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Effect of ITO spreading layer on performance of blue light-emitting diodes

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Operation of blue light emitting diodes with ITO spreading layers of various thicknesses deposited on top of the p-contact layer is considered by simulations. Effects of the ITO layer on the current spreading in and the efficiency of light extraction from the LED dice are examined in detail. The electrical LED parameters, operation voltage and series resistance at a certain forward current, are found to be improved with the thickness of ITO films. In contrast, the optical parameters, external quantum efficiency and output power, become reduced with the thickness because of free-carrier light absorption in the ITO films. These opposite trends make practically unrealistic simultaneous optimization of the electrical and optical parameters by varying the ITO layer properties only. An alternative way is suggested for improvement of the LED performance, based on optimization of light extraction from the LED due to a proper choice of the ITO parameters and of current spreading in the die due to an increase of doping level in the n-contact layer.

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1 Introduction Transparent conductive indium-tin oxide (ITO) is widely employed in III-nitride light emitting diodes (LEDs) as an artificial multifunctional material [1]. First, it can be used as a tunnel contact to p-GaN. Second, ITO is expected to provide a more uniform current spreading in an LED die, since it has the electric conductivity much greater than that of the p-GaN contact layer. Third, substitution of the metallic electrode by ITO avoids the optical losses caused by multiple reflection of the emitted light from the metal-semiconductor interface. Each of the functions utilizes different ITO properties, making non-trivial optimization of the materials parameters and overall chip design.

This paper reports on the comprehensive simulation study of ITO effects on various aspects of blue LED operation and device performance. The focus of the study is made on the current spreading and efficiency of light extraction from the LED die.

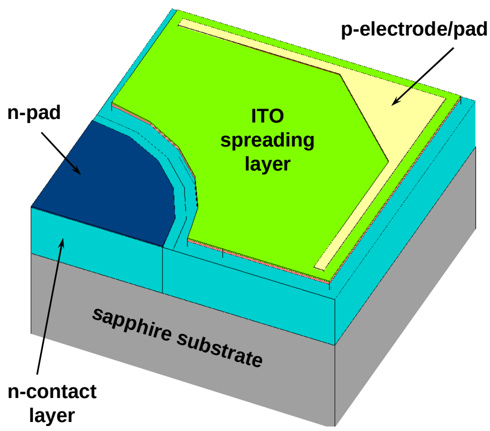

Fig.1 Schematic LED die design.

2 LED structure and chip design We consider in this study a typical blue LED structure consisting of a 3 μm n-GaN contact layer with the electron concentration $n = 1.5\times10^{18}$ cm^{-3} in the basic case, a multiple quantum-well (MQW) active region, and a 40

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nm p-$Al_{0.2}Ga_{0.8}N$ electron blocking layer ([Mg] = 1.5×10^{19} cm^{-3}), followed by a 200 nm p-GaN contact layer ([Mg] = 2.5×10^{19} cm^{-3}). 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 of 450 nm. The structure is assumed to be grown on a sapphire substrate 200 μm thick.

A square-shaped 300×300 μm^2 LED chip analyzed by simulations is shown schematically in Fig.1. A mesa 0.75 μm deep is assumed to be etched through the ITO film, p-contact layer, and active region to form metallic contact to the n-GaN contact layer. ITO spreading layer is deposited on top of the p-contact layer followed by the p-contact electrodes and pad formed on top of the ITO film.

We consider here LED structures operating at room temperature. Though self-heating of LEDs may be noticeable at high current densities, we ignore this effect in our study, as the device heating is controlled by the chip design, rather than by the choice of a particular heterostructure.

Modelling of the LED operation was carried out using the SimuLED package [2] providing coupled 3D analysis of electrical, thermal, and optical processes in the LED die. 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 [3,4]. Optical properties of gold were used in the 3D ray-tracing analysis for both n- and p-electrodes. A thermal resistance of ~40 K/W was used to simulate the heat removal from the LED die.

