High Efficiency Tunneling-regenerated Multi-active Region Light Emitting Diodes*

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ABSTRACT

A new mechanism of tunneling-regenerated multi-active region LEDs with high quantum efficiency and high brightness has been presented. The layer structure, MOCVD growth, device technology, a several of measured curves and their analysis of these new mechanism LEDs were shown in the paper. It was theoretically and experimentally resulted in that the efficiency of the electro-luminescence and the on-axis luminous intensity can linearly increase approximately with the number of the active regions.

Keywords: quantum efficiency, multi-active region, LED

1. INTRODUCTION

AlGaInP is direct band-gap light emitting quaternary material with high radiation recombination rate and wide spectrum which covers from red to greenish-blue, and the AlGaInP light emitting diodes (LEDs) now have been widely applied in the area of automotive lighting, traffic signal lighting, large-area displays, etc.[1] However, except the effect of the material quality, the brightness of traditional LED is limited by the two facts: 1. High density of light power and the over-heat induced by small light emitting region. 2. The low efficiency of light extraction. Many solutions are serves to enhance the brightness such as current spreading layer[2], transparent substrate[3], complicated geometry figure chip[4], etc. But they are both complicated art technology and high cost. The brightness is not obviously enhanced based on light emitting mechanism itself.

In this paper, we bring up a new mechanism of tunnel-regenerated multi-active region LEDs, with high quantum efficiency and high brightness, in which, after an electron-pole pair is recombined in the previous active region, the electrons in the

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p-side valence band, under the action of high electrical field, will tunnel into n-side conduction band and can be radiantly recombinated again in the next active region.[5] In this way, the quantum efficiency and the brightness will linearly increase approximately with the number of the active regions. At the same time, highly doped GaAs tunneling junction region can effectively spreading the current, therefore the thickness of the current spreading layer can be reduced relatively.

2. THE LAYER STRUCTURE GROWTH AND THE DEVICE FABRICATION

The AlGaInP LED epitaxial layer structure was grown by low-pressure MOCVD on n-GaAs substrate. The (100) GaAs substrate was oriented at 15℃ off the <110> direction. The growth temperature was generally between 700℃-750℃. TMGa, TMAl, TMIn were used as grouped V element precursors. The total hydrogen flow was 71liter. The epitaxial layer structure is consisted of a wide band-gap n-AlGaInP confining layer doped with SiH_4, an i-type active layer 0.3-0.5 μm thick, and a p-type wide band-gap injection layer which was doped using DEZn and also serves as a window layer for the light emission. The active layer is lattice matched closely to the GaAs substrate. Between the two active regions there is the GaAS reverse-tunneling junction. Ti/Pt/Au and Au/Ge/Ni were used as p-type and n-type contact materials respectively. The wafer was cleaved into 300X300 μm^2 square slices bounded on the capsules for the measurements. Fig.1 shows the layer structure of the LED chip.

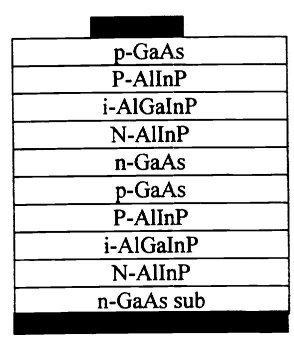
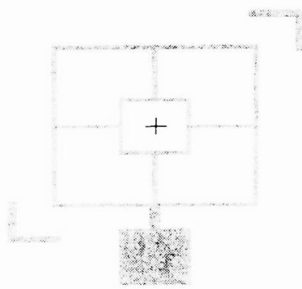


Fig.1 The layer structure of LED device epitaxial structure

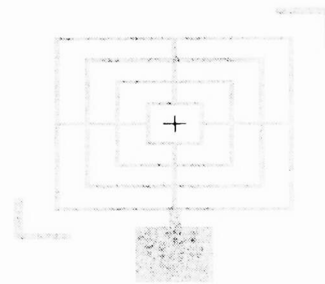
3. EXPERIMENTS AND DISCUSSIONS

3.1 Four kinds of electrodes we used

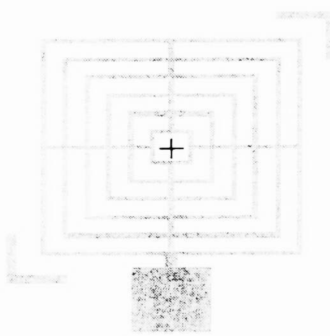
In order to study mainly the physical mechanism, the current spreading layer has not been grown temporarily. Considering the high transverse resistance of p-type AlInP and the small current spreading, so we design several kinds of electrode figures to improve the light extraction efficiency, shown in Fig. 2. The measured results of the on-axis luminous intensity show that the brightness for the four-circle electrode figure with the same current (I=20mA) is the largest. It is almost two to three times than that of the crossed electrode figure or that of the two-circle electrode figure, and it is about 5/4 times than that of the six-circle electrode figure. Obviously, the extraction efficiency for the four-circle electrode figure is the highest.



