Current spreading in GaN-based light-emitting diodes*

Qiang Li(李强)[1,2], Yufeng Li(李虞锋)[1,2], Minyan Zhang(张敏妍)[2], Wen Ding(丁文)[1,2], and Feng Yun(云峰)[1,2,†]

[1] *Key Laboratory of Physical Electronics and Devices of Ministry of Education and Shaanxi Provincial Key Laboratory of Photonics & Information Technology, Xi'an Jiaotong University, Xi'an* 710049, *China*
[2] *Solid-State Lighting Engineering Research Center, Xi'an Jiaotong University, Xi'an* 710049, *China*

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We have investigated the factors affecting the current spreading length (CSL) in GaN-based light-emitting diodes (LEDs) by deriving theoretical expressions and performing simulations with APSYS. For mesa-structure LEDs, the effects of both indium tin oxide (ITO) and n-GaN are taken into account for the first time, and a new Q factor is introduced to explain the effects of different current flow paths on the CSL. The calculations and simulations show that the CSL can be enhanced by increasing the thickness of the ITO layer and resistivity of the n-GaN layer, or by reducing the resistivity of the ITO layer and thickness of the n-GaN layer. The results provide theoretical support for calculating the CSL clearly and directly. For vertical-structure LEDs, the effects of resistivity and thickness of the CSL on the internal quantum efficiency (IQE) have been analyzed. The theoretical expression relating current density and the parameters (resistivity and thickness) of the CSL is obtained, and the results are then verified by simulation. The IQE under different current injection conditions is discussed. The effects of CSL resistivity play a key role at high current injection, and there is an optimal thickness for the largest IQE only at a low current injection.

Keywords: current spreading length, light-emitting diodes, indium tin oxide, quantum efficiency

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1. Introduction

Current spreading is an important issue in many light-emitting diode (LED) materials,[1–4] particularly in materials that possess low conductivity.[5] For mesa-structure LEDs, current spreading in the top p-type layer is very weak, owing to the high resistivity of the p-type top cladding layer. This problem has been avoided by a current-spreading layer that spreads the current under the top electrode to regions not covered by the opaque top electrode. Usually, indium tin oxide (ITO) is employed as the p-type current-spreading layer above the p-GaN layer.[6,7] Many studies have analyzed the effects of ITO on current spreading.[8–15] There are also some studies on the effects of the resistivity and thickness of n-GaN on the current spreading length (CSL).[16,17] In this work, the effects of both ITO and n-GaN are taken into account, and a new Q factor is introduced to explain the effects of different current flow paths on CSL.

Vertical-structure LEDs, in comparison to mesa-structure LEDs, have smaller series resistance and better heat dissipation, which can achieve higher current density.[18] It is desirable to maintain high internal quantum efficiency (IQE) even at high current density level, since high IQE is a key factor to promote LED applications and energy saving. However, the current crowding effect starts to impede IQE improvement more significantly under high current injection, among other droop factors.[19] To address this issue, current-spreading layers have been predominantly employed in the top-emitting LED epi-structures. There are many such experimental or simulation-based studies in the literature to date.[20–26] The CSLs with low resistivity are superior to those with high resistivity, and the current spreading capability of thick CSLs is better than that of thin ones. Moreover, there is an optimal CSL thickness corresponding an IQE peak at low current density.[27,28] However, the current-density-dependent behavior of the fundamental parameters of the CSL as well as their impact on IQE in the high current density regime have not so far been well studied and differentiated in the literature. This requires a direct inquiry into the theoretical relationship between, for example, CSL resistivity/thickness and chip-IQE. In this work, we investigated the effect of CSL on the IQE of vertical-structure, GaN-based LEDs, by varying the basic physical properties, such as resistivity and layer thickness, of CSLs.

2. Calculation for different structures

2.1. Mesa-structure LED

The current spreading path and equivalent circuit of the common mesa-structure LED are shown in Fig. 1. The resistance of the current-spreading region along the lateral direction per unit stripe length $\mathrm{d}y$ is given by $R = \rho L_S/t\,\mathrm{d}y$. The current flowing vertically through the junction in the current spreading region is given approximately by $I = J_0 L_S\,\mathrm{d}y$.

