A Novel GaN LED Structure With Both P and N Discontinuous Ohmic Contacts and Discontinuous CBL

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***Abstract*—In this paper, a novel kind of GaN light-emitting diode (LED) with P and N discontinuous ohmic contact electrodes and discontinuous current blocking layer (CBL) is designed and prepared. Multiple contact windows under the N- and P-electrodes formed by etching help realize the discontinuous ohmic contacts with the N-GaN layer and the ITO layer, respectively. Similarly, by etching a plurality of discontinuous openings with the same pitch in the CBL, a discontinuous CBL structure is formed. As compared with traditional structures, the discontinuous ohmic contacts can maximize the number of current paths which allow the carriers to be collected from all four directions, leading to a more uniform current spreading and thermal management. Furthermore, as the contacts are not continuous any longer, some of the otherwise removed materials (such as the active region) lying between the patches are saved. The optoelectronic characteristics, junction temperature, thermal resistance, and infrared thermography measurements are conducted and the current distribution is simulated. The results show that the novel LED structure has better optoelectronic performances and current spreading ability compared to traditional devices. At 150 mA current, the luminous efficiency is 15.2% higher than the traditional LED, the junction temperature is reduced by 4.9%, and the thermal resistance is reduced by 12%.**

***Index Terms*—GaN LEDs, discontinuous ohmic contact electrodes, current spreading, thermal management.**

I. Introduction

IN RECENT years, with the rapid development of semiconductor technology, LED has gradually become the fourth-generation lighting source to replace traditional light sources due to its outstanding advantages such as high efficiency, energy saving, environmental protection, and long lifetime. It has been widely used in solid-state lighting, visible light communication, high-resolution display devices and other fields [1].

In the conventional LED electrode structure, since sapphire is an insulator, a back electrode is not possible unless the sapphire is removed to form vertical LEDs. Therefore, for standard face-up or flip-chip packaged LEDs, a mesa structure usually has to be formed by etching the device so that the P/N-electrode can be on the same side of the wafer. However, since the sheet resistance of the P-GaN is very high, the current crowding effect may occur on the P-electrode side of the LED [1], which causes the LED to emit light and heat unevenly and reduce the life span [2]–[4]. Hence, people come up with strategies to alleviate the problem. Typically, an indium tin oxide (ITO) transparent electrode is used on top of the P-GaN to help spread the current laterally. Furthermore, some authors suggest that the LED structure can adopt an interdigital electrode structure to improve the uniformity of the current distribution [5]. Nevertheless, that will inevitably enlarge the area of metal electrodes. Thus, the drawback is that a part of the light emitted by the recombination of the carriers in the active region right below the P-metal electrode will be absorbed or reflected by the electrode and cannot escape to the external world. Therefore, a local current blocking layer (CBL) structure is added to reduce the light absorption/reflection of the metal electrode [6], [7], which is basically a piece of insulator e.g., SiO_2 inserted just on top of the P-GaN and under the metal to avoid current being injected into this part of the active region below.

These methods work reasonably well, but there is still room for improvement. In 2013, Zhou *et al.* proposed a discontinuous N-electrode and reflective P-electrode structure, which reduces the area loss of the active area and reduces the light absorption of the metal electrode [8]. Under 350 mA injection current, the luminous efficiency is 6.7% higher than that of the traditional LED electrode structure. In 2019 they further proposed an LED structure using periodic ITO patterns and patterned SiO_2 passivation/CBL layers which improves the light extraction efficiency [9]. Lv *et al.* proposed a type of high power InGaN/GaN flip-chip LEDs with via-hole-based two-level metallizatioN-electrodes [10].

One of the rationales for these researches is as follows. The N-electrode and the active region are not vertically overlapping, and thus the current flowing between the two is mainly horizontal. In that case, the edges of the N-ohmic contact become important in terms of offering more paths for collecting the carriers. When a

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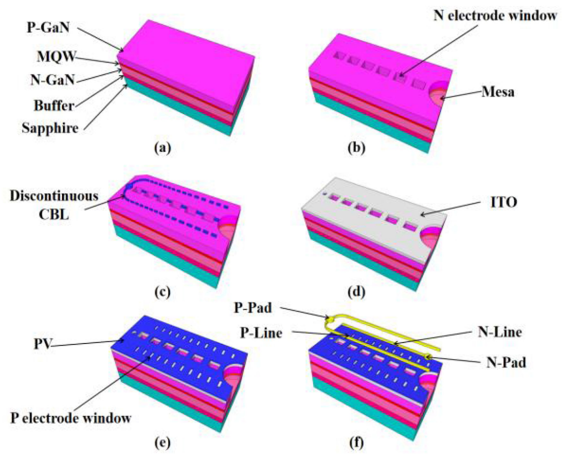


Fig. 1. The manufacturing process of the GaN LED with P and N discontinuous ohmic contact electrodes. PV denotes passivation.

