Theoretical and experimental analysis of the effects of the series resistance on luminous efficacy in GaN-based light emitting diodes*

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In this paper, a new equivalent circuit model of GaN-based light emitting diodes (LEDs) is established. The impact of the series resistance to luminous efficacy is simulated using the MATLAB software. GaN-based LEDs with different n-contact electrode materials (LEDs with Ni/Au and LEDs with Cr/Au) are fabricated. By comparing and analyzing the results of performances, we concluded that both the series resistance and the carrier loss could affect the luminous efficacy severely. LEDs with lower series resistance have higher luminous efficacy and its efficiency droop is alleviated simultaneously. To improve luminous efficacy, the fabrication process should be optimized for lower series resistance.

Keywords: GaN-based light emitting diodes, series resistance, luminous efficacy

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1. Introduction

In recent years, GaN-based light emitting diodes (LEDs) have attracted considerable interest because of its extensive applications, such as traffic signals, outdoor displays, and solid-state lighting.[1–3] However, there are also some problems restricting the development of GaN-based LEDs, one of which is called "efficiency droop",[4] a phenomenon where the internal quantum efficiency decreases severely with the increasing current, which is obvious to power LEDs working at a high current condition. According to Joachim Piprek's[5] model, the carrier loss attributes to the internal quantum efficiency droop. However, the study only investigated current loss in quantum wells; the relationship between the luminous efficacy and the device parameters was not involved. One of the LEDs' parameters, series resistance, which is closely related to heat generation and can be optimized by improving device fabrication, could also lead to luminous efficacy problems. However, there has been no systematic research about the effects of the series resistance on luminous efficacy in GaN-based LEDs.

In this work, we proposed a new model of GaN-based LEDs, in order to calculate and analyze the effects of series resistance on the luminous efficacy, and to obtain consistent experimental and calculation results. The conclusion has an important significance for the device fabrication process, which should be optimized to improve luminous efficacy of LEDs.

2. Theoretical model and simulation

2.1. Wall-plug efficiency $\eta_{\mathrm{wall-plug}}$ and luminous efficacy η

The expressions of wall-plug efficiency and luminous efficacy can be written as

$$\eta_{\mathrm{wall-plug}} = \frac{P_{\mathrm{out}}}{V_{\mathrm{f}} I_{\mathrm{f}}}, \tag{1}$$

$$\eta = \frac{P_{\mathrm{e}}}{V_{\mathrm{f}} I_{\mathrm{f}}}, \tag{2}$$

where P_{out}, V_{f}, and I_{f} are output radiation power (in units of mW), forward voltage, and forward current, respectively, P_{e} is the output light power (in units of lm), V_{f} is the forward operating voltage, and I_{f} is the forward operating current.

For the monochromatic light,

$$P_{\mathrm{e}} = V_{\lambda} P_{\lambda}, \tag{3}$$

where V_{λ} is a function of the wavelength of light and takes different values for different wavelengths of light. If the optical wavelength is given, it is a constant.

For the polychromatic light,

$$P_{\mathrm{e}} = \int V_{\lambda} P_{\lambda} \, \mathrm{d}\lambda. \tag{4}$$

2.2. Wall-plug efficiency and simulation

For a conventional lateral LED grown on an insulting substrate, the cross-sectional view and equivalent circuit are shown in Fig. 1(a), from top to bottom, they are the p-electrode, ITO layer, p-GaN, the quantum well, n-GaN, and the n-electrode. According to the equivalent circuit model proposed by Shah *et al.*,[6] the total series resistances (R_{s}) of the device