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†Corresponding author. E-mail: fyun2010@mail.xjtu.edu.cn

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Using Ohm's law, we obtain

$$\rho \frac{L_S}{t\,dy} J_0 L_S\,dy = \frac{n_{ideal} kT}{e}. \tag{1}$$

Solving this equation for L_S[29]

$$L_S = \sqrt{\frac{n_{ideal} kT}{eJ_0(\rho/t)}}. \tag{2}$$

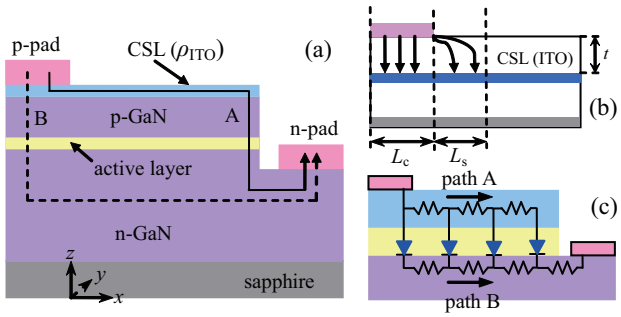


Fig. 1. (color online) (a) Schematic cross-sectional view of mesa-structure B; (b) schematic diagram of current spreading in ITO layer; (c) equivalent circuit consisting of ITO layer resistance, n-GaN layer resistance, and ideal diodes represents the p–n junction.

Shown in Fig. 1(a), paths A and B indicate the extreme current paths from the p- to the n-pad. If only path A (i.e. the effect of the ITO layer) is considered, the CSL can be expressed as

$$L_{S_1} = \sqrt{\frac{n_{ideal} kT}{J_0 e(\rho_{ito}/t_{ito})}}. \tag{3}$$

The same way, if we only consider path B (i.e., the effect of the n-GaN layer), the CSL can be expressed as

$$L_{S_2} = \sqrt{\frac{n_{ideal} kT}{J_0 e(\rho_n/t_n)}}. \tag{4}$$

In fact, path A and B are present in both, and considering the effects of both, the CSL can be integrated as

$$L_S = \sqrt{\frac{2n_{ideal} kT}{J_0 e\left(\dfrac{\rho_{ito}}{t_{ito}} + Q\dfrac{\rho_n}{t_n}\right)}}. \tag{5}$$

Under different conditions, the proportions of paths A and B are not equal; we thus introduce a Q factor, defined as: $Q = \dfrac{\text{Total Current B}}{\text{Total Current A}}$, i.e., $Q = C_B/C_A$. From Eq. (5), we know that the lower the Q factor, the better the spreading effect of ITO.

2.2. Vertical-structure LED

Figure 2 shows a vertical-structure LED with stripe-shaped n-metal. W, t, and d are the width of the stripe-shaped metal, thickness of the CSL, and the total thickness of multiple quantum wells (MQWs), respectively. The level of injected current density can be characterized by the CSL as defined in Eq. (2). When the current spreading length (L_S) is more than 10 times the width of an electrode, the current density level is considered low. However, when L_S is within the width of an electrode, the injected current density level is considered as high. IQE inside the MQW active region is analyzed by means of the well-adopted ABC model, where the current density and the injected carrier concentration are related by

$$J/ed_{active} = An + Bn^2 + Cn^3. \tag{6}$$

For calculation of IQE at different resistivity and thickness of the CSLs, from Fig. 2(b), the total current density J can be expressed as

$$J = J_0 + J_x, \tag{7}$$

where J_0 and J_x are the current density under the contact and in the spreading region, respectively. J_x and J_0 are interrelated, so the expression can be redefined as

$$J = J_0 + kJ_0. \tag{8}$$

Here, k is the correlation coefficient.

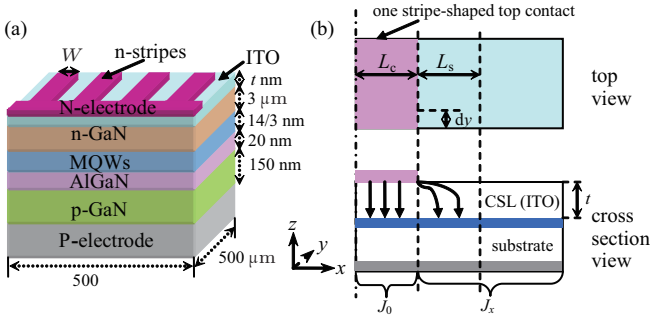


Fig. 2. (color online) (a) Schematic model of a vertical LED chip with a stripe-shaped n-metal. (b) Schematic illustration of current spreading in structure with linear stripe contact.

