Absorption of photons in the thin film AlGaInP light emitting diode*

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Abstract: The path of photons in the thin film (TF) light emitting diode (LED) was analyzed. The reflectivity of reflector in AlGaInP TF LED with and without the AlGaInP layer was contrasted. The absorption of the AlGaInP layer was analyzed and then the light extraction was calculated and shown in figure. The TF AlGaInP LED with 8 μm and 0.6 μm GaP was fabricated. At the driving current of 20 mA, the light output power of the latter is 33% higher. For the 0.6 μm GaP LED, the etching of heavily doped GaP except the ohmic contact dot area is advised. The design and optimizing of current spreading between the n-type electrode and the p-type ohmic contact dot need further research.

Key words: LED; AlGaInP; thin film

DOI: 10.1088/1674-4926/32/1/014012 **PACC:** 7280E; 7865K; 7360F

1. Introduction

Light emitting diodes (LEDs) have various advantages such as high external efficiency, long device lifetime, convenient color tuning, and environmentally friendly material. But the light extraction is still low because of the small escape cone, the drawback of the substrate[1, 2]. Several light improving approaches have in common that the original substrate is removed and replaced by a mirror and a carrier wafer, resulting in thin film LED (TF-LED)[3]. In TF-LED, if photons, generated by the active layer, cannot be directly extracted, photons will be circulated until extracted or absorbed by epi-layer and reflector. The absorption coefficient has been measured in InGaN-on sapphire- and AlGaInP-based LEDs[4]. For the optimization it is important to identify and quantify the loss of each part in LEDs.

In this paper, the light output extraction was analyzed among the output facet and the reflector. The transmittance of AlGaInP layer was measured and then the light output extraction was calculated. LEDs with different thicknesses GaP was fabricated and measured.

2. Calculation and analysis on AlGaInP layer

In TF-LED, if the reflector and the output facet are parallel and there is no influence on photons between them, the photon out of the escape cone will be reflected all through until it can get out from the side face. However, the absorption and the scatter in LED hold this situation back. Gessmann[5] supposed a uniform distribution of elastic scattering centers in the active region. So redirected photons can get into the escape cone again and get out.

Suppose the extraction efficiency (single facet), the reflectivity and the epi-layer transmittance are respectively α, β and γ, and photons are all scattered in the active region. For the isotropic photons P_0, generated by the active layer, the upwards part $P_0/2$ reaches the output facet and α part of $P_0/2$, Out1 = $P_0\alpha/2$, get out. The other part $P_0\,(1-\alpha)/2$ is reflected. Passing through the epi-layer, γ of them, $P_0(1-\alpha)\gamma/2$, reach the reflector. The first circle, reflected by the reflector, include $P_0(1-\alpha)\gamma/2$ and the downward part $P_0/2$. They are named $R = P_0(1-\alpha)\gamma/2 + P_0/2$. The β parts of the R are reflected, and then the γ parts of the reflected part, passing through epi-layer, reaches the output facet. Only the photons in the escape cone, which is Out2 $= R\beta\gamma\alpha$, can get out from the semiconductor. The other parts, $R_2 = R\beta\gamma(1-\alpha)$, are reflected back. Via the epi-layer, the reflector, the epi-layer, photons reach the output facet again. The output part is Out3 = $R_2 r\beta\gamma\alpha$ = Out2 $\times$ $(1-\alpha)r\beta\gamma$. The part $R_3 = R_2 r\beta\gamma(1-\alpha)$ is reflected and pass through the same path until all photons get out or are absorbed.

