Internal quantum efficiency drop induced by the heat generation inside of light emitting diodes (LEDs)*

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The reasons for low output power of AlGaInP Light Emitting Diodes (LEDs) have been analysed. LEDs with AlGaInP material have high internal but low external quantum efficiency and much heat generated inside especially at a large injected current which would reduce both the internal and external quantum efficiencies. Two kinds of LEDs with the same active region but different window layers have been fabricated. The new window layer composed of textured 0.5 μm GaP and thin Indium-Tin-Oxide film has shown that low external quantum efficiency (EQE) has serious impaction on the internal quantum efficiency (IQE), because the carrier distribution will change with the body temperature increasing due to the heat inside, and the test results have shown the evidence of LEDs with lower output power and bigger wavelength red shift.

Keywords: AlGaInP light emitting diodes, internal quantum efficiency, heat, light power

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1. Introduction

Visible-spectrum AlGaInP-based light-emitting diodes (LEDs) are promising candidates in future solid-state lighting.[1] As the technique of material growth and device fabrication has developed a lot, LEDs' light efficiency has been improved by about thousand times; the application field has extended to large-scale display, car lighting, indicator, signal lamp, background source light and general illumination. LEDs have a brilliant future to be the light source of the forth generation solid-state illumination.[2] Now, the internal quantum efficiency (IQE) of LEDs with AlGaInP material is as high as 95%. A significant challenge in the development of high efficiency and high-power AlGaInP LEDs is the extraction of light emitted from the semiconductor into the surrounding media.[3−8] In this study, we have found that low EQE has a serious impaction on the IQE, it is provided experimentally with two kinds of LEDs which have the same active region but the different window layers, it is to say that the two kinds of LEDs with the same IQE but different EQE at the same injected current. The results have shown that low EQE would cause LEDs to generate much heat inside and thus make the device body temperature rising, which would reduce the IQE and cause the emitting wavelength longer for the LEDs with AlGaInP material. If the IQE reduces, the EQE is decreased furtherly, which forms a vicious circle, especially in the case of large injected current.

2. Experiment details

Two kinds of LEDs have been fabricated and they have same active region but different window layers which are grown by the metal organic chemical vapour deposition (MOCVD). Both substrate and buffer layer are GaAs. The active region is multi quantum well of $(Al_xGa_{1-x})_{0.5}In_{0.5}P$ doped unintentionally, and above the buffer layer is a distributed bragg reflector (DBR) used to reflect light to the topside which would emit to the substrate and be absorbed absolutely. The upper and lower cladding layers are $(Al_{0.7}Ga_{0.3})_{0.5}In_{0.5}P$ doped by Mg and Si respectively. The top window layer is GaP with the doping levels up to about $10^{19} - 10^{20}$ cm^{-3}, a thickness of 8 μm for sample A and 0.5 μm for sample B respectively.[9]

In this study, sample A has the conventional structure with a 8 μm GaP window layer only, as shown in Fig. 1(a). Figure 1(b) shows the side view of sample B after dicing process, which has a multiple window layers composed of textured 0.5 μm GaP current spreading layer and a thin conductive Indium-

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Tin-Oxide (ITO) film. Since the textured GaP surface would change the route of light emitting to the top-side, much more light generated inside will find the emitting cone and emit outside at last. The ITO film with the refraction index of $n \approx 1.7$ is between air and semiconductor to ensure the most of light emitting outside and less heat generated inside.[10] The sample B has larger extractive efficiency than sample A. The two samples are packaged by epoxy colophony and both with the same chip size of 8 mil by 8mil (1 mil = 25.4 μm), working at the injected current of 20 mA.

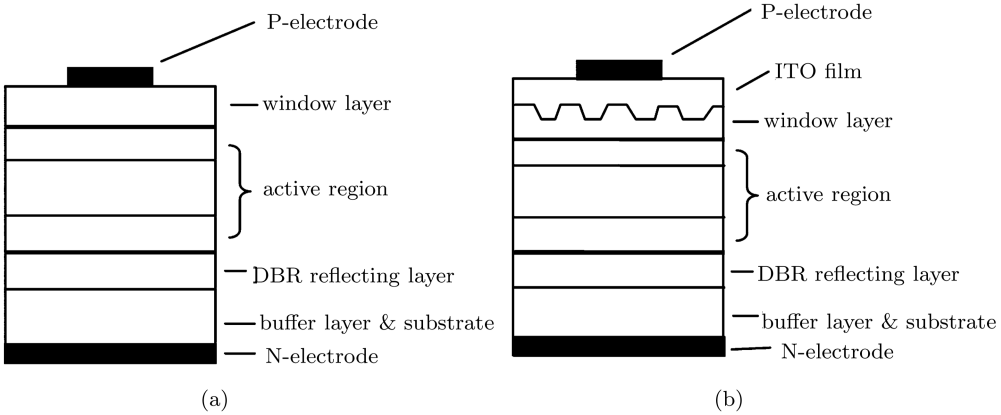


Fig. 1. The device schematics of (a) sample A and (b) sample B.