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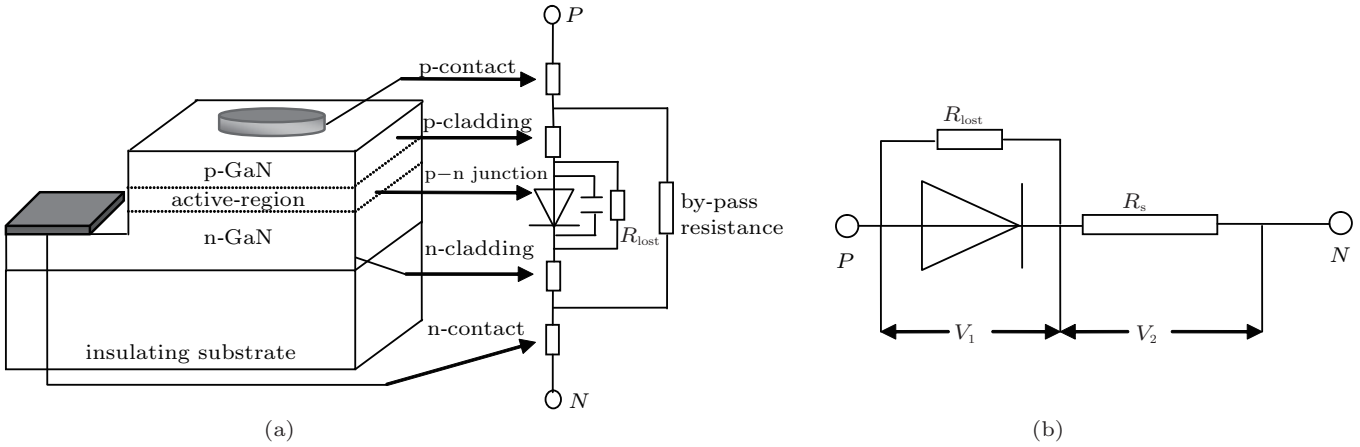


Fig. 1. (a) Schematic view of GaN-based LED structure and the components of series resistance; (b) equivalent circuit of GaN-based LED.

is given by the sum of the resistances from the p-contact resistance, the resistance of the p-cladding layer, the by-pass resistance caused by inductively coupled plasma (ICP), the resistance of the n-spreading layer, the n-contact resistance, and the by-pass capacitor (see in Fig. 1(a)). In addition, the carrier loss caused by non-radiation combination and leakage current could also be equivalent to a resistor ($R_{\rm lost}$). The introduction of a passivation layer would effectively decrease the leakage current of the side wall in LEDs, so the by-pass resistance can be ignored. Furthermore, the by-pass capacitor may not be considered because LEDs keep work under DC. Then a GaN-based LED can be modeled by a diode in parallel with $R_{\rm lost}$ and a series resistor. Such an equivalent circuit is shown in Fig. 1 ($R_{\rm s}$ is the equivalent series resistance consistent of bulk resistance and contact resistance).

According to the equivalent circuit, one part of the bias voltage is applied across the diode, and the other part is applied across the series resistor, that is

$$U = V_1 + V_2. \tag{5}$$

For the diode, the current–voltage (I–V) is given by

$$I = I_{\rm s}\left[\exp\left(\frac{qV_1}{nkT}\right) - 1\right]. \tag{6}$$

Generally, the voltage applied across the diode is far larger than $3KT/q$, thus

$$I = I_{\rm s}\exp\left(\frac{qV_1}{nkT}\right). \tag{7}$$

Therefore

$$V_1 = \frac{nkT}{q}(\ln I - \ln I_{\rm s}). \tag{8}$$

Joule heat generated in the series resistor can be represented as

$$Q = I^2 R_{\rm s}. \tag{9}$$

According to Ref. [7], the carrier loss power dissipation is proportional to the current. Assuming the correlation coefficient is β, $\eta_{\rm wall-plug}$ can be expressed as

$$\eta_{\rm wall-plug} = \frac{UI - \beta I - I^2 R_{\rm s}}{UI} = \frac{U - \beta - IR_{\rm s}}{U}. \tag{10}$$