Figure 1 shows the entire process. It can be seen that the output light after the second time is a geometrical sequence, whose leading term and common ratio are respectively $[P_0(1-\alpha)\gamma/2+P_0/2]\beta\gamma\alpha$ and $(1-\alpha)r\beta\gamma$. So the overall output light P is given by

$$P = \frac{P_0\alpha}{2} + \frac{P_0[1+(1-\alpha)\gamma]\beta\gamma\alpha}{2[1-(1-\alpha)\gamma\beta\gamma]}. \quad (1)$$

The AlGaInP TF-LED epi-layer grown by MOCVD consists of an etching stop layer GaInP, a heavily doped n-GaAs ohmic contact layer, an AlGaInP current spreading layer, active and confinement layers, and a 0.6 μm thick p-GaP layer. In the fabrication of SiO_2/Au ODR (Omni-directional reflector), the conductive ohmic contact holes (Φ 6 μm, period 20 μm) distribute uniformly without any position design. The GaAs and Si were bonded together for one hour at temperature 270 ℃ and pressure 3 MPa using the Au/Au bonding method. After the GaAs substrate, the etching stop layer was etched, and the

* Project supported by the Natural Science Foundation of Beijing (No.4092007) and the National High Technology Research and Development Program of China (Nos. 2008AA03Z402, 2009AA03A1A3).
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Received 23 June 2010, revised manuscript received 11 August 2010

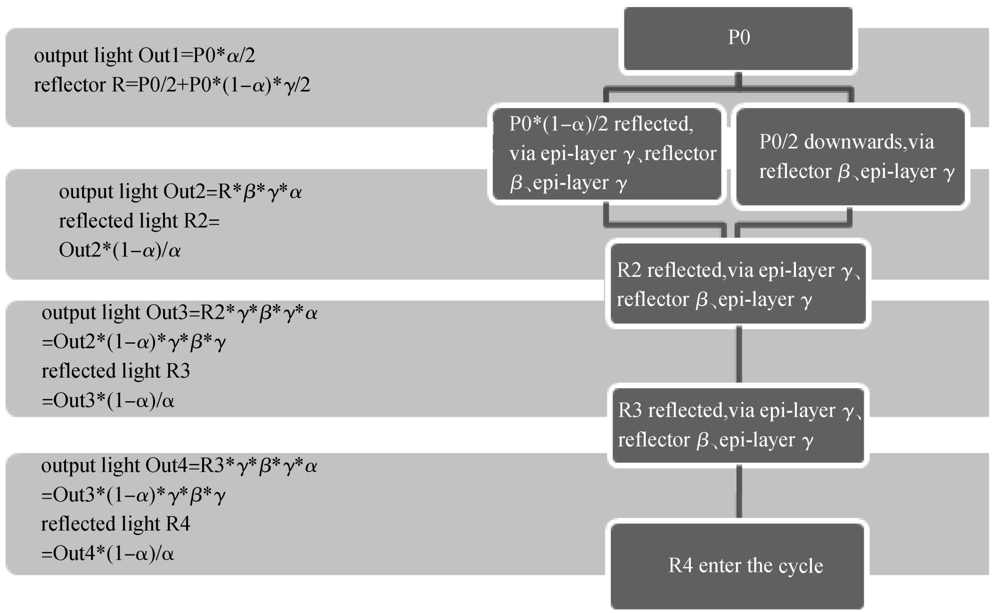

Fig. 1. Schematic of the photon cycle in TF LED.