3. Results and discussion

Measurements are performed for samples A and B. The results as shown in Fig. 2 indicate that the performance of sample B is better than sample A. The output power and EL spectrum distribution are both measured by PMS-50 Plus UV–VIS–Near IR spectrophotometer provided by EVERFINE PHOTO-E-INFO CO., LTD. The output powers of sample A and B are about 6.4 mW and 8.2 mW respectively at 20 mA. Their saturation currents are 80 mA and 100 mA corresponding to the output power of 16.8 mW and 25.2 mW respectively, which shows that sample B has lager EQE than sample A at the condition of having same active region but different window layers. For sample A, a large part of injected current changes into heat which would decrease the light efficiency furtherly. In Fig. 3 the luminous efficiencies decrease with the current increasing for both two samples, but the luminous efficiency of sample B is larger than sample A. Figure 4 is the I–V results measured by the LED Luminous Intensity Distribution Tester, which shows that the resistances of sample A and B are nearly the same. It implies that the much more heat generated in sample A than sample B just results from the low EQE instead of the joule heat by the resistance.

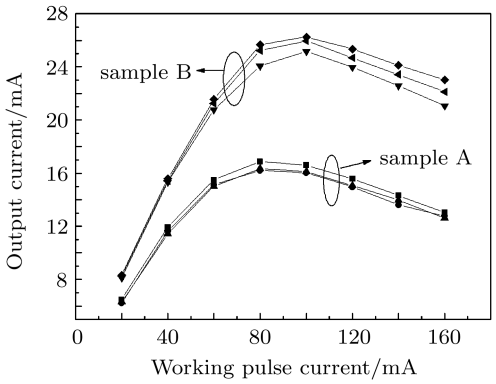


Fig. 2. Output power of the two kinds of packaged LED changed by pulse current.

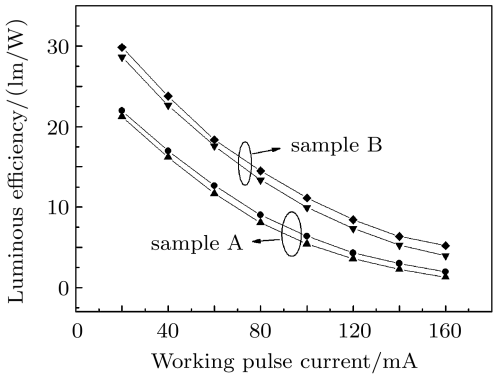


Fig. 3. The luminous efficiency changed by pulse current of the two LEDs.

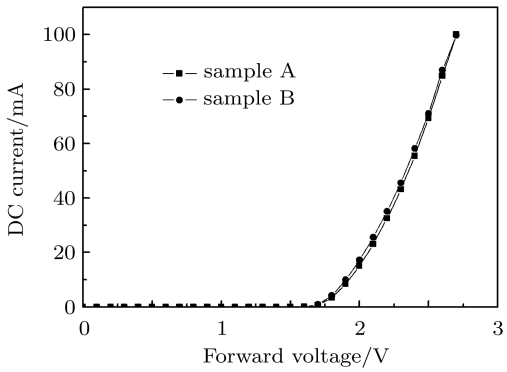


Fig. 4. The I–V characteristic of the the two different LEDs.

The spectrum distribution changed by current has been tested and analysed, Figures 5 and 6 show the spectrum distribution curves with the current ranged from 20 mA to 160 mA. The biggest red shifts are 21 nm and 18 nm, the relative EL intensities are ranged from 14.79 to 29.06 and 17.50 to 42.21 for sample A and sample B, respectively. The Full Maximum of Half Width (FMHW) of sample B is about 2 nm less than that of sample A, because the lower EQE of sample A makes much light generated inside cannot emit outside but changes into heat to raise the body temperature.