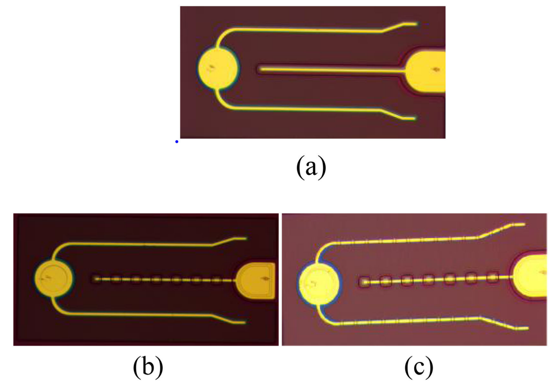


Fig. 2. Top view of the optical microscope diagrams of the (a) LED 1, (b) LED 2, and (c) LED 3. The mesas are 350 μm × 700 μm large.

long stripe of ohmic contact is split into several smaller patches, each piece can collect current from all four directions. Thus, the current profile in the sample is less crowded because of the greater lengths and influences of the edges of the ohmic contacts. When the current is more uniform, not only the lighting efficiency is improved, but also the thermal management is better and the sample will be cooler.

Therefore, in order to further improve the optoelectronic and thermal performance of GaN-based LEDs, this paper prepared a novel device structure with both the P and N ohmic contacts being discontinuous. That is, the N-GaN to metal ohmic contact and the P-GaN to ITO/metal ohmic contact are both discrete. We demonstrate that it has substantially improved the device performances. Furthermore, as the ohmic contacts are no longer continuous, some of the otherwise removed materials lying between the patches are saved. For example, the P-GaN and multiple quantum well (MQW) are only partially etched to form separate windows for contacting the N-GaN below, reducing the active region loss as compared with the conventional scheme. In other words, it maximizes the active region and increases the lighting ability. A discontinuous SiO_2 CBL structure is also introduced under the P and N metal electrodes. Our current distribution simulation and thermal measurement confirm that the new structure indeed improves the current and heat uniformity, respectively. This work demonstrates the advantages of the new device structure, which is of reference value to scientists and engineers in the LED sphere.

II. Sample Preparation

The LED epitaxial wafer structure used in the experiment consists of a 430 μm thick sapphire substrate, a 15 nm GaN buffer layer, a 3.4 μm intrinsic GaN layer, a 2.3 μm N-GaN layer, a 132 nm InGaN/GaN superlattice, 121 nm MQW active layers, an 18.5 nm AlGaN electron blocking layer, and finally a 129 nm P-GaN layer.

The preparation process of the P and N discontinuous ohmic contact electrode LED is shown in Fig. 1: (a) Epitaxial wafer cleaning; (b) Through inductively coupled plasma (ICP) etching, LED mesas (350 μm × 700 μm) with multiple N-electrode contact windows with a size of 15 μm × 17 μm and a spacing of 37 μm are etched from the top P-GaN layer all the way down to the N-GaN layer; (c) A SiO_2 CBL with a thickness of 380 nm is deposited by plasma enhanced chemical vapor deposition (PECVD) onto the P-GaN. Then, it is patterned by photolithography to form a discontinuous CBL. For the CBL under the P-electrode, it is with a pitch of 5 μm and a size of 15 μm × 30 μm. For the CBL under the N-electrode, it lies in between the N-electrode windows. The function of CBL is to avoid the current injection into the semiconductors beneath the ITO, because if it does inject to these areas, the current will be wasted as the photons can hardly emit to the external world due to the blockage from the metal electrodes above. Note that the SiO_2 on the inner sidewalls of the N-electrode windows is also preserved (not shown in Fig. 1(c) for simplicity) for passivation purpose; (d) Grow an ITO film with a thickness of 110 nm on top of the wafer, and then lithographically etch away the parts of ITO that are in the N-electrode contact windows; (e) A SiO_2 passivation layer with a thickness of 235 nm is deposited, and then P-electrode contact windows with a size of 15 μm × 5 μm and a pitch of 30 μm are obtained by photolithography to allow the P-metal to contact the ITO. At the same time, holes are etched in the passivation layer in the N-electrode windows as well, with the SiO_2 on the sidewalls of the N-electrode windows preserved; (f) Sputtering both the P- and N-metal electrodes, which climb up and down the SiO_2 passivation layer, and contacting the ITO and N-GaN in the windows, respectively. For the segments of metal lines that are not in the windows, there are SiO_2 CBL buried right below.