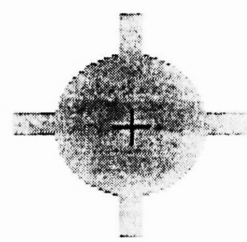
Two–circle electrode



Four-circle electrode



Six–circle electrode



Crossed electrode

Fig.2 Four kinds of electrode figures

3.2 Absorption

In order to study the absorption of GaAs layer and its influence on the on-axis luminous intensity, we have measured the dependences of the on-axis luminous intensity with etching time of GaAs layer. The etching solution is H_3PO_4, CH_3OH and H_2O, and the etch temperature is freezing point. It can been seen from Fig.3 that when GaAs layer is thicker, the more is GaAs layer etched, the higher is the on-axis luminous intensity, which could be dependence with the strong light (620nm) absorption of GaAs layer. However, during the process of experiment, we also find that when the GaAs layer is thinner, the on-axis luminous intensity is highest for a certain thickness GaAs layer, especially for the n-type GaAs, which may result from that the mobility of n-type GaAs is comparatively high and the transverse resistance of GaAs is relatively small, so that the current transverse spreading plays a major role and the absorption becomes a minor effect instead.

3.3 The new device structure of fabrication

In order to compare the on-axis luminous intensity of two active regions LEDs by experiments under the same preparation technology and test condition. We adopted the technological structure shown in Fig.4 using photolithography method,

