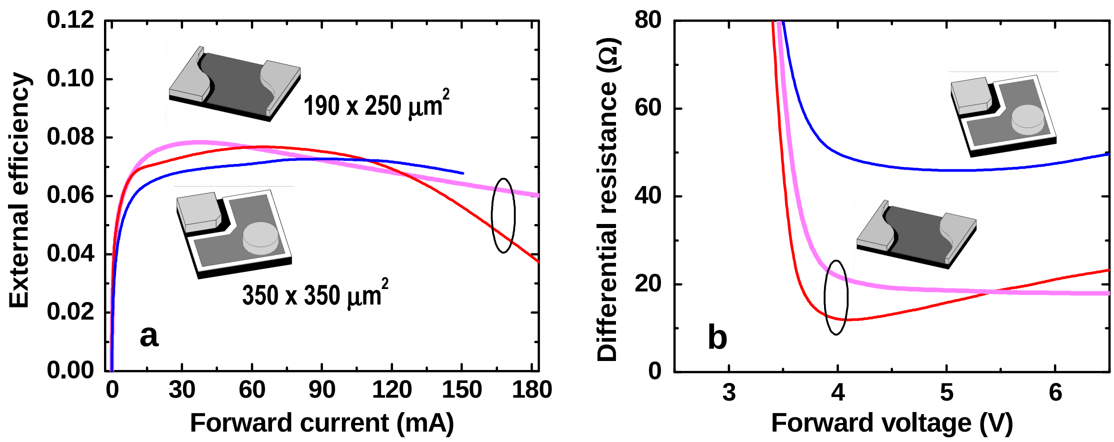

Fig. 3 External quantum efficiency *versus* current (a) and the differential resistance *versus* forward voltage (b) computed for two types of LED die. Dotted and solid lines correspond to the rectangular die and the die shown in Fig.1, respectively. Gray lines present the computations performed, neglecting the thermal effects.

In order to highlight the impact of the electrode configuration on the LED characteristics, two different chip designs have been compared. One is the chip considered above (Fig.1) and another is the 350×350 μm^2 rectangular chip shown schematically in the insets of Fig.3 where the computed external quantum efficiencies as a function of the current and the differential resistances of the diodes as a function of the forward voltage are plotted. In both cases, the same MQW heterostructure described above and the light extraction efficiency of 9% were chosen for simulations.

It is seen from Fig.3a that the external quantum efficiency is weakly dependent on the chip design but is rather controlled by properties of the LED heterostructure. The only difference arises at high-current operation where the heat removal from the active region becomes essential. For both dice, the computed differential resistance first drops down, then reaches a minimum, and then increases gradually with the voltage applied. At a low voltage, the *p-n* junction resistance provides the major contribution to the differential resistance of the diode. Thus the initial resistance drop is caused by a strong decrease in the *p-n* junction resistance with the forward voltage. In contrast, the distributed series resistance of the diode attributed to the current spreading in the *n*-contact layer determines the differential resistance at a high voltage. The computations performed with neglect of the heat transfer in the LED die do not exhibit a gradual increase in the differential resistance (see gray line in Fig.3b). Hence, the resistance increase can be associated with thermal effects.

We would suggest the following mechanism of the series resistance increase at high voltages/currents. The local overheating of the device results in a slight increase of the contact layer conductivity. In turn, this leads to redistribution of the current density in such a way as to reduce the effective area of the current spread in the die (the current crowding becomes more pronounced). As the resistance is in a reverse proportion to the spread area, the total resistance of the diode eventually increases with the forward current.

Fig.3b shows also that the series resistances of two LED dice considered here differ significantly. Despite a larger area of the rectangular chip, it has an approximately two times higher resistance than the chip presented in Fig.1. The detailed analysis has shown that this effect can be attributed to a larger inter-electrode gap in the rectangular die. 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 Summary Using simulations, we have analyzed the current spreading and self-heating effects on characteristics of blue LED dice. Self-heating, as well as the chip design, is found to affect remarkably the I-V characteristic of the diode. In particular, the series resistance of an LED is predicted to vary with current, exhibiting a minimum at a certain forward voltage. A crucial factor determining the series resistance is the width of the inter-electrode gap that can be controlled by the die processing technology. In contrast, the LED external efficiency largely depends on the heterostructure properties, rather than on the chip design. Self-heating of an LED is found to result in remarkable degradation of its external efficiency under high-current operation conditions, i. e. the self-heating is one of the mechanisms responsible for the commonly observed efficiency decreasing with current.

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