

Energy band adjustment of 808 nm GaAs laser power converters via gradient doping

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Abstract: The gradient doping regions were employed in the emitter layer and the base layer of GaAs based laser power converters (LPCs). Silvaco TCAD was used to numerically simulate the linear gradient doping and exponential gradient doping structure, and analyze the transport process of photogenerated carriers. Energy band adjustment via gradient doping improved the separation and transport efficiency of photogenerated carriers and reduced the total recombination rate of GaAs LPCs. Compared with traditional structure of LPCs, the photoelectric conversion efficiency of LPCs with linear and exponential gradient doping structure were improved from 52.7% to 57.2% and 57.7%, respectively, under 808 nm laser light at the power density of 1 W/cm².

Key words: gradient doping; laser power converters (LPCs); energy band adjustment; numerical simulation

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1. Introduction

Following the introduction of the concept of a space-based solar power station, wireless energy transmission has once again entered our field of vision. Wireless energy transmission is mainly divided into microwave wireless energy transmission and laser wireless energy transmission. Due to the excellent directivity of lasers, low transmission loss, lack of electromagnetic interference during energy transmission, and compactness of the receiving device, laser wireless energy transmission has potential applications in various fields, such as precision instrument manufacturing and aerospace^[1–6]. Laser power converters (LPCs) are one of the key components of laser wireless energy transmission systems.

To match the material band gap with the laser wavelength, numerous semiconductor materials have been used for different laser wavelength, such as GaAs for 808 nm laser light, InGaAs^[7] and Si^[8] for 1064 nm and GaInAsP^[9] and GaSb^[10] for 1550 nm. Among these materials, GaAs LPCs for converting the power of 808 nm laser light have attracted the most attention thanks to their well-characterized fabrication methods and high conversion efficiency^[11–13].

In addition to the conventional structure^[14,15] of LPCs, numerous optimized structures have been recently reported, such as the no-cap-layer structure^[16] adopted by Khvostikov *et al.*, the selective rear-contact structure^[17] proposed by Hwang *et al.* and the gradient doping structure^[18] mentioned here. From a mathematical point of view, as shown in Fig. 1, there are four shapes of gradient doping structure^[19]. But among them, logarithmic and smooth gradient doping have more than one variable, which is very complicated to sim-

ulate. Consequently, this article only selects linear and exponential gradient doping for discussion.

2. Theory and structure

Owing to their epitaxial characteristics, the previously used LPCs all possess a uniform doping structure, therefore, the energy bands outside of the PN junction are approximately flat. Consequently, the photogenerated carriers generated in these regions are mainly transported via diffusion, which is very inefficient. Furthermore, those carries cannot be separated by diffusion along, resulting in severe recombination in this area. By introducing gradient doping regions into the conventional structure, the energy band can be adjusted purposefully, and forming a stable electric field in the gradient doping region^[18,20]. This electric field can assist the photogenerated electron–hole pairs generated in the gradient doping region in separation and transport, and reduce the recombination rate in these regions, and then improve the performance of LPCs^[21].

To achieve the effect of improving the carrier transport, the energy band needs to be continuously tilted downward from the emitter layer to the base layer^[20]. Therefore, the gradient doping region in the emitter layer and the base layer should be heavy-doped away from the junction region, and as the distance from the junction region gets closer, the doping concentration gradually decreases. The LPC structure used in this article is schematically illustrated in Fig. 2. The area surrounded by the red dotted line is a gradient doped region. The change in doping concentration is indicated by a gradient from green to blue, green indicates the heavy-doped region, and blue indicates the light-doped region. According to the difference of position of the gradient doping region in the emitter layer and the base layer, there are four different structures as shown in Fig. 2. And for linear and exponential gradient doping structure, there are a total of eight different structures (which are discussed in this article).

