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Effect of two n-electron blocking layers on internal quantum efficiency droop of InGaN/GaN multi-quantum well blue light-emitting diode

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We have simulated the effect of two n-electron blocking layers with varied aluminum composition in AlGaN. Usual 20nm n-AlGaN electron blocking layer was replaced with two AlGaN layers with varied Al composition.

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Keywords: Light-emitting diodes (LEDs), Multi Quantum Well (MQW), efficiency droop, Electron Blocking Layer (EBL), Internal quantum efficiency (IQE)

1. Introduction

The InGaN/GaN multi-quantum well light-emitting diodes (LEDs) are being studied due to their wide applications in rural lighting [1], etc. To increase the internal quantum efficiency, variations in well width [2], barrier width [2], with p-AlGaN, n-AlGaN electron blocking layers [5], with InGaN barriers [4] have been studied. At higher currents p-AlGaN layers are not efficient to prevent electron leakage hence degradation in output power as well as radiative recombination rate. However, with n-AlGaN electron blocking layer, there is remarkable improvement in IQE as well as output power [5].

In this study, we propose to replace the n-AlGaN electron-blocking layer with two n-AlGaN electron-blocking layers having Al composition 0.05 and 0.10 respectively.

The radiative recombination rate, IQE, and output power of the multi-quantum well LED structure have been simulated on Silvaco ATLAS, which is capable to deal with the physical properties of LEDs by solving the self-consistence Schrödinger-Poisson equation, current continuity equations, carrier transport equation, quantum mechanical wave equation, and photon rate equation.

2. Structure and parameters

We have compared the effect with two n-AlGaN layers with original structure described in [5]. The optimized structure is shown in figure 1.

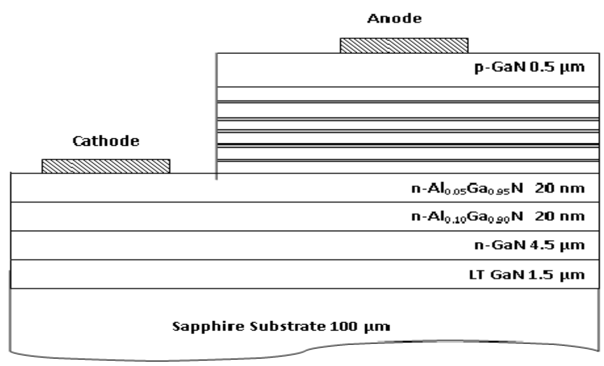

Fig. 1 Structure simulated with two n-electron blocking layers.

It is grown on a c-plane sapphire substrate, followed by a 1.5-um –thick undoped GaN layer, and a 4.5 um-thick n-GaN layer (n-doping= 5 x 10^{18} cm^{-3}).The active region consisted of five 2-nm-thick undoped $In_{0.21}Ga_{0.79}N$ QWs sandwiched by six 15-nm-thick undoped GaN barrier layers. On top of the active region were a 0.5-um-thick p-GaN cap layer (p-doping = 1.2 x 10^{18} cm^{-3}). The area of the device geometry was 300 x 300 um^2. For the LED with N-AlGaN, the P-AlGaN EBL was removed while the n-type $Al_{0.15}Ga_{0.85}N$ (n-doping= 5 x 10^{18} cm^{-3}) was placed between the active region and n-GaN layer.

The band gap energies of $In_xGa_{1-x}N$ and $Al_xGa_{1-x}N$ ternary alloys can be expressed as [6]:

$$Eg(In_x Ga_{1-x} N) = xEg(InN) + (1-x)\ Eg(InN) - 3.8.x.(1-x) \quad (1)$$

$$Eg(Al_x Ga_{1-x} N) = xEg(AlN) + (1-x)\ Eg(GaN) - 1.3.x.(1-x) \quad (2)$$

Where Eg(InN) , Eg(AlN), and Eg(GaN) are the band gap energies of InN, AlN, and GaN values determined as[6]:

$$Eg(GaN) = 3.507 - \frac{0.909\ x10^{-3} T^2}{T + 830.0} \quad (3)$$

$$Eg(GaN) = 1.994 - \frac{0.245\ x10^{-3} T^2}{T + 624.0} \quad (4)$$

$$Eg(GaN) = 6.23 - \frac{1.799\ x10^{-3} T^2}{T + 1462.0} \quad (5)$$

Other material parameters of the relevant binary semiconductors used in the simulation can be found in [6]. The operating temperature is assumed to be 300K.