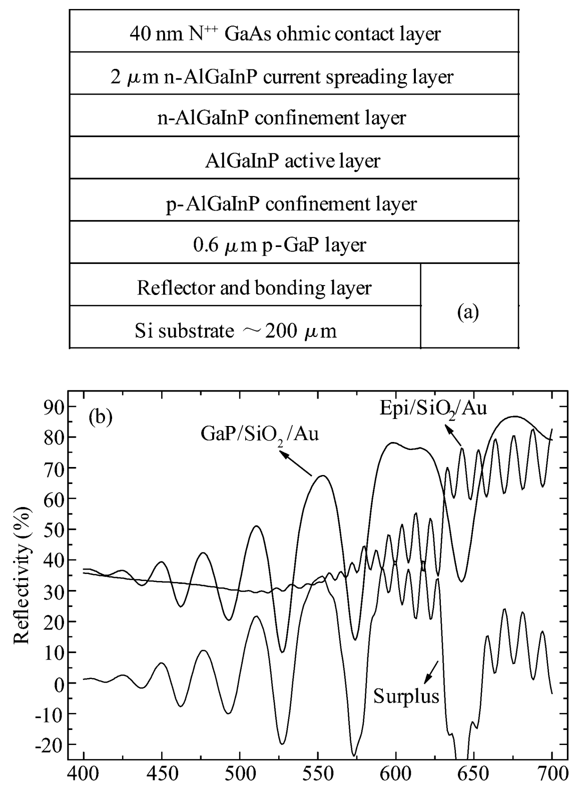

Fig. 2. (a) Schematic of the several layers of TF-LED. (b) Reflectivity versus wavelength of epi–SiO_2–Au and GaP–SiO_2–Au.

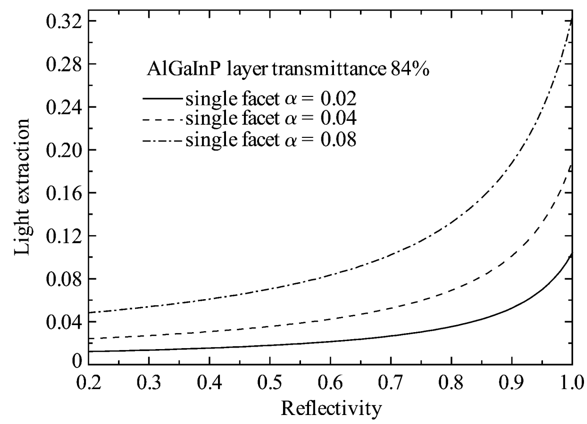

Fig. 3. Light extraction versus reflectivity with different single facet extractions.

schematic of it is shown in Fig. 2(a). After the heavily doped ohmic contact GaAs layer was removed, the reflectivity of the epi-layer with SiO_2/Au ODR was measured using spectrophotometer. As shown in Fig. 2(b), the reflectivity of epi/SiO_2/Au is vibratory because of interference between the light reflected by different refractive index thin layers in epi-layer.

Then, the AlGaInP layer, including 2 μm n-type current spreading layer and the active and confinement layer, was removed by hydrochloric acid. The 0.6 μm GaP cannot be dissolved and was kept. The reflectivity of GaP/SiO_2/Au was measured again. As can be seen from Fig. 2(b), at the emitted wavelength region, the contrast between epi-layer/SiO_2/Au and GaP/SiO_2/Au was remarkable. The surplus was also calculated and shown in Fig. 2(b).

The back and forth absorption of AlGaInP layer is corresponding to the surplus. The transmittance of AlGaInP layer is about 84%, if taking the surplus as 30%. Supposing the absorption of GaP was ignored, Figure 3 shows the relation between the light extraction and the reflectivity with different single facet extraction efficiency α. Here supposing the extraction angle 17°of GaP and according to the simple calculation $\alpha = 0.5(1 - \cos\theta)$, single facet extraction efficiency 2% was received[6]. Considering the roughed surface and epoxy encapsulation, 4% and 8% were also included. For high light extraction, both the internal quantum efficiency and absorption should be considered and optimized in the epi-layer.

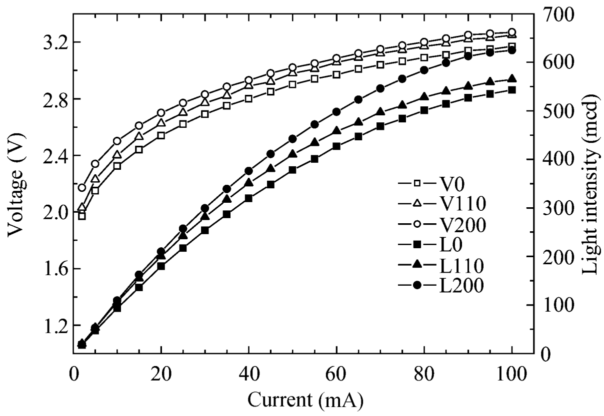

Fig. 5. L–I–V characteristics of 0.6 μm GaP LED etched by different heights.