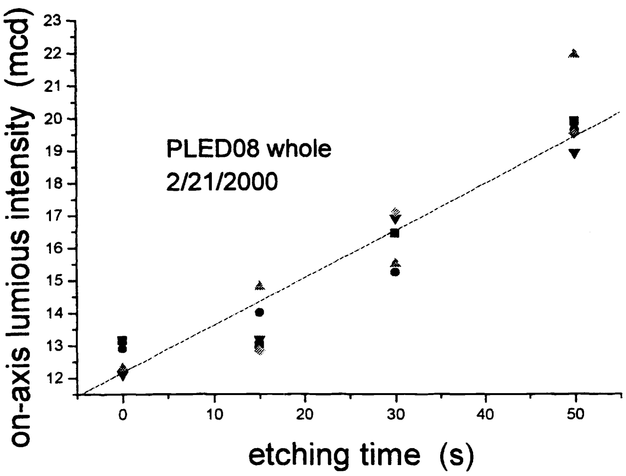


Fig.3 On-axis luminous intensity vs. etching time

The dots represent experimental results

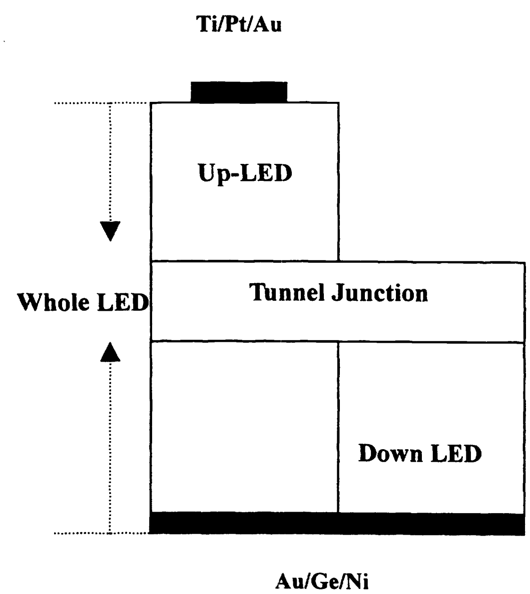
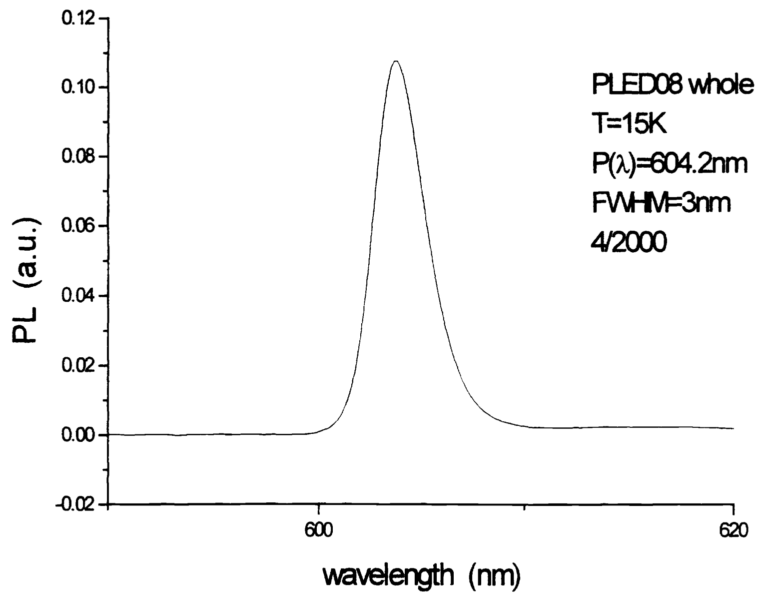
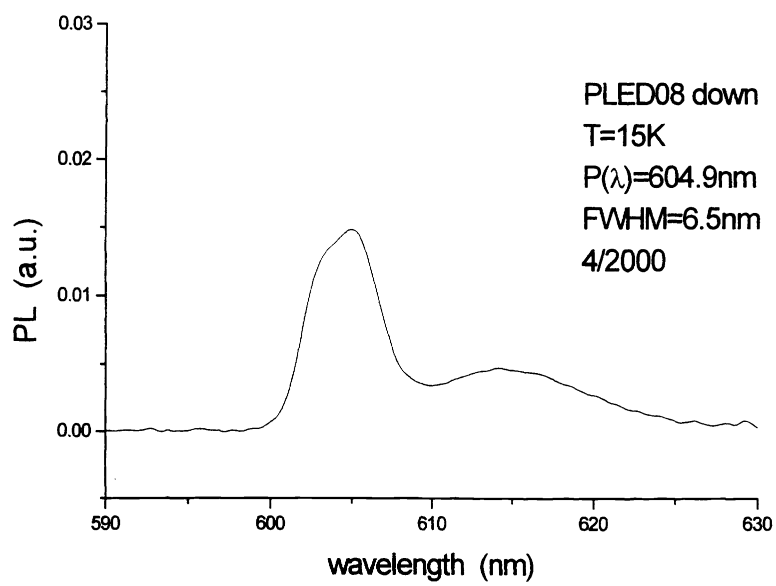


Fig.4 The schematic diagram of the device structure

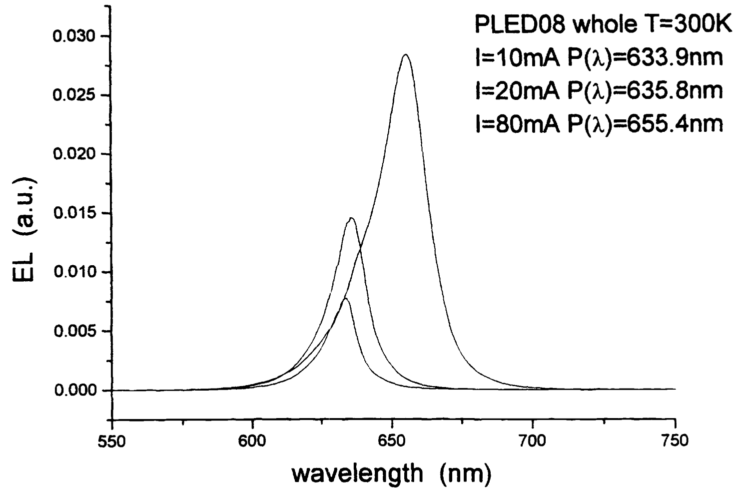


(a)

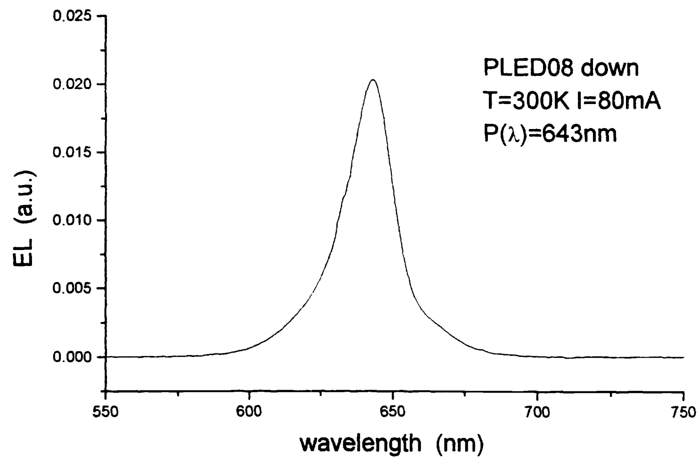


(b)