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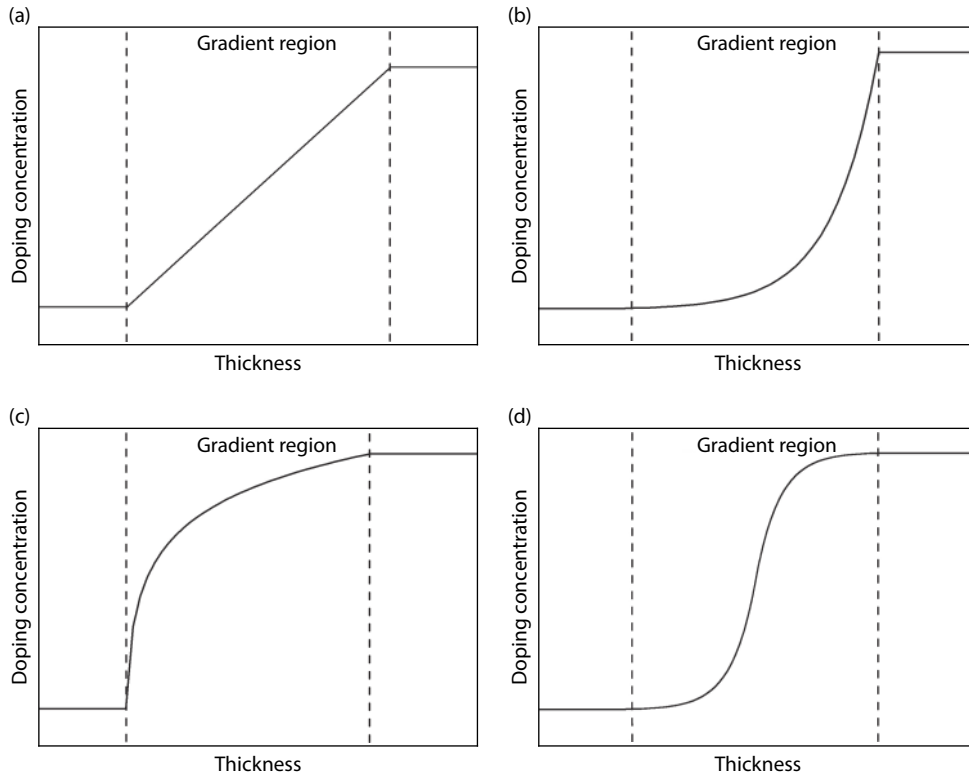


Fig. 1. The shapes of gradient doping structure. (a) Linear gradient doping. (b) Exponential gradient doping. (c) Logarithmic gradient doping. (d) Smooth gradient doping.

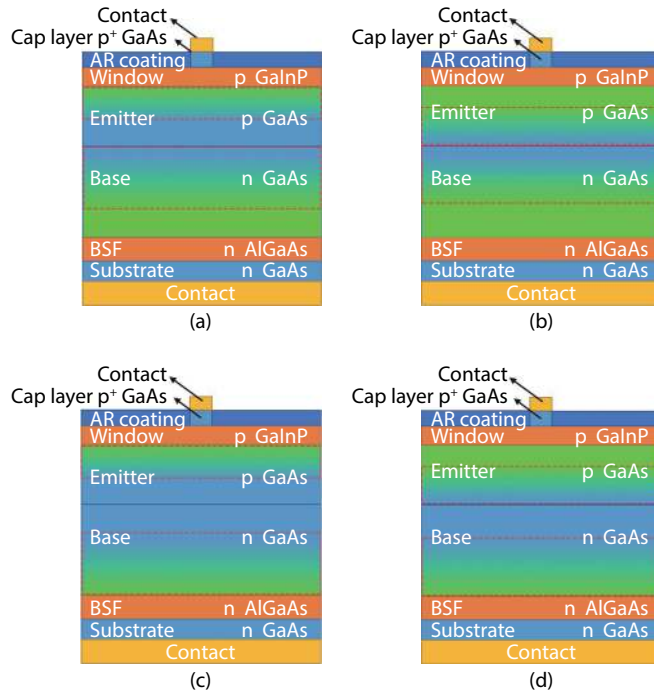


Fig. 2. (Color online) Structures of GaAs LPCs with different position of gradient doping region.