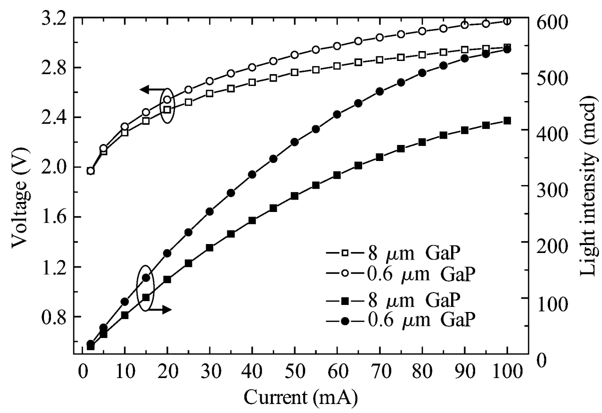

Fig. 4. L–I–V characteristics of LED with 8 μm and 0.6 μm GaP.

3. Experiment and analysis on GaP layer

Various thicknesses of GaP in AlGaInP LED have been seen in papers, for example, 8 μm[7], 5 μm[8] and 1.2 μm[9]. Two group AlGaInP LEDs with 8 μm and 0.6 μm thickness GaP were grown by MOCVD. Then the TF-LED was made with the same process above before the heavily-doped GaAs ohmic contact layer was removed. The n-type electrode AuGeNi was sputtered, and the metal and GaAs layer were etched with starlike shape. Then the bottom electrode, annealing, cutting, bonding and measuring was processed.

Figure 4 shows the light intensity–current–voltage (L–I–V) characteristics of LEDs with 8 μm and 0.6 μm GaP. The p-type concentration from the p-confinement layer to the light output facet was doped from lightly to heavily step by step. The P-type heavily doped concentration was 10^{19}–10^{20}, and the thickness in the two types GaP was respectively 200 nm and 100 nm. At 20 mA current, the light intensity of TF-LED with 8 μm and 0.6 μm GaP was 133 mcd and 180 mcd. The light output power at 20 mA was 2.5 mW and 3.34 mW respectively. The latter is 33% higher. The voltage of LED with 0.6 μm GaP was higher because of the higher series resistance.

For the LED with 0.6 μm GaP, different heights were etched using the ICP (inductively coupled plasma) etching system, which could keep the roughness of the etching surface constant. The etching height was 110 nm and 200 nm without any patterns. Figure 5 shows the L–I–V characteristics of LEDs. The light output power of the three groups LED is 3.34, 3.67 and 3.88 mW, respectively. The forward voltages (@ 20 mA) of LEDs increased because of the etching of heavily doped layer. The ohmic contact could not be formed very well which can be seen from the high turn-on voltage.

It can be seen that the thinner GaP, the higher the output light. One of the reasons is that the light cycle amplifies the absorption of GaP. Because GaP absorbs the photons, especially the heavily doped layer, the remove of GaP under the reflector is necessary. Another reason is the current spreading. Both the n-type electrode and the p-type ohmic contact dot absorb light. Only the light generated by the active layer corresponding to the other area can be extracted. The design and optimizing need further research.

4. Conclusion

The transmittance of the AlGaInP current spreading layer, active and confinement layers is about 84%. It was estimated equal to the reflectivity surplus of two reflectors in TF AlGaInP LED with and without AlGaInP layer. The TF AlGaInP LED with 8 μm and 0.6 μm GaP was fabricated. At the driving current 20 mA, the light output power of the latter is 33% higher. Two reason including absorption and current spreading is analyzed for the high output of the thin GaP LED.

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