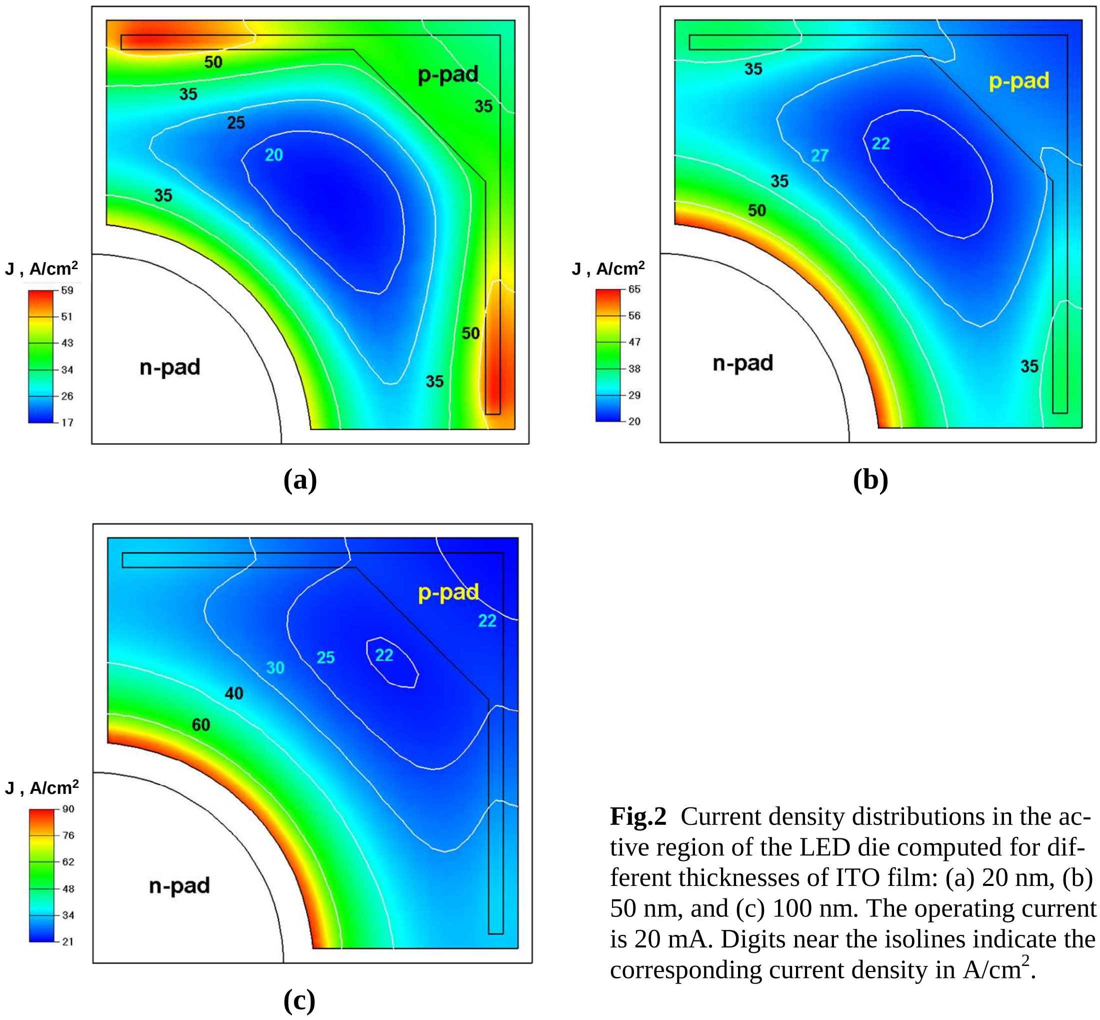

Fig.2 Current density distributions in the active region of the LED die computed for different thicknesses of ITO film: (a) 20 nm, (b) 50 nm, and (c) 100 nm. The operating current is 20 mA. Digits near the isolines indicate the corresponding current density in A/cm^2.

3 Results Coupled 3D modelling of electrical, optical, and thermal processes has been performed for LEDs with ITO spreading layers of various thicknesses, from 20 to 500 nm. Figure 2 shows 2D distributions of the vertical current density in the active region of the LED dice computed for the operating current of 20 mA. One can see a remarkable current crowding near the edges of p-electrode in the die with a thin ITO layer or along the mesa edge next to the n-electrode in the dice with thick ITO film. Transition from one type of distribution to another occurs sharply upon increasing the ITO layer thickness, and the current density never becomes more or less homogeneous. Substantial current crowding reduction can be achieved by increasing the electron concentration in the n-GaN contact layer to ~4-5×10^{18} cm^{-3}. In this case, in particular, the maximum-to-minimum current density ratio falls down from the value of 4.3 typical for LEDs with the low-doped n-contact layer to that of 1.2 (the latter data correspond to the dice with 100 nm ITO film operating at the forward current of 20 mA).