The current spreading length (L_S) is proportional to the thickness t, and inversely proportional to the resistivity ρ. Thus, k can be defined as

$$k = c_0\sqrt{t/t_0}\sqrt{\rho_0/\rho}. \tag{9}$$

We define $c_0 = L_{S1}/W$, where L_{S1} is the current spreading length at 300 K in the condition of $J_0 = 100$ mA/mm^2, $\rho_0 = 1\times10^{-4}$ Ω·cm, $t_0 = 5$ μm, and $W = 2$ μm. From above, an expression for J is obtained as

$$J = J_0 + J_x = \left(1 + c_0\sqrt{\frac{t}{t_0}}\sqrt{\frac{\rho_0}{\rho}}\right)J_0. \tag{10}$$

3. Simulation and discussion

3.1. Simulation results for mesa-structure LED

The simulation structure is shown in Fig. 1. The LED layer structures are grown on a sapphire substrate. MQW active layers consist of five 2.5-nm-thick $In_{0.11}Ga_{0.89}N$ quantum wells (QWs) separated by 15-nm-thick GaN barriers. Below each MQW layer is an n-type GaN layer, which acts as an n-type current spreading layer. A p-type 20-nm-thick $Al_{0.1}Ga_{0.9}N$ electron blocking layer (EBL) and a 200-nm-thick p-type GaN layer are grown above each MQW layer. The electron concentration at the n-GaN layer and the hole concentration at the p-type layer are set as 5×10^{24} m^{-3} and 5×10^{23} m^{-3}, respectively. The ITO is above the p-type layer, which acts as a p-type current-spreading layer. The thickness of the ITO is 200 nm. In the model, the width of the LED chip is 300 μm, and the widths of the p- and n-electrode are 35 μm.

The effect of n-GaN on current spreading has been simulated, the results of which are shown in Figs. 4(d)–4(f). Only the resistivity and thickness of n-GaN have changed. From Figs. 3(b) and 4(d), the CSL becomes shorter because of doubling the thickness of n-GaN. However, doubling the resistivity of n-GaN increases the CSL, as seen by comparing Figs. 3(b) and 4(e). The CSL is also the same as Fig. 3(b) by doubling the thickness and resistivity of n-GaN, and the result is shown in Fig. 4(f). It seems that above conclusions do not all fit with the theoretical explanation in Eq. (5) ($L_S \propto 1/\sqrt{(\rho_n/t_n)}$), so the Q factor is introduced.

Firstly, the effect of ITO on current spreading is investigated. Figure 3 shows the two-dimensional distribution of current density when the injected current is 300 mA. Figure 3(a) shows the case for an LED chip without an ITO layer. The current is assembled under the electrode, and the current spreading length is very short. Figure 3(b) shows the case for an LED chip with an ITO layer (resistivity $\rho = 3.5\times10^{-6}$ Ω·m, thickness $t = 200$ nm). Here, the current spreading effect is very strong. By comparing Figs. 3(a) and 3(b), the ITO layer has been proven to enhance the current spreading effect.

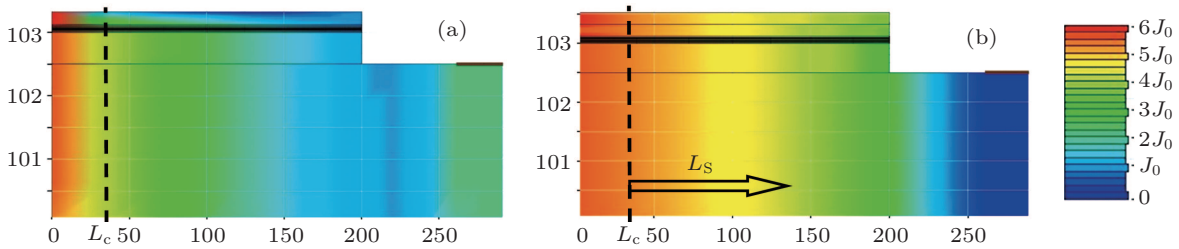


Fig. 3. (color online) Two-dimensional distribution of current density (a) without ITO layer and (b) with ITO layer.