3. Method and discussion

3.1. Simulation method

Silvaco TCAD was used to numerically simulate the structures mentioned above. From a mathematical point of view, there are thousands of specific doping methods for each structure. For calculation convenience and efficiency, we have sim-

plified the discussion process. From the distribution of the recombination rate of the traditional structure (Fig. 3) we know that, the recombination of the base layer is mainly concentrated away from the junction region. When the gradient doping region in the base layer is near the junction region (Figs. 2(a) and 2(b)), the electric field generated by it cannot be effectively applied to the position with a higher recombina-

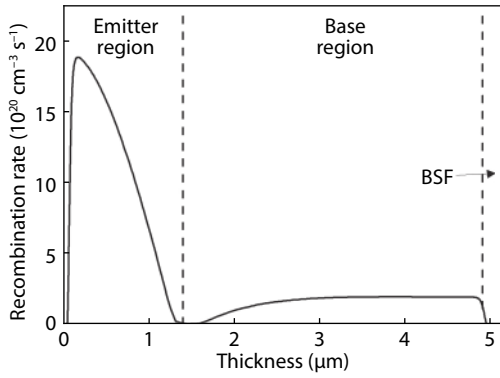


Fig. 3. Distribution of recombination rate in traditional structure of GaAs LPCs.

tion rate. Therefore, in theory, only when the gradient doping region is located away from the junction (Figs. 2(c) and 2(d)), can it effectively reduce the recombination rate, so we only need to discuss this structure later. But for emitter layer, the thickness of the emitter is relatively thin, the electric field generated by the window layer and the junction can extend to the inside of the emitter layer to a certain extent, so it is arduous to infer the optimal position of the gradient doping region in the emitter layer. As a result, both structures near and away from the junction region need to be discussed.

Therefore, the specific discussion method is: In the case where the entire base layer is doped gradually, the optimal doping concentration on the front (the incident surface of the laser) and back surfaces of the gradient doping region is determined first. Subsequently, the optimal thickness of gradient doping region in the base layer (the gradient doping region is away from the PN junction of LPC) is determined by simulation, until now the optimal doping parameters of the base region are maintained. Then, the emitter layer is discussed in the same way, and finally, the best gradient doping structure is determined. (To avoid band offset, the doping concentration of the non-gradually doping region on the front or back side of the gradient doping region is the same as that of the front or back surface of the gradient doping region, as shown in Fig. 1.) Based on the structure that we previously used, taking into account the actual situation and simplifying the discussion process, the doping concentration on the front surface (for convenience, we call it surface EF) of the gradient doping region in the emitter layer and the doping concentration on the back surface (for convenience, we call it surface BB) of the gradient doping region in the base layer are tentatively fixed at 1×10^{17} and 5×10^{18} cm^{-3} , respectively^[18].

3.2. Optimization of the linear gradient doping structure

The simulation results of the base layer of linear gradient doping LPC are shown in Fig. 4. When the entire base layer is doped gradually, as the doping concentration on the front surface gradually decreases (the difference between the doping concentration of front and back surface gradually increases), the photoelectric conversion efficiency of LPC first increases and then decreases (Fig. 4(a)). The highest efficiency is obtained when the doping concentration on the front surface is 3×10^{16} cm^{-3} . This is because as the doping concentration on the front surface of the gradient doping region de-