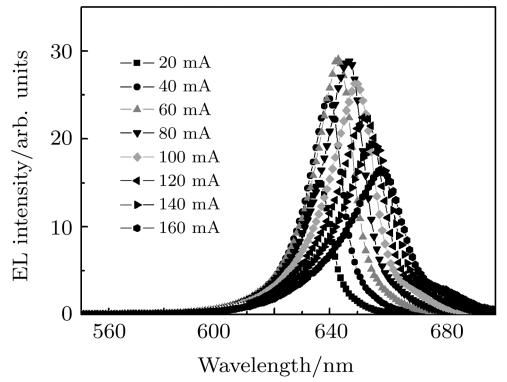


Fig. 5. The spectrum distributions of sample A under different currents.

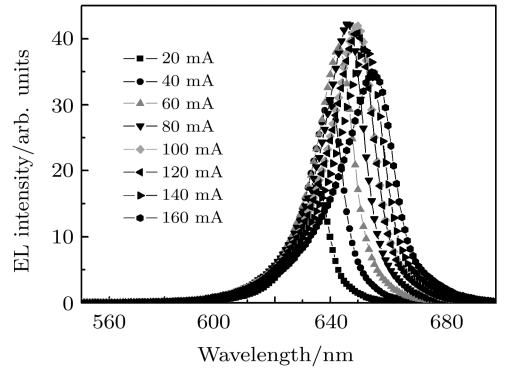


Fig. 6. The spectrum distributions of sample B under different currents.

Semiconductor's energy bandgap, carrier distribution and the efficiency of radiation recombination are changed with temperature, the III–V compound semiconductor has the same type of energy bandgap with Si and Ge. The relationship between the energy bandgap and temperature is as follows:

$$E_{\rm g}(T) = E_{\rm g}(0) - \frac{\alpha T^2}{T+\beta}, \tag{1}$$

where α and β are temperature parameters, $E_{\rm g}(T)$ and $E_{\rm g}(0)$ are the energy bandgaps for temperatures at T and 0 K respectively. If the temperature T is raised, according to Eq. (1), the energy band gap $E_{\rm g}$ becomes narrow and the energy band is broadened. For the LED with AlGaInP material, when the carrier distribution is not changed, its emitting wavelength has the following relationship with the energy bandgap:

$$hv \approx E_{\rm g}, \quad v \approx c/\lambda, \tag{2}$$

$$E_{\rm g} \approx hc/\lambda, \tag{3}$$

where h is the Planck constant, c is the light speed in the air. Equations (2) and (3) show that when the bandgap reduces, the LED's wavelength would become longer, and brings the evidence of red shift.

A simple model of energy band and electron density in conductive band is developed, as shown in Fig. 7, the energy band gap $E_{\rm g}$ is corresponding to the LED's emitting wavelength.

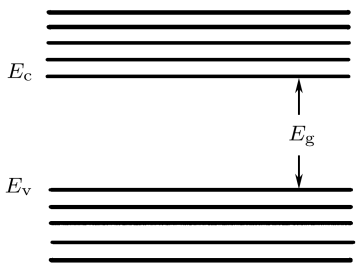


Fig. 7. The energy band diagram of semiconductor.

On the assumption that the quantum state in the space of energy from E to $E + {\rm d}E$ is ${\rm d}Z$, which is related with the energy E as follows:[11]

$${\rm d}Z = 4\pi V \frac{(2m_n^*)^{3/2}}{h^3}(E - E_c)^{1/2}{\rm d}E, \tag{4}$$

where V is the quantum state density, in the k space, the quantum state density is 2 V. To explain the relationship between quantum state and energy distribution, we can take a constant A to simplify Eq. (4),

$$A = 4\pi V \frac{(2m_n^*)^{3/2}}{h^3}, \tag{5}$$

$$\mathrm{d}Z = A(E - E_c)^{1/2}\mathrm{d}E. \quad (6)$$

When the energy band gap E_g becomes narrow in sample A, the quantum state $\mathrm{d}Z$ would be increased. At same injected current, the electron number is the same for the two LED samples, thus the electron density $\mathrm{d}N/\mathrm{d}Z$ in the conductive band for sample A is decreased, it means that electron and hole in every energy unit would be reduced, at the same time the radiation combination rate and internal quantum efficiency would decrease. This is the reason why the spectrum FMHW of sample A is larger than sample B and sample B has wider energy band gap and larger EL relative intensity.

The results have shown that sample B has larger EQE than sample A and also larger IQE with less red shift.

4. Conclusion

In summary, the reasons for LED having a low output power have been analysed, which is mainly because of the low EQE which has serious impaction on the IQE. The radiation combination rate reduced with the evidence of low output power and wavelength red shift. The experiment for the two kinds of LEDs with the same active region but different EQE have shown that by the low EQE, the IQE is decreased rapidly and the whole performance is getting worse with lower luminous intensity, lower light efficiency and bigger wavelength red shift.

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