According to Ohm's law, the voltage applied across the series resistor is given by

$$V_2 = IR_{\rm s}. \tag{11}$$

Combining Eqs. (5) and (7)–(11), $\eta_{\rm wall-plug}$ can be written as

$$\eta_{\rm wall-plug} = \frac{\frac{nkT}{q}(\ln I - \ln I_{\rm s}) - \beta}{\frac{nkT}{q}(\ln I - \ln I_{\rm s}) + IR_{\rm s}}. \tag{12}$$

Finally, the simulation results using the MATLAB software are shown in Fig. 2 (parameter selections: $\beta = 0.45$, $I_{\rm s} = 10^{-7}$, $n = 2.5$, $T = 300$ K, $q = 1.6 \times 10^{-19}$ C). Figure 2 also shows the simulation results of $\eta_{\rm wall-plug}$ with different $R_{\rm s}$, indicating that $\eta_{\rm wall-plug}$ reduces with the increase of $R_{\rm s}$.

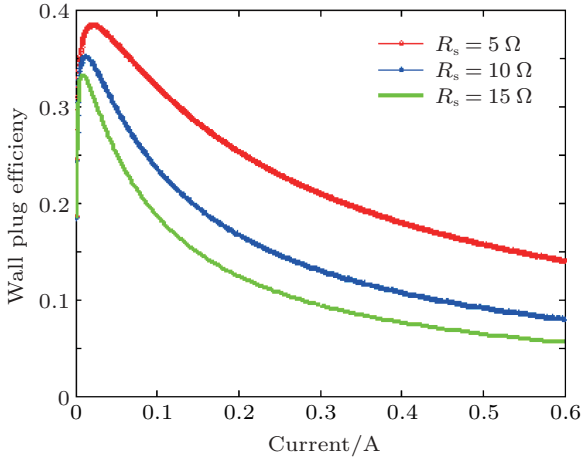


Fig. 2. (color online) Simulation results of $\eta_{\rm wall-plug}$ with different $R_{\rm s}$.

In order to investigate whether the luminous efficacy of LEDs has the same tendency with the simulation of $\eta_{\rm wall-plug}$,

we test the luminous efficacy of an LED with different series resistors. The schematic diagram of the test experiment is shown in Fig. 3(a) and the results are shown in Fig. 3(b), in which external resistors were regarded as R_s. It can be seen that the experimental curves are consistent with the simulational curves.

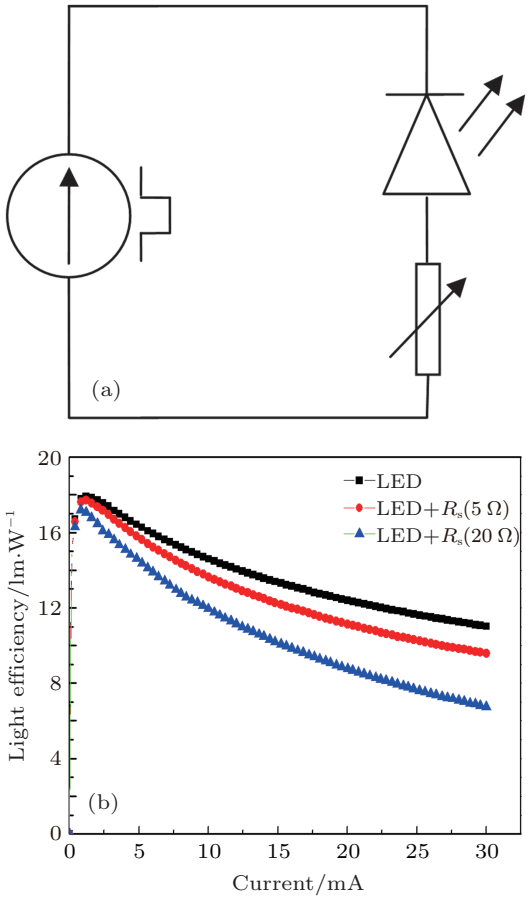


Fig. 3. (color online) (a) Schematic diagram of the verified experiment. (b) The result of the verified experiment.