For comparison, we also prepared conventional LEDs with the same epitaxial structure and N-electrode discontinuous ohmic contact LEDs. In this article, the conventional LED is called LED 1, the N-electrode discontinuous ohmic contact LED is called LED 2, and the P and N electrode discontinuous ohmic contact LED is called LED 3. Fig. 2 shows the top view of the optical micrographs of the three LED samples.

III. Measurement and Analysis

A. Measurement of Optoelectronic Characteristics

The optoelectronic characteristics of the three types of LEDs are shown in Fig. 3(a) and (b). Fig. 3(a) is the electrical

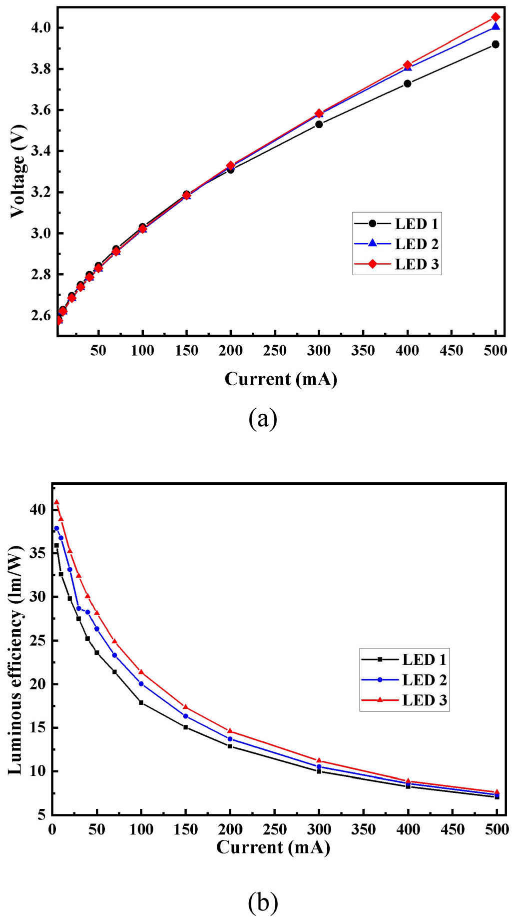


Fig. 3. (a) Forward voltage and (b) luminous efficiency plotted against the current of three types of LEDs.

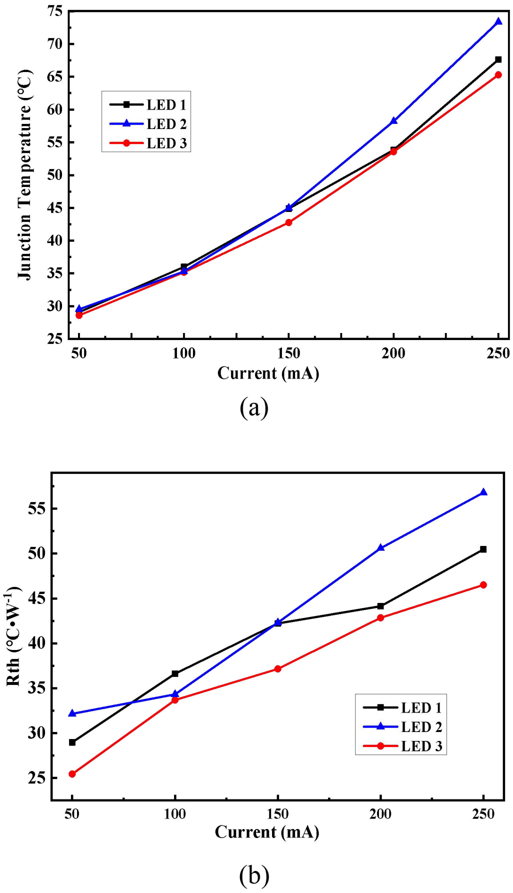


Fig. 4. (a) Junction temperature and (b) thermal resistance plotted against the current of three types of LED.