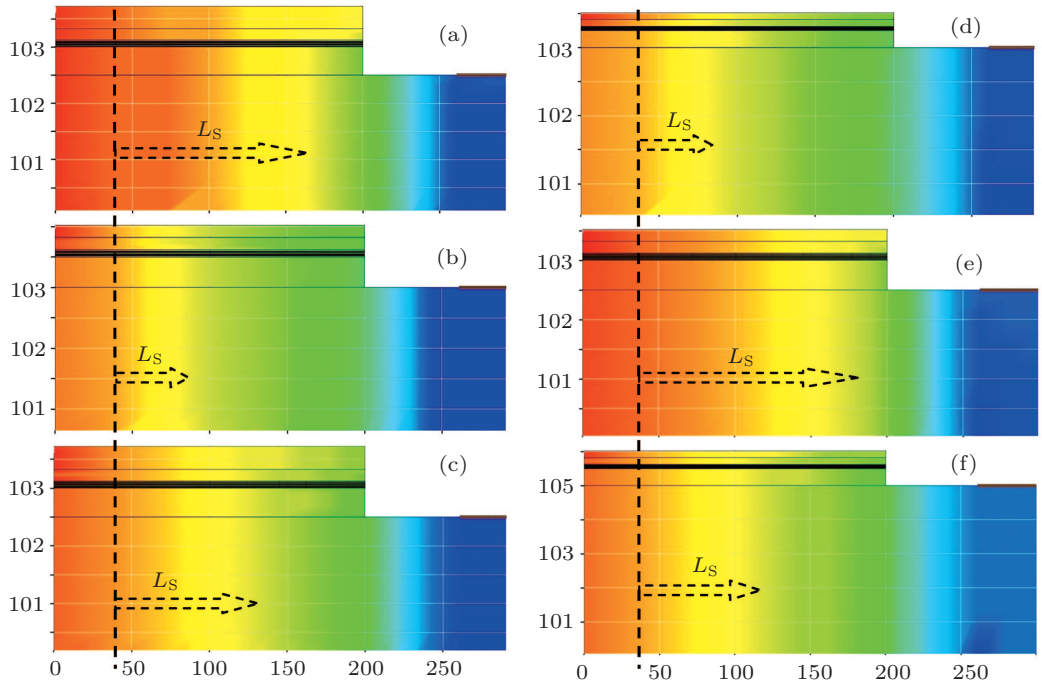


Fig. 4. (color online) Two-dimensional distribution of current density. (a) Only double the thickness of the ITO layer ($\rho_{ito} = 3.5\times10^{-6}$ Ω·m, $t_{ito} = 400$ nm). (b) Only double the resistivity of the ITO layer ($\rho_{ito} = 7.0\times10^{-6}$ Ω·m, $t_{ito} = 200$ nm). (c) Double both the thickness and resistivity of the ITO layer ($\rho_{ito} = 7.0\times10^{-6}$ Ω·m, $t_{ito} = 400$ nm). (d) Only double the thickness of the n-GaN layer ($\rho = 9.09\times10^{-4}$ Ω·m, $t = 5$ μm). (e) Only double the resistivity of the n-GaN layer ($\rho = 18.18\times10^{-4}$ Ω·m, $t = 2.5$ μm). (f) Double both the thickness and resistivity of the n-GaN layer ($\rho = 18.18\times10^{-4}$ Ω·m, $t = 5$ μm).

To verify the effect of resistivity and thickness of ITO layer on the CSL, we consider Figs. 4(a)–4(c). From Figs. 3(b) and 4(a), the CSL becomes longer when the thickness is doubled (for fixed resistivity). By increasing the thickness of ITO, the current spreading effect can be enhanced. The CSL gets shorter by doubling the resistivity (for fixed thickness), and the results are shown in Figs. 3(b) and 4(b). The current spreading effect can be reduced by increasing the resistivity of the ITO layer. When the resistivity and thickness of the ITO layer are both doubled, the result (Fig. 4(c)) is the same as Fig. 3(b). Therefore, the relationship $L_S \propto 1/\sqrt{\rho_{ito}/t_{ito}}$ in Eq. (5) is reliable.