The simulation and verified experimental results reveal that series resistance of LEDs is an important factor to affect the luminous efficacy of LEDs. Thus reducing the series resistance of the LED can also improve the luminous efficacy of LEDs. The following experiments are designed in the next section to improve the luminous efficacy in the fabrication process of LEDs. Here, we optimize the process by growing different materials electrodes.

3. Experiment

The GaN LED structure used in this study was grown using metal organic chemical vapor deposition (MOCVD) on (0001) sapphire substrates. The LED structure (dominant wavelength at 460 nm) consisted of a low-temperature 100-nm-thick GaN buffer layer, a 2-μm-thick undoped GaN layer, a 2-μm-thick highly conductive n-type GaN layer, a 0.4-μm-thick InGaN/GaN multiple quantum-well active layer, and a 0.6-μm-thick p-type GaN layer. Before deposition of the ITO layer, GaN epitaxial wafers were cleaned with ultrasonic cleaning immersed in the first acetone, and then in an anhydrous ethanol solution, in order to remove the organic contaminations on the surface of the epitaxial wafers, then the GaN epitaxial wafer was boiled for 5 min in aqua regia (HCl: HNO_3 = 3:1) solution, which could not only remove the surface oxide layer, but also increase the concentration of holes in the P surface.[8] After the above process, a thickness of 240-nm ITO was deposited by electron beam evaporation method as a current spreading layer, and then annealed at 550 °C for 30 min, followed by ICP etching. Finally, the wafer was divided into two parts, to deposit Cr/Au (30 nm/300 nm) and Ni/Au (30 nm/300 nm) as electrodes, respectively, and then a passivation layer of 200-nm SiO_2. The chip size was 8 mil×10 mil. The characteristics of current–voltage–light efficiency of the diodes were measured using the HAAS2000 integrating sphere made in Evefine Company.

4. Results and analysis

Both the two LEDs with different electrode materials have the same p-GaN contact with the ITO, otherwise, because of the high conductance of the ITO, the distinction of ITO with different metals can be ignored, therefore, we only measure the contact resistance of n-GaN by using the TLM method. As shown in Fig. 4, both of the two electrode materials possess good ohmic contact with n-GaN. It is also found that LEDs with Cr/Au give an n-GaN contact resistance of 10.5 Ω, which is lower than that (14.2 Ω) of LEDs with Ni/Au. Contact resistance can be described by specific contact resistance (ρ_c), which is proportional to the work function of metal (ϕ_m).[9] Since ϕ_m of the metal Ni is considerably higher than that of Cr, the contact resistance of LEDs with Ni/Au is greater than that with Cr/Au. This analysis is coincident with the results in Fig. 4.

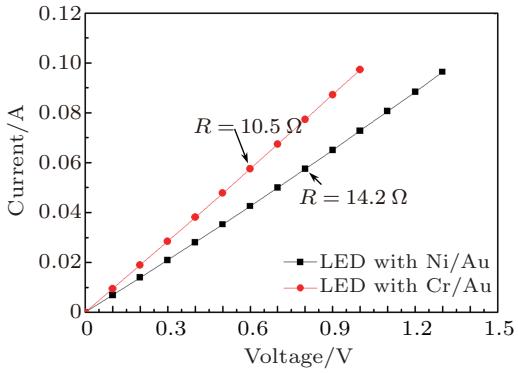


Fig. 4. (color online) Typical I–V characteristics measured with Ni/Au and Cr/Au contacts formed on n-GaN.