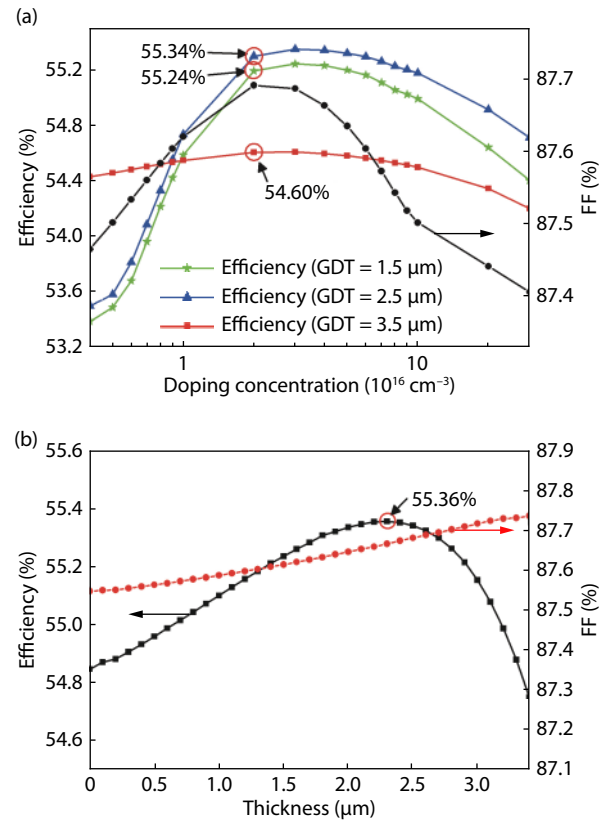


Fig. 4. (Color online) Simulation results of the base layer of linear gradient doping LPC. (a) Simulation about doping concentration when the gradient doping region thickness (GDT) in base layer is 1.5, 2.5, and 3.5 μm . (b) Simulation about the thickness of gradient doping region.

creases, the internal electric field in the base layer increases (Fig. 5(a)), which facilitates the separation and transport of photogenerated electron-hole pairs generated here, The reduction recombination rate of the base layer (Fig. 5(b)), which in turn contributes to the improvement of V_{OC} and FF of LPC. At the same time,

$$V_D = \frac{k_0 T}{q} \ln \frac{N_D N_A}{n_i^2}, \quad (1)$$

where V_D is the contact potential difference of the PN junction, k_0 is the Boltzmann constant, T is the temperature, q is the electronic charge, N_D and N_A is the doping concentration of N and P region, n_i is the intrinsic carrier concentration. It can be known from Eq. (1) that when the doping concentration on the front surface of the gradient doping region decreases, the electric field intensity and the potential difference V_D of the junction region will decrease accordingly, which will lead to an increase in the recombination rate of the junction region and a decrease in the V_{OC} of the device^[21]. Therefore, when the doping concentration on the front surface of the gradient doping region is lower than a certain level, the influence of the junction region on the V_{OC} and FF starts to play a leading role, which in turn leads to the reduction of the V_{OC} and FF of LPC, and ultimately to the reduction of efficiency.

To confirm whether the optimal doping concentration on the front surface (For convenience, we call it surface BF) of gradient doping region in the base layer will change due to the change of the thickness of the gradient doping region, we also simulate it when the thickness of gradient doping re-

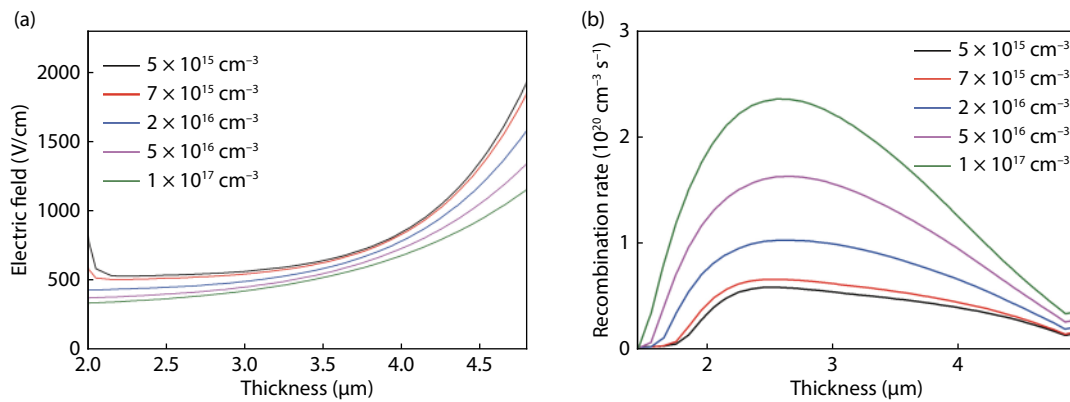


Fig. 5. (Color online) (a) Distribution of electric field in base layer with different front surface doping concentration. (b) Distribution of recombination rate in base layer with different front surface doping concentration.