A detailed explanation considering the Q factor is as follows. An increase in resistivity (ρ_n) results in an increase in the equivalent resistance (path B in Fig. 1(a)). The total current B decreases, and then the remaining current A increases. When the injection current is fixed, the Q factor ($Q = C_B\downarrow/C_A\uparrow$) reduced. Despite ρ_n increasing, the final result ($Q\frac{\rho_n\uparrow}{t_n} = \frac{C_B\downarrow}{C_A\uparrow}\frac{\rho_n\uparrow}{t_n}$) is decreased. Based on $L_S \propto 1/\sqrt{Q(\rho_n/t_n)}$, the current spreading length L_S becomes longer. In another case, path B becomes clearer by increasing the thickness (t_n) of the n-GaN layer, because the equivalent resistance of path B is smaller than before. The Q factor ($Q = C_B\uparrow/C_A\downarrow$) becomes larger, which leads to an increase of the final result ($Q\frac{\rho_n}{t_n\uparrow} = \frac{C_B\uparrow}{C_A\downarrow}\frac{\rho_n}{t_n\uparrow}$). Thus, the current spreading length (L_S) has shortened by increasing the thickness of the n-GaN layer.

From the analysis, the theoretical explanation of the effects of the n-GaN layer has been perfected by the introduction of the Q factor.

3.2. Calculation results for vertical-structure LED

The parameters of Fig. 2(a) are used in our calculation, including the n-GaN layer with high conductivity (5 μm, doping 5×10^{18} cm^{-3}) which has the same effect as the CSL in VLED, undoped InGaN/GaN MQWs (14/3 nm, five-period), $Al_{0.1}Ga_{0.9}N$-based EBL (20 nm, doping 5×10^{19} cm^{-3}), and a p-GaN layer (150 nm, doping 5×10^{19} cm^{-3}). The dimensions of the device are assumed to be 200×200 μm^2.

It has been reported that Auger nonradiative recombination plays a major role in the efficiency drop of MQW LEDs at high current density.[25] When the Auger recombination term is not considered, i.e., $C = 0$ in the ABC model, taking $B = 2\times10^{-11}$ cm^3·s^{-1} (at 300 K)[30] and substituting Eq. (10) into $\eta_{IQE} = Bn^2/(J/ed_{active})$,[25,31,32] the result is shown in Fig. 5(a). The IQE of LEDs with CSL is much higher than that of those without CSL at low current density (region I), but in the case of high current density (region III), this effect is diminishing. In order to verify the effect of CSL thickness on IQE, we assume the same CSL material (with fixed resistivity) and increase its thickness by a factor of 10. It is found that IQE is obviously boosted in region I with the CSL thickness increase, while in region III this is not so obvious. Next, when the thickness is fixed and the resistivity increases by a factor of 10, the IQE decreases sharply. Thus, increasing the thickness and decreasing the resistivity of the CSL can both improve the IQE at low current density.

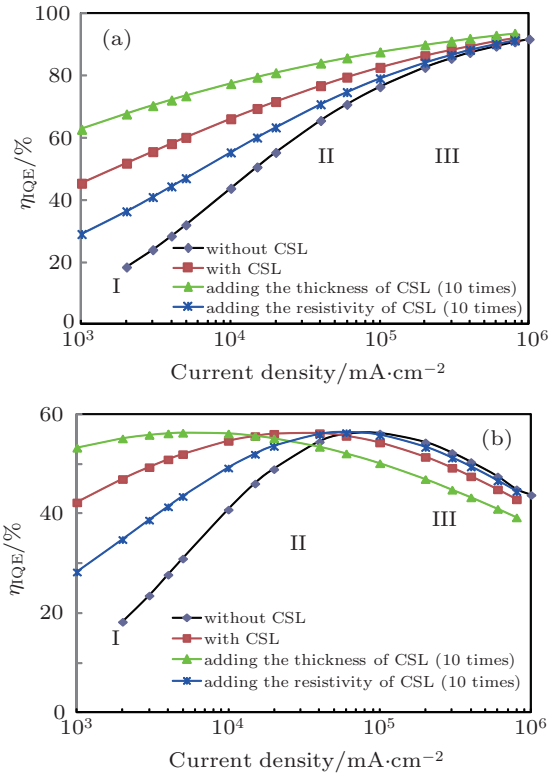


Fig. 5. (color online) Relationship between IQE and current density in the case of changing various parameters. (a) Auger recombination is not considered. (b) Auger recombination is considered. Region I: 10^3–10^4; region II: 10^4–10^5; region III: 10^5–10^6.

