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IDEALITY FACTOR IN INGAN/GAN MULTIPLE QUANTUM WELL LIGHT-EMITTING DIODES WITH NONUNIFORM CURRENT SPREADING

In this research we demonstrate that a high p-n junction ideality factor (β) in multiple quantum well InGaN-based light-emitting diodes grown on sapphire substrate may be connected to the current crowding effect. This effect is due to the localization of the current flow routes in some regions of a multilayer LED structure whose position are difficult to predict a priori. In lateral structures the current crowding forms regions of high current density in the vicinity of the contacts, resulting in a reduction of the effectively emitting area and the local overheating of the emitting structure. Numerous efforts have been made to identify the effect of the current crowding on the InGaN-based light-emitting diodes performance. Following this tendency, we show that high nonuniformity of current flow can lead to the increasing of the "apparent" ideality factor. This result shows that the ideality factor is not uniquely determined by carrier recombination and transport mechanism in the space charge region as it is predicted by classical one-dimensional theory of p-n junction. The experimental investigation of InGaN blue (λ=460 nm) light-emitting diodes with two different contact geometries confirm that the ideality factor increase from 2.2 (current spreading geometry) up to 3.6 (current crowding geometry). These findings reveal that the ideality factor obtained from I-V measurements in light-emitting diodes employing lateral injection can not be considered as a pure internal parameter of the p-n junction. This the current crowding affected modification of the ideality factor occurs mostly in the intermediate range of current where the space charge region dominates in the light-emitting diodes performance and erroneously could be treated as the change of carrier transport mechanism and carrier recombination nature.

Key words: *InGaN, light-emitting diodes, ideality factor, current crowding.*

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ФАКТОР ІДЕАЛЬНОСТІ В СВІТЛОДІОДАХ НА ОСНОВІ INGAN/GAN КВАНТОВИХ ЯМ З НЕОДНОРІДНИМ РОЗТІКАННЯМ СТРУМУ

У цій роботі ми показуємо, що високе значення фактору ідеальності в світло діодах на основі InGaN, вирощених на сапфірових підкладках, може бути пов'язане з ефектом концентрування струму. Цей ефект виникає внаслідок локалізації ліній протікання струму в деяких областях світлодіодної структури, які важко передбачити a priori. В структурах з латеральною інжекцією ефект концентрування призводить до формування високої густини струму поблизу контактів, що викликає зменшення ефективно випромінюючої прощі та локальний розігрів. Численні роботи були направлені та те, щоб зясувати вплив ефекту концентрування на ефективність роботи InGaN світлодіодів. Слідуючи цій тенденції, ми показали, що значна неоднорідність протікання струму може призводити до збільшення "видимого" фактору ідеальності. Такий результат доводить, що фактор ідеальності не визначається лише механізмами рекомбінації та транспорту носіїв заряду як це передбачається класичною теорією p-n переходу. Експериментальні дослідження InGaN (460 нм) світлодіодів з двома різними геометріями контактів доводять, що фактор ідеальності збільшується від 2,2 (геометрія з розтіканням струму) до 3,6 (геометрія концентрування струму). Ці висновки розкривають фактор ідеальності не як суто "внутрішній" параметр p-n переходу. Модифікація фактору ідеальності під дією ефекту концентрування трапляється, переважно, в проміжному інтервалі струмів, де область об'ємного заряду визначає ефективність роботи світлодіодів і може бути помилково трактована, як така, що виникає в результаті зміни механізмів транспорту і рекомбінації носіїв заряду.

Ключові слова: *InGaN, світлодіод, фактор ідеальності, ефект концентрування струму.*

Introduction

InGaN/GaN multiple quantum well (MQW) LEDs have attracted much attention because of their applications in general illuminations, back lighting and displays. Researches in this field have resulted in a great progress in the material quality, efficiency and lumen output of the nitride-based LEDs. Despite this, there are number of LED parameters which must be carefully determined for further improvement of the device performance. One of those parameters is the *p-n* junction ideality factor (β). According to the classical Sah-Noyce-Shockley theory of the p-n junction under forward voltage, the current is dominated by the recombination of minority carriers in the neutral regions of the junction [1]. This results in the ideality factor equal to β=1.0. One of generalizations of the ideal p-n junction theory takes into account the recombination of carriers in the space charge region. In this case the ideality factor is equal to β=2.0. Both theories can not predict the ideality factors greater than 2.0. However it is well known that in MQW InGaN/