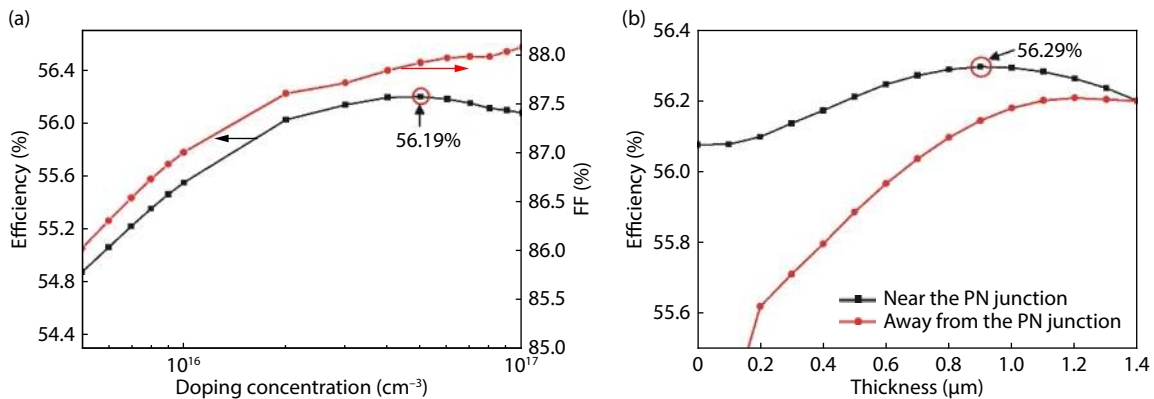


Fig. 6. (Color online) Simulation results of the emitter layer of linear gradient doping LPC. (a) Simulation about doping concentration when the entire emitter layer is doped gradually. (b) Simulation about the thickness of gradient doping region in different position.

gion is 1.5 and 2.5 μm , respectively. The simulation result is shown in Fig. 4(a). It can be seen that the thickness of the gradient doping region does not affect the optimal doping concentration.

When the doping concentration on the front and back surfaces of the gradient doping region is unchanged, as the thickness of the gradient doping region decreases, the gradient of doping concentration in the gradient doping region gradually increases, and the internal electric field will gradually increase. And the photogenerated electron-hole pairs generated here will be more efficiently separated and transported. Therefore, the reduction of the thickness of the gradient doping region is beneficial to the reduction of the recombination rate inside the gradient doping region. But at the same time, the thickness of the non-gradient doping region will increase accordingly. Since there is no electric field in the non-gradient doping region, the recombination rate is relatively high. In other words, as the thickness of the gradient doping region gradually decreases, the overall recombination rate of the base layer will first decrease and then increase, which is obviously reflected in Fig. 4(b). With the gradual increase in the thickness of the gradient doping region of the base layer, the efficiency of LPC increases first and then decreases. The maximum efficiency is obtained when the thickness of the gradient doping region is 2.3 μm .

After the optimal structure of the base layer is obtained, the simulation results for the emitter layer are shown in

Fig. 6. When the doping concentration on the back surface (for convenience, we call it surface EB) of the emitter layer is $5 \times 10^{16} \text{ cm}^{-3}$, and the thickness of the gradient doping region is 0.9 μm (the gradient doping region is close to the PN junction), the highest efficiency obtained is 56.29%.

