Indian Journal of Pure & Applied Physics
Vol. 59, April 2021, pp. 335-338

Droop reduction in ZnO/GaN Hybrid Light Emitting Diodes

Aadarsh Kumar Chaudhri[a], B C Joshi[b*], Vanita Devi[b] & Mahipal Singh[c]

[a]Department of Physics, Govt PG College Bazpur, India

[b]Department of Physics and Materials Science and Engineering,
Jaypee Institute of Information Technology, Noida 201 307, India

[c]Department of Physics, R H G P G College Kashipur, India

Received 11 September 2020; accepted 5 February 2021

PN junction is the basic building block for the fabrication of optoelectronic devices. ZnO shows the n-type behaviour. P-type doping with suitable hole concentration and reduced defects is one of the major challenges in the fabrication of ZnO based devices. Nitrogen, Phosphorus, Arsenic and Bismuth are some of the potential p-type dopants, but none of them have desired electrical properties to fabricate p-n junction from ZnO. In the present work, we proposed a hybrid n-ZnO/p-GaN hetero-structure, in which n-type ZnO film is placed on Mg doped GaN film. Simulation results revealed that the electroluminescence intensities increases in hybrid LED structure and there is a strong sensitivity towards the layer properties in hybrid structure.

Keywords: ZnO, GaN, p-n, Light Emitting Diode, Droop

1 Introduction

Direct band gap materials like GaN, and GaAs are important compound semiconducting materials for the fabrication of optoelectronic devices. All optoelectronic devices require good material quality and ease to fabricate p-n junctions[1]. In recent decades, ZnO has attracted considerable attention due to its unique properties, like high electron mobility, wide and direct bandgap, and bandgap tailoring. This has been considered as some promising parameters for fabricating devices like light-emitting diodes, laser diodes, photo detectors, and solar cells. Moreover, hetero-structures are also possible on ZnO materials, which make ZnO ternary alloys-based materials as an alternate to III-Nitride semiconductors for fabricating optoelectronic devices [2-3]. ZnO films grown by pulsed laser deposition, vapor phase epitaxy, and sol-gel unintentionally show n-type behaviour due to bulk and deep level defects [4-6]. Thus, growing good quality p-type material with suitable hole mobility is one of the major challenges faced by researchers in ZnO. Although, N, P, As, Sb, and Bi show potential p-type dopants for ZnO, none of them show enough electrical and optical properties, to fabricate a good p-n junction. Samanta *et.al*. deposited p-type ZnO films on a sapphire substrate by Sb doping with hole concentration and mobility around 6.5×10^{18} cm^{-3} and 53 cm^2/V-s respectively[7]. The sample shows good structural properties but due to low hole mobility was not suitable for optoelectronic applications. Many authors suggest p-type substrates as an alternative to p-ZnO for fabricating p-n junctions. p-GaN and p-SiC with similar structural, electronic, and optical properties can be good alternatives. Moreover, their super-lattices and hetero-junctions structures show more electroluminescence due to large charge carrier accumulation at the interface.

In this work, we studied a hybrid GaN/ZnO quantum well structure with p-GaN as p-type material and n-ZnO as n-type material. Our previous study in III-Nitride reveals that GaN-based LEDs show a high reduction in internal quantum efficiency (efficiency droop) at high injection current levels[8]. This may be due to auger recombination, interface fields, and lattice defects. In another study, we also reveal that quantum well structures have more emission intensity, and the efficiency of LED increases with grading[1]. The same methodology has been used here to study the hybrid ZnO/GaN quantum well structure. In the numerical simulations, Poisson's equation, current continuity equations, and carrier drift-diffusion transport equations were solved for self-consistency.