3. Simulation results

Fig. 2 shows the simulated light-current (L-I) performance comparison of the LEDs with N-$Al_{0.15}Ga_{0.85}N$ electron-blocking layer and with two N-AlGaN EBLs with Al composition 0.05 and 0.10 respectively.

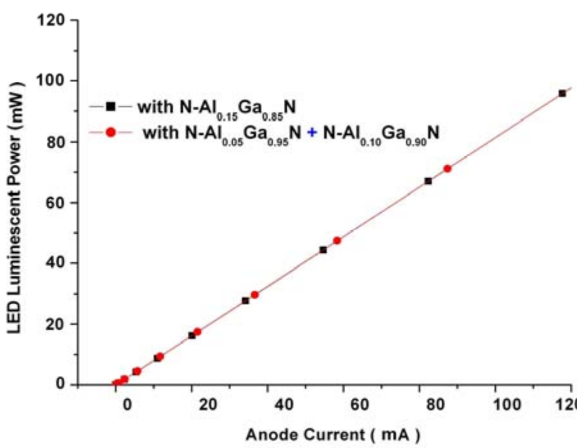

Fig. 2. L-I curves of the LEDs with N-AlGaN and two N-AlGaN layers with different Al composition.

The LED luminescent power and LED radiative rate was improved with a factor 1.021 times.

In Fig. 3, there is 0.04 % improvement in IQE droop at 120 mA current.

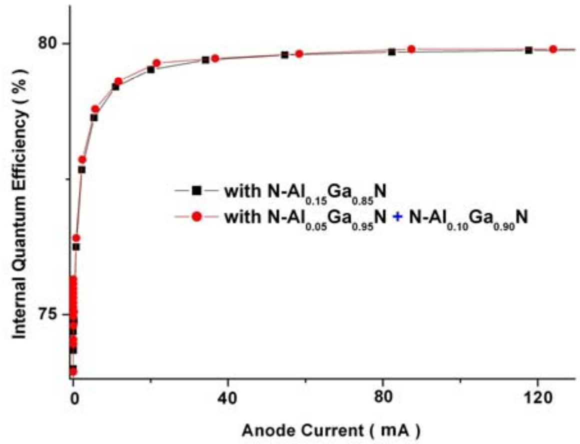

Fig. 3. IQE curves for LEDs with single N-AlGaN layer and with two N-AlGaN layers with different Al composition.

In Fig. 4, we see the increased concentration of holes in comparison to the reference structure with single N-AlGaN layer.

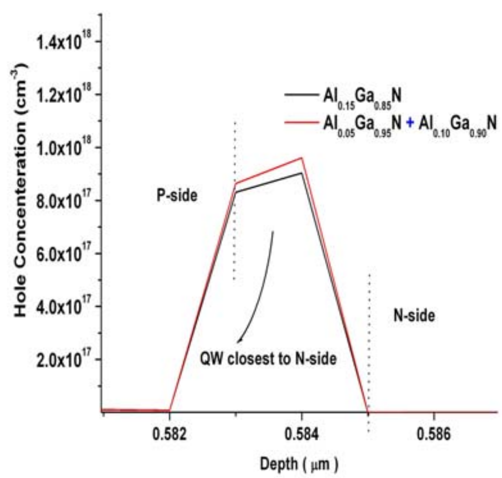

Fig.4 Comparison of hole concentration in QW closest to the N-side.

This is possibly due to decreased polarization at the interface GaN (barrier)/$Al_{0.05}Ga_{0.95}N$ than that of at the interface GaN (barrier)/$Al_{0.15}Ga_{0.85}N$. A hole finds a less polarization field at the interface $In_{0.21}Ga_{0.79}N$ (QW)/ GaN (barrier) than that of in case of single N- $Al_{0.15}Ga_{0.85}N$ blocking layer. Hence, it provides an increase in radiative recombination rate in this QW.