characteristic curve. At a rated current of 150 mA, the voltage of LED 1 is 3.19 V, which is almost the same as 3.179 V of LED 2 and 3.185 V of LED 3. Nevertheless, when the current is larger, the voltage difference between the three device types gradually increases. This may be because the N-electrode ohmic contact areas of LED 2 and LED 3 are smaller than that of the LED 1, resulting in a slight increase in the device resistance. Compared with LED 2, LED 3 has a further reduced ohmic contact area at the P electrode and, therefore, among the three device types, LED 3 has the highest voltage. Fig. 3(b) shows the curves of the luminous efficiency versus the current. Under the measuring current of 150 mA, the luminous efficiency of LED 3 is 17.34 lm/W, the luminous efficiency of LED 2 is 16.33 lm/W, and the luminous efficiency of LED 1 is only 15.05 lm/W. Compared with LED 1, the luminous efficiency of LED 2 and LED 3 are increased by 8.5% and 15.2%, respectively. The improvement in the light efficiency of LED 2 compared to LED 1 is mainly a result of the increase in the area of the sidewalls. Apparently, LED 2 has more sidewalls than LED 1 due to the opening of the N electrode windows. Since we have properly passivated the sidewalls, the negative effects of the non-radiation centers caused by the dry etching induced defects are very limited. On the other hand, the light extraction surface increases. At relatively small currents, the I-V curves of the two devices are almost the same (see Fig. 3(a)). Therefore, under the same current, the power consumption is basically the same, but the new device shows a higher luminous efficiency due to the larger light extraction. When the current increases, the improvement in luminous efficiency becomes less noticeable because the new device shows a slightly larger power consumption, which to some extent cancels out the effect. Compared with LED 2, the further improvement of the light efficiency of LED 3 is due to the increase of the current path of the device. The discontinuous ohmic contact structure of the P electrode prepared on LED 3 relieves the current crowding around the P-electrode, thereby obtaining a better luminous efficiency.

B. Junction Temperature and Thermal Resistance Measurement

We have performed variable current junction temperature and thermal resistance measurements at 50-250 mA for the three kinds of LEDs, as shown in Fig. 4(a) and (b). At a rated current of 150 mA, the junction temperature of LED 1 is 44.9 °C, and the thermal resistance is 42.22 °C/W. The junction temperature of LED 2 is 44.99 °C, and the thermal resistance is 42.32 °C/W. The junction temperature of LED 3 is 42.76 °C, and the thermal resistance is 37.15 °C/W. Compared with LED 1, the junction temperature and thermal resistance of LED 3 are reduced by

TABLE I
MATERIAL PROPERTIES OF THE SIMULATED STRUCTURE

Material	Thermal Conductivity(W/(m*k))	Resistivity (Ω·m)
Al	237	2.40E-8
SiO_2	1.75	1E14
ITO	8.2	5E-6
P-GaN	175	3.08E-04
MQW	30.1	0.5
N-GaN	175	1.6E-4
Sapphire	35	1E10

4.9% and 12%, respectively, while the junction temperature and thermal resistance of LED 2 have actually increased. This is because, compared with LED 1, LED 2 reduces the ohmic contact area between the N electrode and the N-GaN layer, thereby increasing the resistance of the device and deteriorating the thermal characteristics. Although LED 3 reduces the ohmic contact area between the electrode and the N-GaN layer or ITO layer as well, the P-electrode with discontinuous ohmic contact structure improves the uniformity of the LED current spreading. This reduces the hot spot generation and improves the heat dissipation [11]. The results show that the uniformity of the current distribution has a significant impact on the chip, and the discontinuous ohmic contact structure of the P electrode makes the thermal characteristics of the LED 3 better than the other two LEDs.

IV. CURRENT DISTRIBUTION SIMULATION AND INFRARED THERMOGRAPHY MEASUREMENT

A. Simulation Model and Parameters

In order to further study the superior performance of the novel LED, this paper uses ANSYS software to simulate. Using Solid226 thermoelectric coupling unit, the corresponding model is established in ANSYS APDL and meshed, as shown in Fig. 5.

The material dimension parameter settings of the device model in this article are: LED mesa size 350 μm $\times$ 700 μm, aluminum metal electrodes (2400 nm), SiO_2 passivation layer (250 nm), ITO transparent conductive layer (200 nm), CBL (100 nm), P-GaN layer (200 nm), multiple quantum well (100 nm), N-GaN (2.5 μm), and sapphire substrate (146.6 μm). The numbers in the parentheses are the thickness.