Fig.5 Low temperature (15K) PL spectrum result of i-AlGaInP active region of whole LED (a) and down LED (b)



(a)



(b)

Fig.6 Room temperature (300K) EL spectrum result of (a) the whole LED and (b) the down LED

considering that there is good selective etching between GaAs and AlInP. We made electrodes respectively on the surface of GaAs cap layer and GaAs tunnel junction layer. Now, we define Whole LED, Down LED and Up LED as show in the Fig.4.

3.4. Photo Luminescence (PL) spectrum measurement

Fig 5 is the PL spectrum measurement result of (a) the whole LED with two active regions and (b) the down LED with single active region at T=15K. The measurement system is IFS 120HR Fourier Transform Spectrometer of the BRUKER Corporation. The pumping light source is Ar iron laser with peak wavelength is 514.5nm. In the measurement process, we etched only GaAs cap layer to measure the Whole LEDs and etched the GaAs cap layer, Up LED and tunnel junction to measure PL spectrum of Down LEDs. The PL spectrum peak wavelength for the whole LED is 604.2nm and it is 604.9nm for the down LEDs, obviously, their difference is small, about 0.7nm. This small difference maybe results from the condition variation in the process of growth.

3.5 Electrical Luminescence (EL) spectrum measurement

Fig. 8 is the El spectrum measurement result of (a) the whole LED and the (b) the down LED at T=300K. The EL spectrum peak wavelength of the whole LED is 633.9nm at I=10mA and is 635.8nm with half width being 15nm at I=20mA, and is 655.4nm at I=80mA. With current increasing, the peak wavelength should move towards the blue light (short wavelength) direction due to the injection effect, but the thermal resistance of AlGaInP material is so large that the device severely heats, then the heat effect plays a major role, thus with the current increase, the wavelength moves towards the red light direction. The EL spectrum peak wavelength of the down LED is 643nm at room temperature with the half width being 20nm at I=20mA and its heat effect is similar with that of the whole LED. From Fig.8, it also shows that the integrated increasing of EL spectrum is increases linearly with the current increasing approximately.

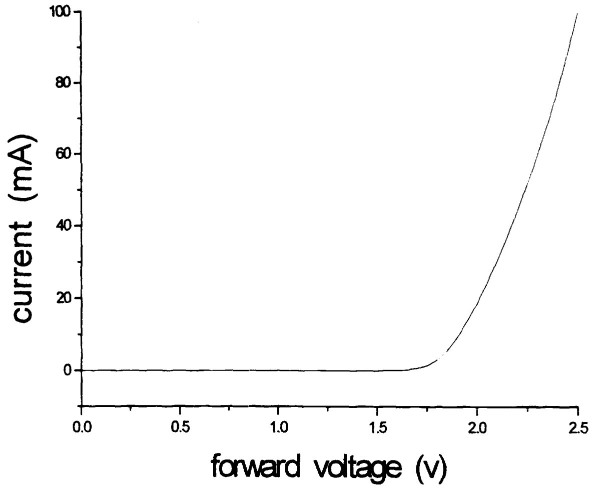
3.6 I-V characteristic

The voltage drop over the down LEDs is about 2.0v at I=20mA and that over the whole LEDs is almost 4.0v. It is obviously that the electrical performance of the whole LEDs is still normal and does not become worse although a reverse tunnel junction is added. Besides, it can be seen that the voltage dropped in the reverse tunnel junction is so small to be almost negligible, thus it has almost no influence on the heating of the devices.