Auger recombination is further considered at 300 K, taking $C = 2\times10^{-30}$ cm^6·s^{-1},[30] with the obtained results shown in Fig. 5(b). It is demonstrated that with Auger recombination, IQE has improved significantly with the CSL at low current density (region I), but the efficiency droop is more serious at high current densities (region III), which means that the CSL can, to a certain extent, exacerbate the efficiency droop effect. The effects on IQE by increasing the thickness of CSL are consistent with Fig. 5(a), where Auger recombination was not considered; however, the efficiency droop can be reduced by increasing the resistivity at low current density with Auger consideration.

Equation (10) reveals a more direct relationship between IQE and resistivity/thickness as shown in Fig. 6. It is clear from Fig. 6(a) that increasing the resistivity of CSL has a significant effect in improving IQE at high current injection. In addition, there is an IQE maximum, corresponding to an optimal CSL thickness as depicted in Fig. 6(b). This conclusion of an optimal CSL thickness for IQE agrees well with the reported experimental results at low current density,[33,34] but

further indicates that, when extending the current density level to high injection, this trend does not hold, and the IQE is always decreasing regardless of the CSL layer thickness.

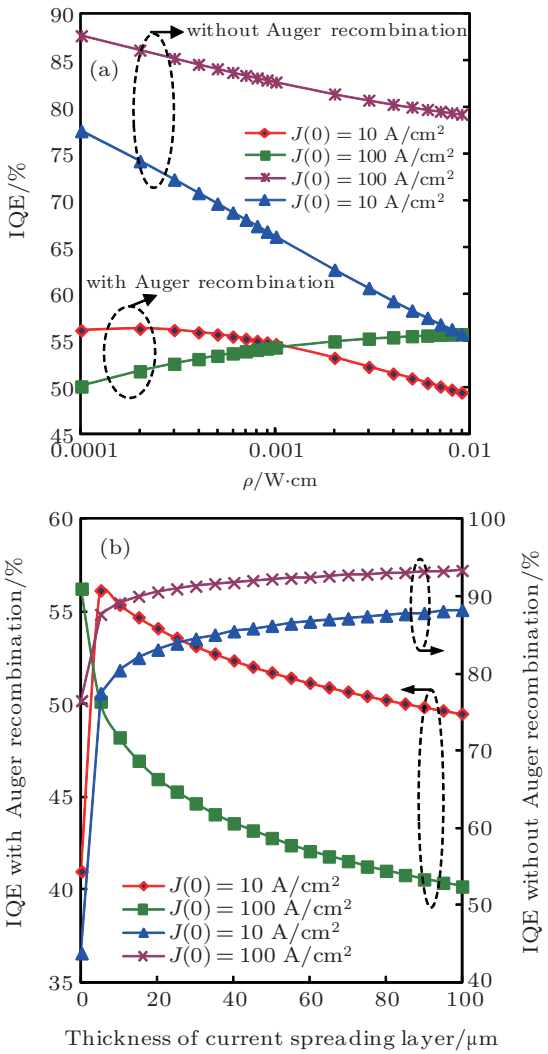


Fig. 6. (color online) Relationship between (a) IQE and the resistivity ρ, and (b) IQE and the thickness t. The $J(0) = 100$ A/cm^2 is defined as high current density, and an order of magnitude smaller than this is defined as low current density. All the data are un-normalized.

In order to further verify the effect of the CSL on IQE in the device (there are defects and dislocations in the device, i.e., considering the electronic leakage), the software APSYS is used to simulate. The simulation results are shown in Fig. 7.