In the model, the resistivity of the P-GaN, MQW, and N-GaN layers is calculated by formula (1):

$$\rho = \frac{1}{\delta} = \frac{1}{nq\mu_n + pq\mu_p} \quad (1)$$

where n is the electron doping concentration (cm^{-3}), p is the hole doping concentration (cm^{-3}), and q is the elementary charge. The electron mobility $\mu_{\rm n} = 1500$ cm^2/V•s, and the hole mobility $\mu_{\rm p}$ = 100 cm^2/V•s. The material parameters in the simulation are summarized in Table I.

In the simulation, the ambient temperature is set to 18 °C, the convection coefficient between the model and the air convection is 10 W/(m^2·°C), and the bottom surface of the aluminum substrate is set to 18 °C. We set all nodes on the upper surface

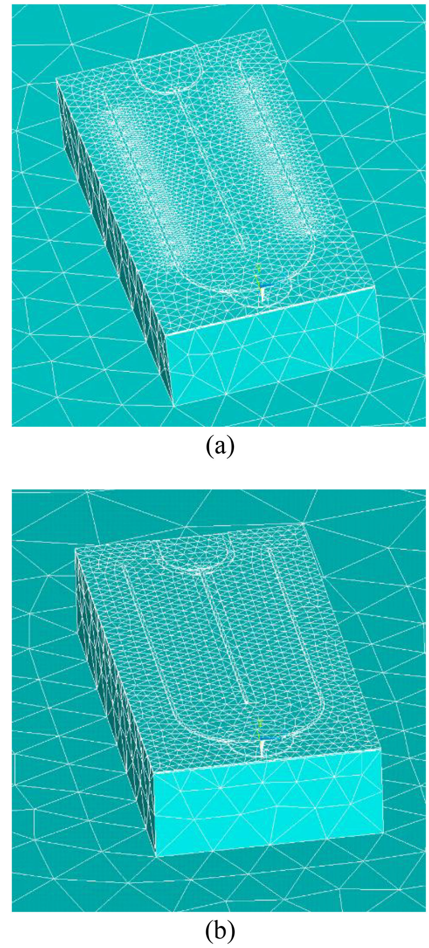
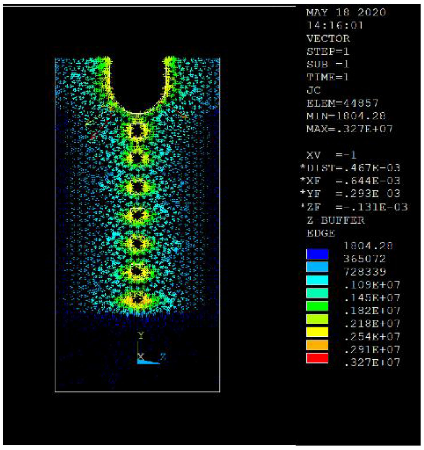


Fig. 5. Meshing models of (a) novel LED and (b) conventional LED.

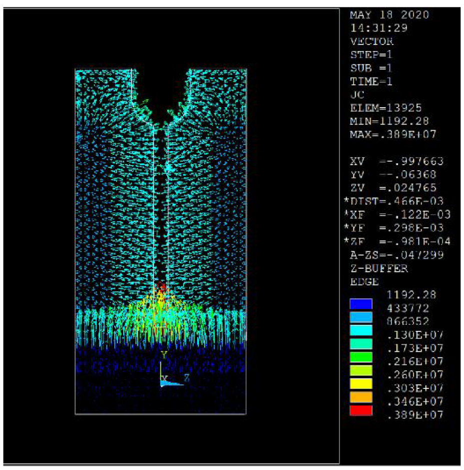
of the P electrode disk to the current coupling mode. When applying a current, set the voltage on the upper surface of the N electrode disk to 0 V, so that the current flows from the P electrode to the N electrode.

B. Current Distribution Simulation

In order to further verify that the novel LED has a better current spreading effect than the conventional LED, a current distribution simulation is performed on the two devices, and their current density distributions are studied. In the simulation, the N-electrode is grounded, and a current is applied, flowing from the P-electrode to the N-electrode. The results are shown in Fig. 6(a) and (b), where the current density vector distribution of the active region of the novel LED and the conventional LED is simulated under the 150 mA driving current. In this figure, it is seen that the current in the active region of the novel type LED is mainly distributed around the N-electrode contact windows, whereas that of the conventional LED is mainly concentrated towards the far end of the N-electrode that is near the P-pad. The simulation results clearly indicate that the current density distribution of the novel LED is comparably more uniform. Therefore, it will lead to a better current injection as well as a better thermal profile.