Since the doping concentration of surface EF and surface BB is tentatively fixed at 1×10^{17} and $5 \times 10^{18} \text{ cm}^{-3}$ before, in order to obtain the optimal doping concentration of them, after the optimal structure of linear gradient doping LPC is determined, we have carried out the simulation under the condition that the thickness and position of gradient doping region are unchanged. The specific simulation method is: The optimal doping concentration of surface BB is determined first, and then optimal doping concentration of surface BF is determined by simulation. As mentioned earlier, the optimal doping concentration of the gradient doping region is independent of the thickness, so there is no need to discuss the thickness of the gradient doping region at this time; then the optimal doping concentration of surface EF and surface EB will be obtained by the same method. The simulation results are shown in Fig. 7. When the doping concentration on the surface EF, EB, BF and BB are 7×10^{17} , 3×10^{16} , 3×10^{16} and $2 \times 10^{18} \text{ cm}^{-3}$, respectively, the highest efficiency obtained is 57.22%.

3.3. Optimization of the exponential gradient doping structure

From the simulation results (Figs. 8 and 9) for exponen-

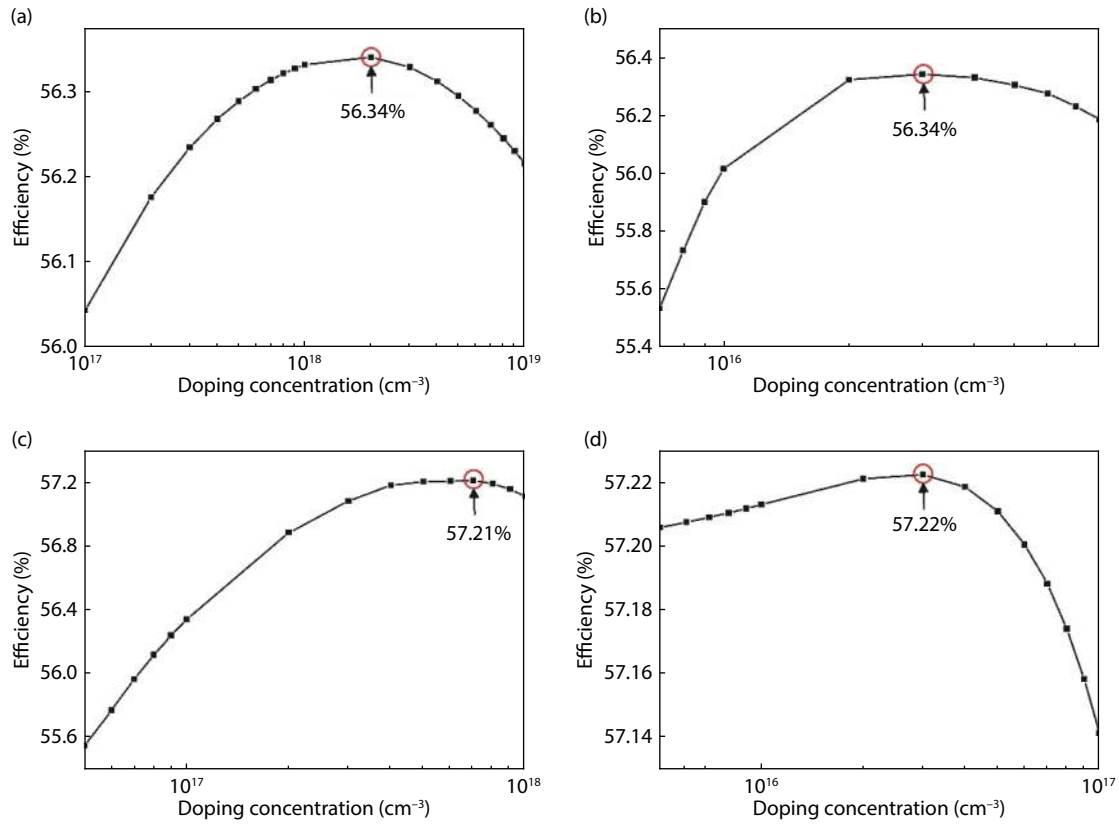


Fig. 7. Simulation about doping concentration on the (a) back and (b) front surface of the gradient doping region in base layer. Simulation about doping concentration on the (c) front and (d) back surface of the gradient doping region in emitter layer.