GaN LEDs grown on sapphire substrates β factor has anomalously high value β>>2. High ideality factor results in the increasing of the diode forward voltage and decreasing of the power conversion efficiency. To date, the reason of high β factor is not fully understood and explained. It is believed that β exceeding 2 in InGaN based p-n junctions originates from the trap-assisted tunneling [2, 3], carrier leakage inside the active MQW LED region [4], spontaneous and piezoelectric polarization in the quantum barriers [5] or is due to additional junctions available in the LED circuit [6]. In this work we show that the reason of high ideality factor may be the current crowding effect (CC), which is well known in InGaN/GaN LEDs on sapphire substrate [7,8]. This effect is due to the localization of the current flow routes in some regions of a multilayer LED structure whose position are difficult to predict *a priori*. The numerical simulation and experimental testing of blue lateral LEDs with two different contact geometries indicates the increasing of the ideality factor in the devices with nonuniform current spreading. This the CC affected modification of the ideality factor occurs mostly in the intermediate range of current where the space charge region dominates in the LED performance and erroneously could be treated as the change of carrier transport mechanism and carrier recombination nature.

Experiment and simulation

The objects of our investigation are blue InGaN/GaN MQW LEDs (λ=460 nm) grown on sapphire substrate by the metal organic chemical vapor deposition. Two different electrode patterns are investigated: a conventional *p*-side up bar-shaped structure and *p*-side down flip-chip structure with a wide reflecting *p*-contact (Fig. 1). Both types of LEDs have the same internal structure consisting of an *n*-GaN layer, MQW active region (five QWs and barriers), AlGaN electron blocking layer and *p*-GaN layer. Throughout this paper we refer to the first structure as the current crowding contact geometry and the second structure as the current spreading contact geometry. The measurements of the current-voltage (*I-V*) characteristics have been performed in a pulsed mode with 1% duty cycle and 200 Hz frequency. A small duty cycle was chosen in order to minimize the self-heating effect. The field electroluminescence patterns have been monitored with the optical microscope connected to the CCD camera.

For the numerical simulations of the LED electrical properties we have considered commonly accepted parameters and LED dimensions: *n*-GaN layer (d_n=2.5 μm, n=5×10^{18} cm^{-3}), active layer with nonlinear *p-n* junction conductivity, *p*-GaN layer (d_p=0.1 μm, p=5×10^{17} cm^{-3}), 1×1 mm^2 area. The conductivity of the active layer was represented by using diode-like current-voltage dependence $I=I_0(exp(eV_{a.l.}/\beta kT)-1)$, where I_0 is the saturation current, $V_{a.l.}$ is the voltage drop across the active layer, β is *p-n* junction ideality factor, k is Boltzmann's constant and T is temperature. We suppose that $\beta=2$ (recombination process in the space charge region) [9] and the saturation current $I_0=1.5\times10^{-23}$ A. The contact resistance, unipolar and metal-GaN junction were not taken into account. It was assumed that the electric charges are localized in the space-charge region of the *p-n* junction, that the other regions of a structure are neutral and that the diffusion component of the current in these regions may be neglected. Therefore, the electric potential distribution follows from the Laplace equation $\vec{\nabla}(\sigma(x,y,z,V_{a.l.})\vec{\nabla}\varphi)=0$, while the local current density is connected to the potential gradient via the Ohm law $\vec{J}=-\sigma(x,y,z,V_{a.l.})\vec{\nabla}\varphi$ (where $\sigma(x,y,z,V_{a.l.})$ is the conductivities of the layers). The numerical simulations of the current flow have been performed in 3D mode with the finite element discretization scheme.

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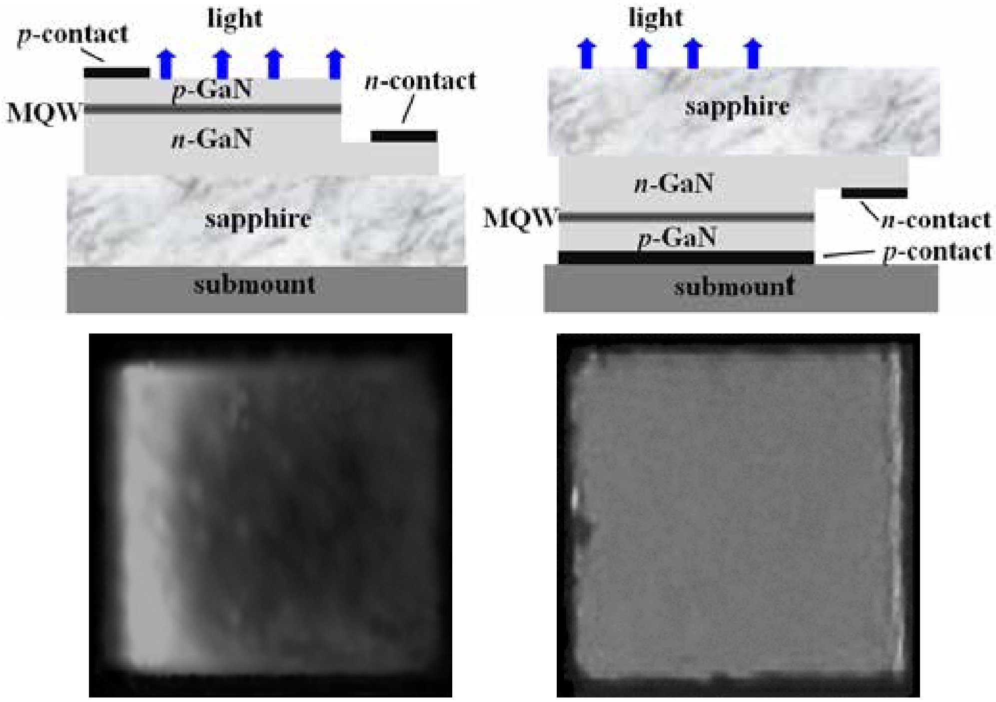