In Fig. 5, we can see the increased electron concentration in above QW. This is due to decreased barrier height at the interface of two EBLs as wells at both interfaces at 0.6μm and 0.62 μm as shown in Fig. 6.

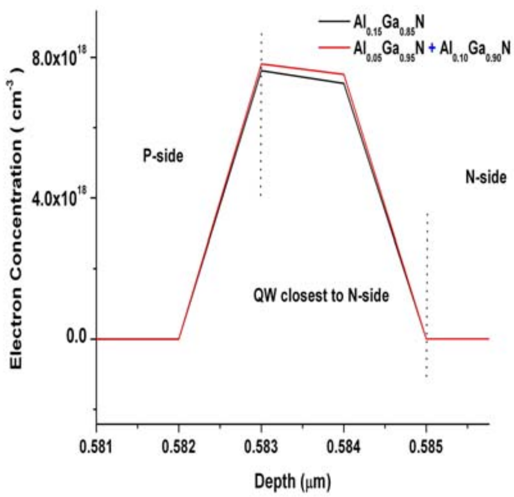

Fig.5 Comparison of electron concentration in QW closest to the N-side.

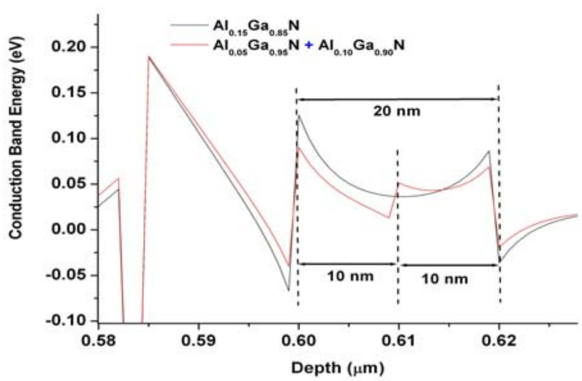

Fig. 6. Comparison of conduction band energy profile at interface of barrier and AlGaN layer.

Fig. 7 shows polarization effects on conduction band energies.

Due to less strain the polarization at the interface GaN (barrier)/$Al_{0.05}Ga_{0.95}N$ is lower than that of GaN (barrier)/$Al_{0.05}Ga_{0.95}N$. The same effect of decreased polarization is being occurred at the interface $Al_{0.10}Ga_{0.90}N$/n-GaN. The energy barriers at both interfaces are lower than that of in case of single N-AlGaN blocking layer.

Similar effects are on valence band offset heights at interfaces GaN(barrier)/$Al_{0.05}Ga_{0.95}N$ and $Al_{0.10}Ga_{0.90}N$/(n-GaN).

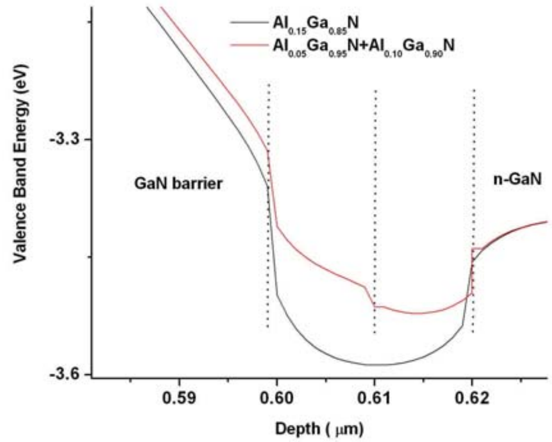

Fig.7 Comparison of valence band energy profile at interface of barrier and AlGaN layer.

4. Conclusions

In this letter, it was proposed that a combination of two n-type electron blocking layers with varied Al composition 0.05 and 0.10 shows enhanced IQE and improvement in L-I curve over those of in-case of a single 20-nm-thick n-type $Al_{0.15}Ga_{0.85}N$ electron blocking layer. The simulation results suggests that a lower barrier height as well as lower value of polarization fields at interface GaN(barrier)/ $Al_{0.05}Ga_{0.95}N$ allows more electrons to transport towards p-side hence an increase in radiative recombination rate , power and IQE droop reduction.

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