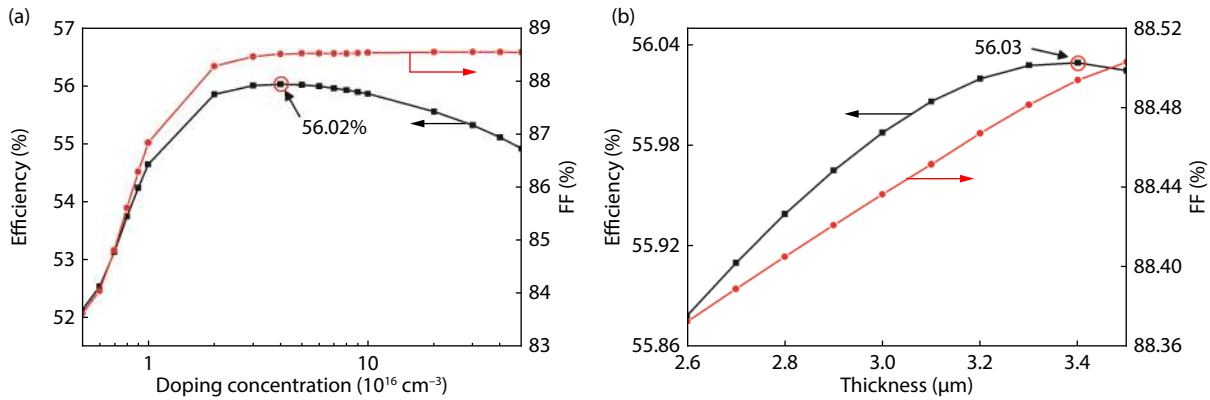


Fig. 8. (Color online) Simulation results of the base layer of exponential gradient doping LPC. (a) Simulation about doping concentration when the entire base layer is doped gradually. (b) Simulation about the thickness of gradient doping region

tial gradient doping structure (for the convenience of comparison, the doping concentration on surface EF and surface BB of exponential gradient doping structure are fixed at 7×10^{17} and $2 \times 10^{18} \text{ cm}^{-3}$, respectively) we know that, because this kind of gradient doping method and linear gradient doping are the same in the mechanism of improving the performance of LPC, the change trends of these two are similar. When the doping concentration on the surface BF is $6 \times 10^{16} \text{ cm}^{-3}$ and the thickness is $3.4 \mu\text{m}$; when the doping concentration on the surface EB is $9 \times 10^{16} \text{ cm}^{-3}$ and the thickness is $1.1 \mu\text{m}$, and the gradient doping region is near the junction, the highest efficiency obtained is 57.65%.

Due to the change rate of doping concentration of exponential gradient doping in the depth of the gradient doping re-

gion is significantly higher than the linear gradient (Fig. 1), in the depth of the gradient doping region, the exponential gradient can generate a larger electric field^[20] (Fig. 10(a)), has the effect of better enhancing the separation and transport of photogenerated carriers and reducing the recombination rate (Fig. 10(b)). Therefore, after performing exponential gradient doping on both base and emitter layer, the device has achieved an efficiency of 57.65%, while linear gradient doping has only achieved a maximum efficiency of 57.22%. It can be seen that exponential gradient doping is more suitable for this kind LPC structure than linear gradient.