Fig. 1. Schematic representation of the InGaN/GaN LED structures under investigation and spatial distributions of the light emitted by the LEDs at *I*=1 mA: (left) *p*-side up structure (the current crowding contact geometry); (right) *p*-side down flip-chip structure (the current spreading contact geometry)

(where $\sigma(x,y,z,V_{a.l.})$ is the conductivities of the layers). The numerical simulations of the current flow have been performed in 3D mode with the finite element discretization scheme.

Results and discussion

In Fig. 1 it is compared the spatial distribution of the light emitted at I=5 mA by both types of LEDs investigated in this paper. In case of the current spreading geometry whole emitting region emits almost uniformly, which indicates a good current spreading in the active layer. Alternatively, in case of the CC geometry the light spatial distribution becomes remarkably nonuniform even at very low injection levels ($I\approx5$ mA). The experimental forward biased *I-V* characteristics and corresponding ideality factor versus current (β-I) dependences for two LED geometries are plotted in Fig. 2(a, b). Such *I-V* characteristics are typical for the lateral InGaN/GaN MQW LEDs [5, 9]. The high ideality factor in the low current range ($I<10^{-4}$ A) are due to the shunt resistance (that is lower than the *p-n* junction resistance). The shunt resistance has been suggested to originate from the tunneling of carrier [10] and the surface carrier leakage [11]. In this range the ideality factor is almost identical for both geometries. At the high currents ($I>10^{-2}$ A), the ideality factor increases due to domination of the series resistance (R_s). The R_s value is the function of the lengths of the lateral current transport path in both *p* and *n*-GaN layers and thereby will be dependent on the CC. Due to relatively low doping level, low mobility of holes and small thickness of the *p*-GaN layer, this layer is suggested to be responsible for nonuniform current spreading across the LED structure and thus affects the series resistance. Indeed, in the *p*-side up structure the more pronounced CC makes the R_s value (determined via the linear fit from the *I-V* characteristic at the high injection levels) to increase (R_s=3.1 Ω) in comparison with the *p*-side down flip-chip structure (R_s=1.8 Ω). In the intermediate current range (10^{-4} A$<I<10^{-2}$ A), where the space charge region dominates, *I-V* characteristic is approximated by the exponential function and the ideality factor reaches its minimum value. As we can see from Fig.2, this minimum value depends on the LED geometry. In case of the current spreading geometry minimum β value is equal to 2.2 while in the CC geometry $\beta\approx3.6$. Since both *I-V* characteristics in Fig. 2 refer to the same internal LED structure, this modification of the ideality factor connects to the CC and can not be treated as the change of carrier transport mechanism in the space charge region.

To identify whether the CC affects on the ideality factor, the numerical simulation have been performed for both types of the LEDs. For the conventional *p*-side up structure we have performed the simulations with different widths of the *p*-contact from 50 to 900 μm. At I=5 mA in the flip-chip LED the current spreads practically uniform over the whole active layer (the insert in Fig.2(c)). Contrary to that, in the conventional *p*-side up LED, the length of the lateral current path (determined as the distance from the beginning of the *p*-contact to the position where the current density reduces to 50% of the value under the contact) decreases to a value as low as ≈100 μm. The smaller is the *p*-contact width, the smaller is the length of the lateral current path and thus the CC is stronger. In Fig. 2 (c, d) it is presented the simulated *I-V* and *β-I* characteristics for both types of LEDs. Inspection of these results yields that the shorter is the *p*-contact width, the higher becomes the device series resistance (R_s) that dominates in the high current range. While very low in the flip-chip LED (R_s = 0.3 Ω), this value increases by ~12 times in the conventional *p*-side up LED (R_s = 3.5 Ω). At the low currents, when the CC is negligible, all characteristics almost coincide and $\beta \approx 2$ for both LEDs (the shunt resistance was not taken into account in the simulations). However, in the intermediate range the ideality factors are significantly different. Particularly, β≈2.1 for the current spreading geometry and β≈4.0 for the CC geometry. Despite the fact that the simulation was performed with identical internal parameters for all LEDs, the CC makes the "apparent" ideality factor to increase. This result shows that the ideality factor is not uniquely determined by carrier recombination and transport mechanism in the space charge region as it is predicted by classical one-dimensional theory of *p-n* junction.