(a)

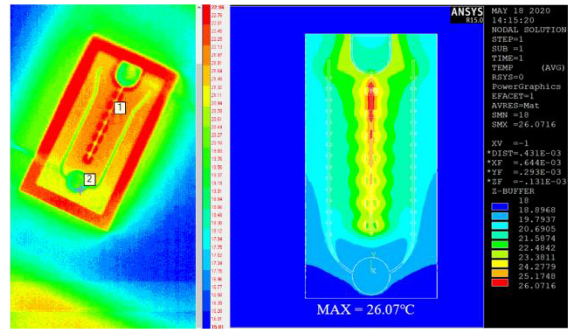


(b)

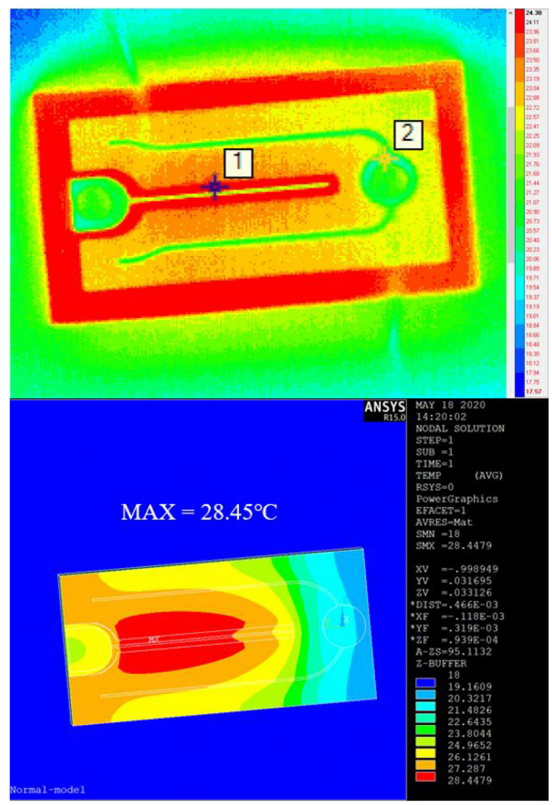
Fig. 6. Vector distribution of the current density in the active region of (a) the novel LED and (b) the conventional LED.

C. Temperature Distribution Simulation and Infrared Thermography Results.

To further analyze the thermoelectric properties of the novel LED and the conventional LED, this paper has conducted temperature distribution simulation and infrared thermography measurements on the temperature distribution of the device under the rated current of 150 mA. The comparison of infrared thermal image and temperature simulation of the two devices at steady state is shown in Fig. 7(a) and (b) (the color bars in the figure represent the temperature, and the marked 1, 2 spots are the positions with the highest temperature and the lowest temperature, respectively). Comparing the infrared thermal image and the temperature simulation chart, it can be seen that the simulation results are consistent with the actually measured temperature distribution profile. The values are similar, which indicates that the simulation model is accurate enough to mimic the actual device working state. From the actual thermal imaging measurement results, it can be seen that the highest temperature spot of the novel LED is located near the N-electrode pad with a value of 23.58 °C, while that of the conventional LED is located near the N-electrode strip, with a value of 25.27 °C. That is, the maximum temperature of the novel LED is 1.69 °C lower than that of the conventional LED. Apparently, this is also due to the novel LED structure designed in this article having a better current distribution uniformity, thereby translating into a better thermal distribution and hence thermal dissipation of the device.



(a)



(b)

Fig. 7. Comparison of infrared thermography and temperature distribution simulation of the novel LED (a) and conventional LED (b).

V. Conclusion

In summary, in this paper, the prepared novel LED with P and N discontinuous ohmic contact electrode and discontinuous CBL structure has been compared with the conventional LED in terms of optoelectronic characteristics, junction temperature, thermal resistance, current density vector distribution, and surface heat distribution. The results show that at a rated current of 150 mA, the luminous efficiency of the novel LED is 15.2% higher than that of the conventional LED, and the junction temperature and thermal resistance are reduced by 4.9% and 12%, respectively, which confirms that the structure proposed in this paper is superior to its counterpart in performance. The improved results are explained by the discrete ohmic contacts that are able to collect currents from all four directions, which leads to an improvement in the current and heat spreading. The reduction of the loss of the active region also makes a contribution. In future work, more detailed analysis is needed to improve the maturity of the technique towards real applications.

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