From Fig. 7(a), at low current injection, IQE is very slightly reduced with increasing doping concentration. The inset shows an enlargement of the IQE scale, wherein the trend is opposite that at high current injection. The resistivity of the CSL is mainly determined by the doping concentration, but it is also restricted by the quality of epitaxial growth.[35] In Fig. 7(a), based on the current level of epitaxial growth, when the n-type doping concentration is increased from 10^{18} to 10^{21} cm^{-3}, the corresponding variation range of the resistivity is 2×10^{-4} to 1×10^{-6} Ω·m. Owing to proportionality of the resistivity of n-GaN to the doping concentration, the simulation results are inconsistent with the theoretical calculation results (Fig. 6(a), only considering Auger recombination and ignoring the electronic leakage). It is known that the electronic leakage can be intensified by increasing the doping concentration and current injection.[26] The AlGaN EBL in this model structure (Fig. 2(a)) cannot prevent the electronic leakage effectively at high current injection. From the above analysis, the Auger recombination is not the main reason for droop efficiency; rather, electronic leakage may be the chief culprit at high current injection. We should focus on how to improve the structure of LEDs to prevent the electronic leakage. From Fig. 7(b), an optimal CSL thickness still exists only at low current injection, and the IQE increases and fluctuates marginally at high current density. The effect of CSL thickness on IQE is more obvious at low current injection, which is consistent with the final results from Fig. 6(b).

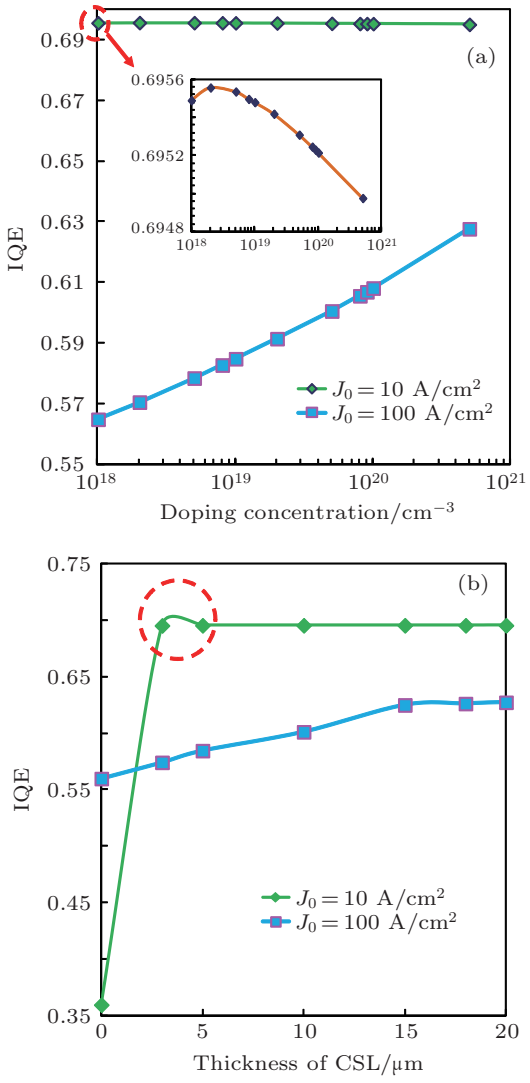


Fig. 7. (color online) The relationship between (a) IQE and the doping concentration, and (b) IQE and the thickness t, based on simulation by APSYS.

4. Conclusion

We have investigated the effect factors of CSL in mesa-structure LEDs. The effect of current spreading can be strengthened by increasing the thickness or reducing the resistivity of the ITO layer. A Q factor has been introduced for studying the effect of the n-GaN layer on current spreading, the value of which can be reduced by increasing resistivity or decreasing the thickness of n-GaN, thereby enhancing the CSL. Finally, the theoretical expressions are verified by using APSYS simulation software. The results of this work provide theoretical support for calculating the CSL of different mesa-structure LEDs more clearly and directly.

Moreover, the theoretical relationship between current density and the parameters (resistivity and thickness) of the CSL is obtained for the vertical GaN-based LEDs. IQE is discussed for different current injection conditions, which increases with the decrease of CSL resistivity and the increase of CSL thickness only in the low current density region. Through calculation with and without Auger recombination, IQE increases steadily and the efficiency droop is reduced with increasing of resistivity of CSL at high current injection; therefore, the effects of CSL resistivity play a key role. Only at low current injection, there is an optimal thickness for the maximal IQE, when the effects of thickness play a dominant role.

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