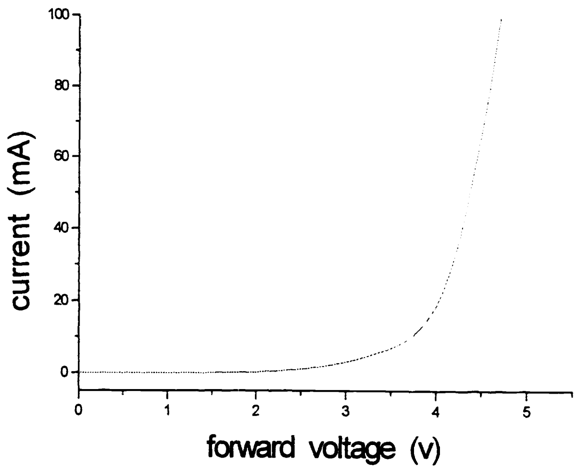
3.7 The on-axis luminous intensity

Fig.8 illuminates that the on-axis luminous intensity is about 13mcd for the down LEDs and is about 25mcd for the whole LEDs at I=20mA. We can see from Fig.9 that both the double DC resistance compared with traditional LEDs and the middle tunnel junction resistance do not influence the heat characteristic of the whole LEDs. With the current increase, the on-axis luminous intensity of the whole LEDs increase more quickly than that of the down LEDs. Of course, we can't rule out the influence of the high contact resistance of the down LEDs.

From these two figures, we can also get the result that the absorption of the GaAs tunnel junction is small, therefore, n-type current spreading layer can be used, which has higher mobility than that of p-type current spreading layer. For example, the mobility of n-type GaP is about $150cm^2/v*s$, while that of p-type GaP is only about $120cm^2/v*s$; the mobility of n-type GaAs is about $8000cm^2/v*s$, while that of p-type GaAs is only about $3000cm^2/v*s$, etc. Using n-type current spreading layer can dramatically reduce the transverse resistance and improve the current spreading, therefore the thickness of the total current spreading layer can be reduced relatively and the difficulty of high doped p-type material growth can be avoided.



(a)



(b)

Fig.7 The I-V characteristics of (a) the whole LED and (b) the down LED. While I=20mA, the voltage drop of the whole LED is 4.0v,and the voltage drop of the down LED is 2.0v

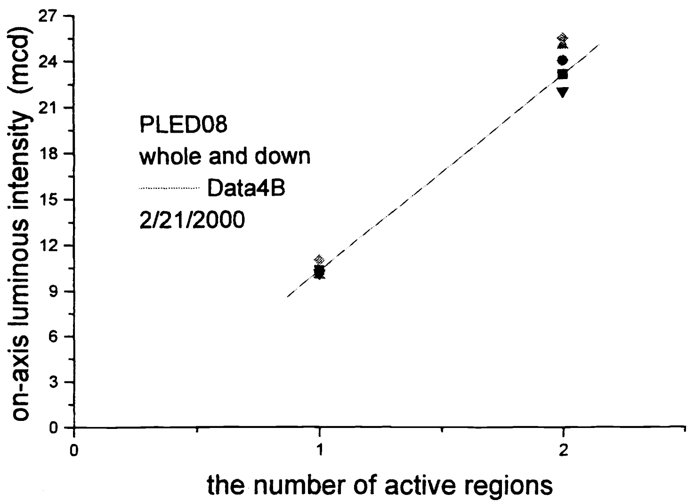


Fig.8 On-axis luminous intensity vs. the number of active region

The dots are the data of experiment, and the line is the linear fit of the data

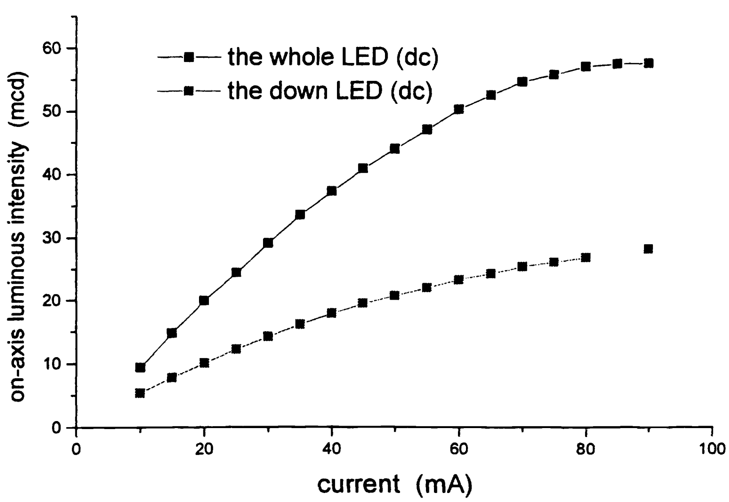


Fig.9 On-axis luminous intensity vs. forward current (dc)

4. CONCLUSION

A new mechanism of high efficiency tunnel-regenerated multi-active region LEDs has been presented theoretically and validated experimentally. The on-axis luminous intensity increases with the number of active region. The new LEDs would be easy fabrication, low cost and excellent optic-electronic performance.

5. ACKNOWLEDGMENTS

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