The insert of Fig. 5 shows the characteristics of typical current–voltage (I–V). The measured forward voltages under an injection current of 20 mA at room temperature for LEDs with Cr/Au and LEDs with Ni/Au are 3.15 V and 3.4 V, respectively. The series resistance of the two different LEDs is

shown in Fig. 5. Notably, the series resistance of both structures decreased rapidly at low injection current. As we know, the contact resistance does not change with the injection current, however, as to the bulk resistance, the resistivity of which mainly depends on impurity ionization, thus the increase of current causes the rise of the device's temperature and further improves the carrier concentration, so the bulk resistance decreases with the increase of current. Thereafter, the series resistance tends to a constant value since impurities have been all ionized, and the contact resistance turns into the dominant sector of series resistance. In addition, the series resistance of LEDs with Cr/Au is lower than that with Ni/Au, which could be a result of the lower work function of Cr, as mentioned above. On the other hand, after heat treating in air or pure oxygen, the Ni constituent of Ni/Au film transformed to NiO, which has a wide band gap of about 4 eV[10] and high hole concentration. Thus the oxidized film can be considered as a p-type semiconductor, which causes an increase in barrier height.

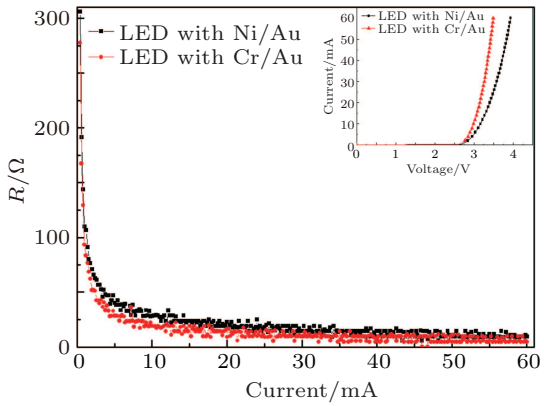


Fig. 5. (color online) Series resistance versus current for the studied LEDs.

The luminous efficacy of the two LEDs structures is shown in Fig. 6. It can be seen that the luminous efficacy rises and peaks at a low injection current, and then drops with the increase of injection current. The peak-efficiency of LEDs with Cr/Au and that with Ni/Au are 8 lm/W and 7.7 lm/W, respectively, and the luminous efficacy of LEDs with Ni/Au decreases more rapidly. Under injection current 20 mA, the efficiency droop is 25.97% of LEDs with Ni/Au, however, for LEDs with Cr/Au, it reduces to 18.75%, which is significantly improved compared with the former.

At a low injection current, the luminous efficacy rises promptly with the increase of injection current, because both carrier loss power dissipation and Joule heat generated by series resistance are so low that the p–n junction converts the most input power to luminous power. With the increase of injection current, the probability of non-radiation combination and carrier leakage in the quantum well are increasing, and the input power consumed by series resistance is growing promptly. Obviously, this part of electrical power has no contribution to the generation of photons. Therefore, the rapid increase of carrier loss and electrical power dissipated by series resistance can result in the decline of luminous efficacy. Otherwise, as stated above, the efficiency droop is also alleviated in LEDs with Cr/Au, and we believe that this improvement is attributed to the lower series resistance.

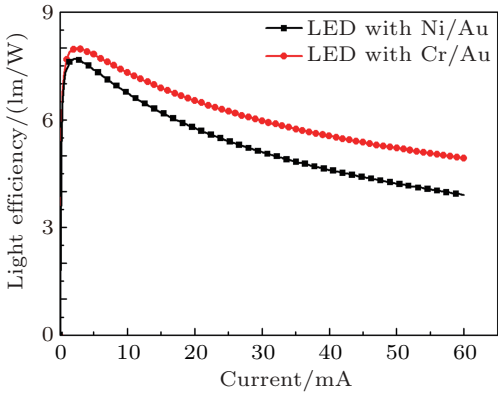


Fig. 6. (color online) Luminous efficacy versus DC current for the studied LEDs.

5. Conclusion

In summary, the impact of the series resistance on luminous efficacy in GaN-based LEDs is investigated. The simulation and experiment results show consistently that LEDs with lower series resistance have better performances in luminous efficacy. The main reasons should be attributed to the power dissipation and temperature increment that are caused by the series resistance. This result confirms the importance of optimizing the LED device fabrication process, so methods such as territory design, anneal condition and materials selection for electrodes should be optimized to reduce the series resistances so as to enhance the luminous efficacy.

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