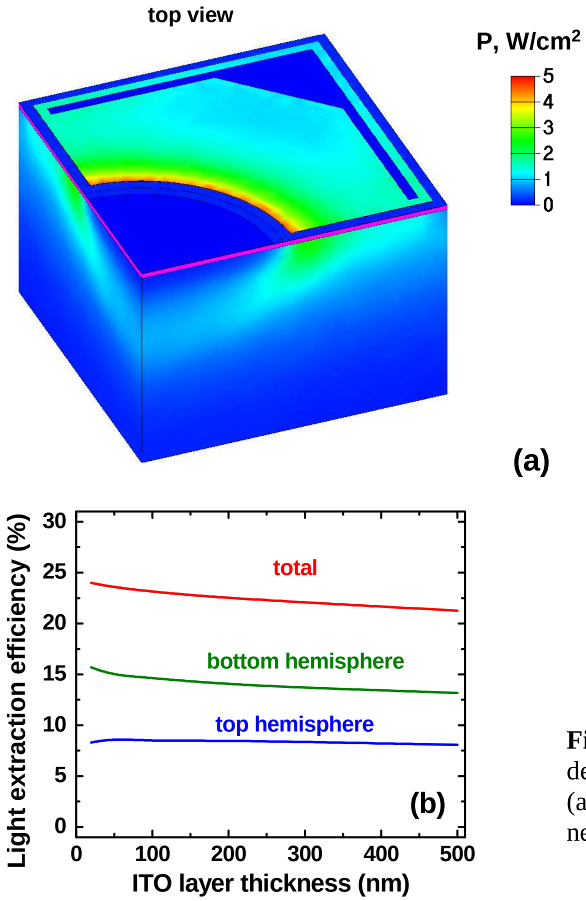

Fig.3 Distribution of emitted optical power density *P* over outer surfaces of the LED die (a) and LEE as a function of ITO layer thickness (b) at the forward current of 20 mA.

Ray-tracing performed in a wide range of the operating current variation predicts dominant light extraction through the side walls and back side of sapphire substrate (Fig.3a). As a result, the power of light emitted to the top hemisphere is ~1.5 times smaller than that of light outgoing to the bottom hemisphere (see Fig.3b).

The total light extraction efficiency (LEE) of the LEDs is found to be practically independent of operating current. LEE slightly decays with the thickness of the ITO film (Fig.3b), which is caused by free-carrier light absorption in the material. Increasing electron concentration in ITO, favourable for current spreading in the LED die, and decreasing electron mobility would enhance the light absorption in the spreading layer, negatively affecting the LEE. In particular, the increase in the ITO electric conductivity from 2000 to 5000 S/cm, keeping the electron mobility unchanged, results in the corresponding increase of the absorption coefficient from 320 to 850 cm^{-1} and, hence, in decreasing of the LEE decay at the ITO thickness of 500 nm from 2.7% to 7.3%. Since both the electron concentration and mobility of the ITO semiconductors may vary in a wide range [1], depending on conditions of their deposition and annealing, the control of these intrinsic materials properties becomes an important factor affecting the overall LED performance.

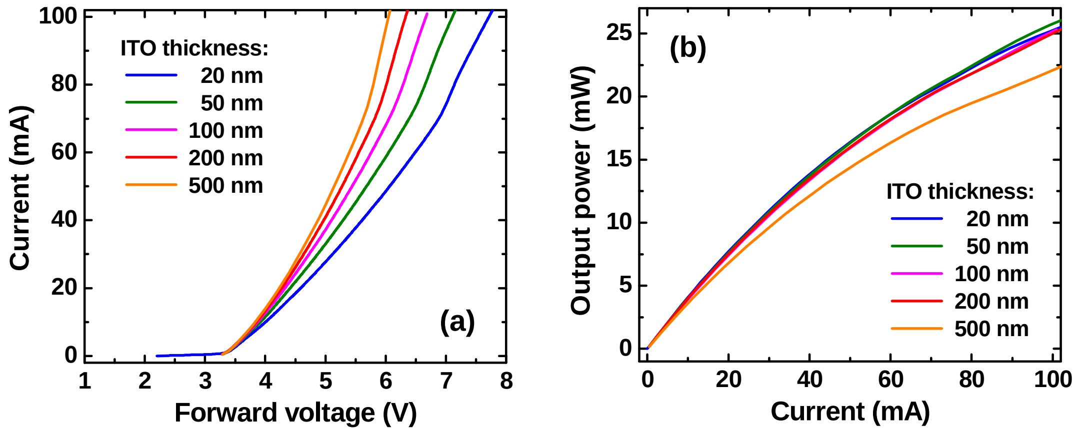

Fig.3 Distribution of emitted optical power density P over outer surfaces of the LED die (a) and LEE as a function of ITO layer thickness (b) at the forward current of 20 mA.

4 Conclusion Using simulations, we have examined the effects of ITO spreading layer parameters on the current spreading in an LED die and its LEE. The ITO thickness is found to affect the 2D current density distribution in the active region but no substantial homogenization of the distribution can be achieved by this way. Much more effective for the current crowding reduction is increasing the electron concentration in the n-contact layer of the LED heterostructure. Both LED operation voltage and series resistance are predicted to be improved at a larger thickness of the ITO film. In contrast, the LED external quantum efficiency and output optical power decrease with the ITO layer thickness. This decrease depends essentially on free-carrier absorption of emitted light in the ITO film. Therefore, an accurate control of the intrinsic ITO properties, like electrical conductivity and electron concentration, is required at the stage of deposition and annealing of the material to optimize the LED performance.

The fact that increasing of the ITO layer thickness results in better electrical but worse optical characteristics enables us to conclude that their simultaneous improvement by optimization of the ITO layer parameters only is practically unrealistic. In our opinion, combination of the LEE optimization by an appropriate choice of the ITO properties with the optimization of the current spreading in the LED die by variation of the n-contact layer parameters is the most effective way for improvement of the LED performance.

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