4. Conclusion

Through the numerical simulation of LPC with different

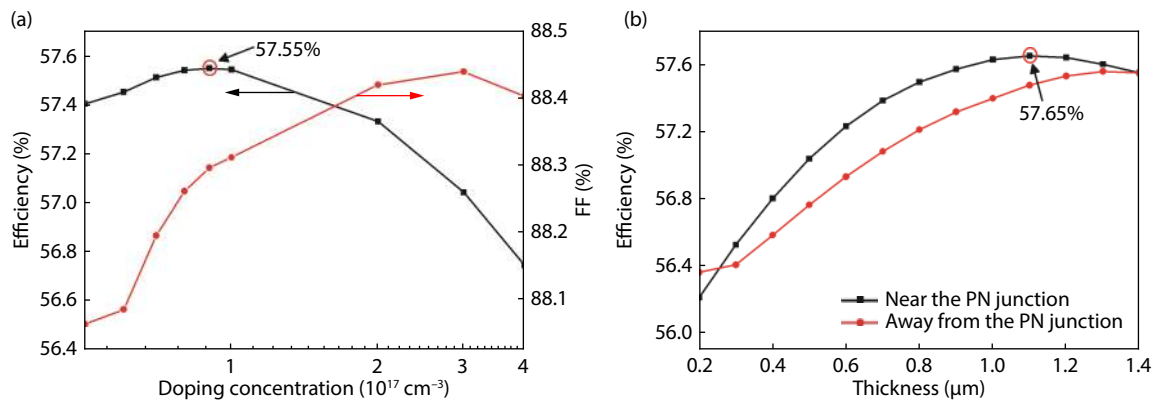


Fig. 9. (Color online) Simulation results of the emitter layer of exponential gradient doping LPC. (a) Simulation about doping concentration when the entire emitter layer is doped gradually. (b) Simulation about the thickness of gradient doping region in different position.

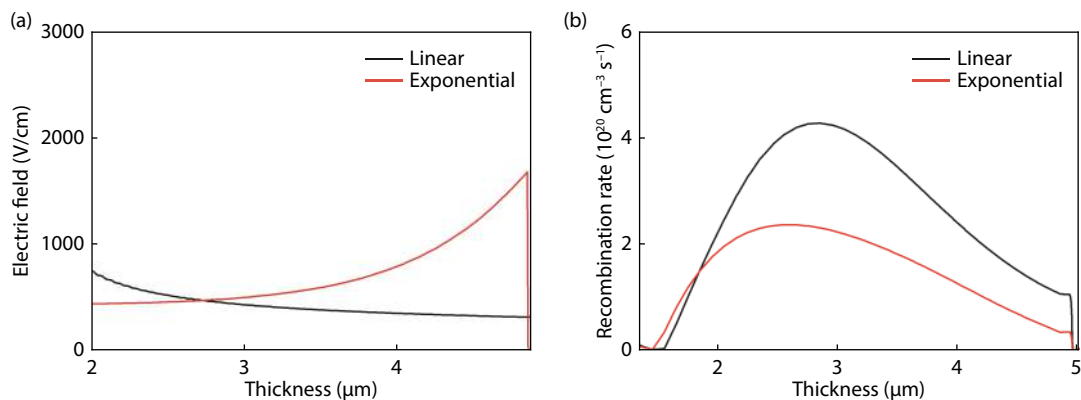


Fig. 10. (Color online) (a) Distribution of electric field in base layer of linear and exponential gradient doping LPCs. (b) Distribution of recombination rate in base layer of linear and exponential gradient doping LPCs.

structures using two shapes of gradient doping methods, linear gradient, and exponential gradient, it is confirmed that the gradient doping method can effectively improve the separation and transport capacity and reduce the recombination rate of photogenerated carriers in the gradient doping region. Furthermore, the photoelectric conversion efficiency of LPC is improved. At the same time, compared to the linear gradient, the improvement of efficiency of the exponential gradient doping structure is more obvious. For exponential gradient doping structure, when the doping concentration of surface BF and surface BB are 6×10^{16} and $2 \times 10^{18} \text{ cm}^{-3}$, respectively, the thickness is $3.4 \mu\text{m}$, and the gradient doping region is away from the junction region; the doping concentration of surface EF and surface EB are 7×10^{17} and $9 \times 10^{16} \text{ cm}^{-3}$, respectively, and the thickness is $1.1 \mu\text{m}$, and the gradient doping region is close to the junction region, an efficiency of 57.65% is obtained.

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