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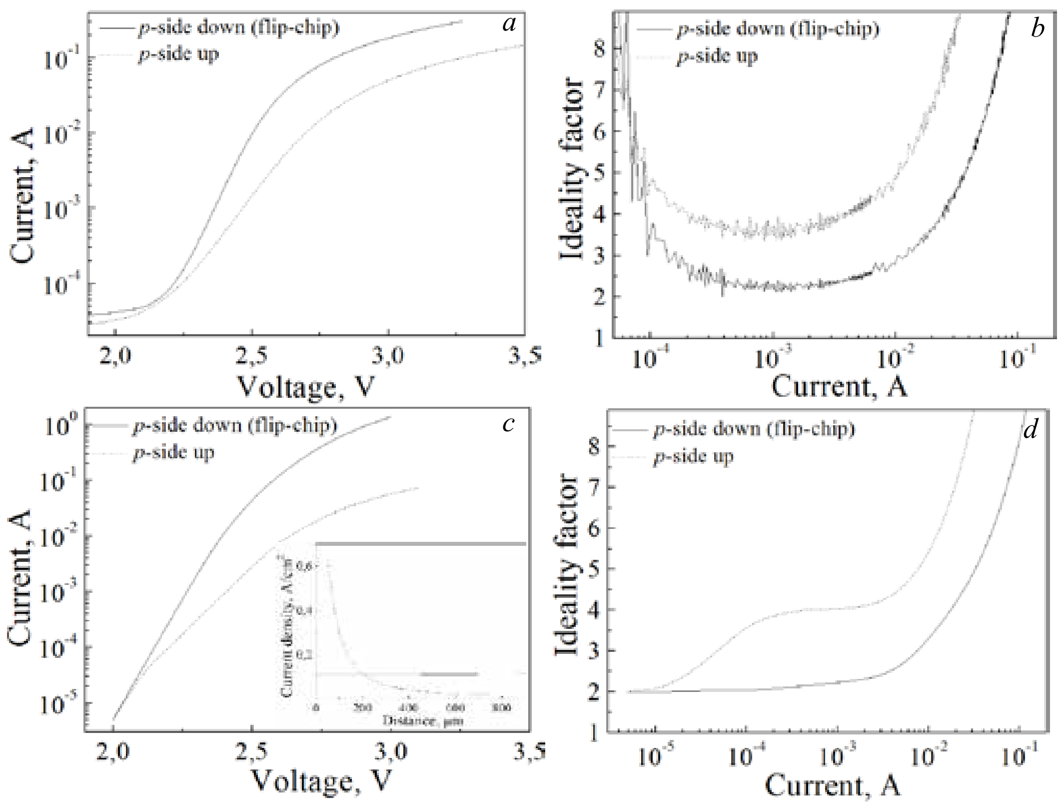

Fig. 2. Experimental (*a, b*) and calculated (*c, d*) *I-V* and *β-I* characteristics of the LEDs: solid lines – *p*-side down flip-chip structure (the current spreading contact geometry); dotted lines – *p*-side up structure (the current crowding contact geometry). The insert in (c) shows calculated local current density distributions in active layers of the LEDs at *I*=5 mA.

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Conclusion

In conclusion, we have investigated the CC effect on the *p-n* junction ideality factor in InGaN/GaN MQW LEDs on sapphire substrate. The results of the numerical simulations and the experimental tests indicate that the measurable ideality factor in LEDs employing lateral injection can not be considered as a pure internal parameter of the *p-n* junction. The CC effect makes the ideality factor to increase (β>2). The classical one-dimensional theory of the *p-n* junction, in which β value is connected to the carrier transport mechanism and carrier recombination nature, can not be applied for LEDs with nonuniform current spreading. We show that the *p-n* junction ideality is not uniquely determined by carrier recombination and transport mechanisms in the quantum well/barrier structure but also depends on the device design.

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