*Corresponding author (E-mail: bhubesh.joshi@jiit.ac.in)

2 Device Structure & Physical Model

Schematic of hybrid(GaN/ZnO) and basic (InGaN/GaN) p-n hetero junction LED structures used in this study are shown in Fig. 1. In hybrid structure, 200 nm n-type ZnO(Al dopped) is taken as cladding layer with doping concentration of $1.0x10^{17}$ cm^{-3}, 5 nm thick $Zn_{0.80}Cd_{0.20}O$ quantum well as an active layer, 7nm thick un-doped ZnO as a barrier layer and 500 nm thick p-type GaN withholes concentration of $1.0x10^{19}$ cm^{-3} is taken as a top layer. In basic structure, 200 nm of n-GaN is taken as base layer, 5 stacks of In GaN/GaN as active quantum wells layers and 500 nm of p-GaN as a top p-type layer.

GaN material system has a built-in electric field due to high electro negativity of Nitrogen atom, which plays significant role in LED emission characteristics. The built in (Spontaneous) charges and strain related (piezoelectric) charges at GaN/ZnO interfaces are also included in simulations. The three band Chuang and Chang model based on optical transitions between the conduction band and heavy and light hole and the crystal field split-off valence bands has been accounted in calculation for analysing the spectral characteristics, such as emission wavelength and emission spectra[9]. Shockley-Read-Hall recombination (SRH) and three carrier Auger non radiative model are also introduced, to study the effect of high injection current density on electroluminescence and internal quantum efficiency of modelled LED. For ternary compound semiconductors like CdZnO and InGaN, the bandgap (E_g) is calculated as:

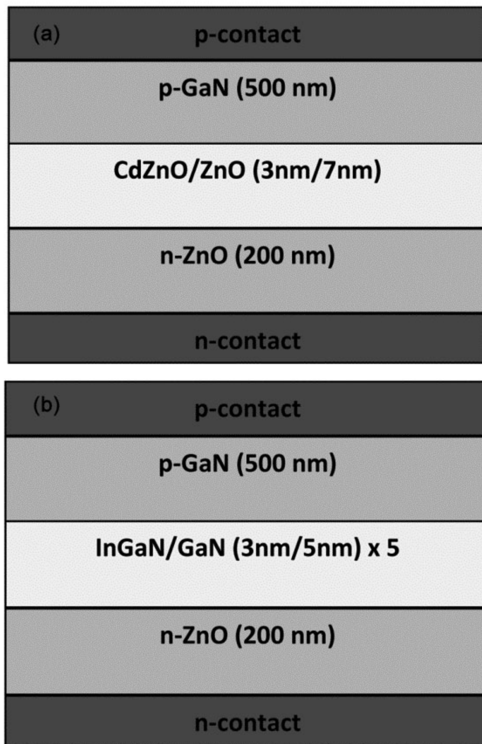

Fig. 1 — (a) Hybrid p-n (GaN-ZnO) LED structure with 3 nm CdZnO quantum well and 7 nm ZnO barrier; (b) Basic p-n junction LED structure with 5 stacks of InGaN/GaN quantum wells

$$E_g(A_xB_{1-x}N) = E_g(AN)x + E_g(BN)(1-x) - qx(1-x)$$

Where, x is the mole fraction and q is the bowing parameter. The electron affinity rule is used to define band alignment in conduction band and valence band at the interface between ZnO and GaN [10].

$\Delta E_C = \chi_1 - \chi_2$ and

$\Delta E_v = \Delta E_g - \Delta E_c$

Where, ΔE_c & ΔE_V are discontinuities at conduction band and valance band edges, respectively.χ_1&χ_2 are electron affinities of semiconducting materials and ΔE_g is the difference in bandgap. The temperature dependency of band gap is taken in account as

$$E_g(T) = E_g(0) - \frac{mT^2}{T+n}$$

Where, $Eg(T)$is the bandgap of the semiconductor at the temperature T, $Eg(0)$ is the bandgap at 0K and m and n are thermal constants. The Farahm and Modified Caughey Thomas (FMCT) mobility model is employed to determine the low field mobility[11].

3 Results and Discussion

3.1 Hybrid and basicp-n hetero-junction structure

I-V characteristics of hybrid and basic LED structure is shown in Fig. 2. Both LEDs show

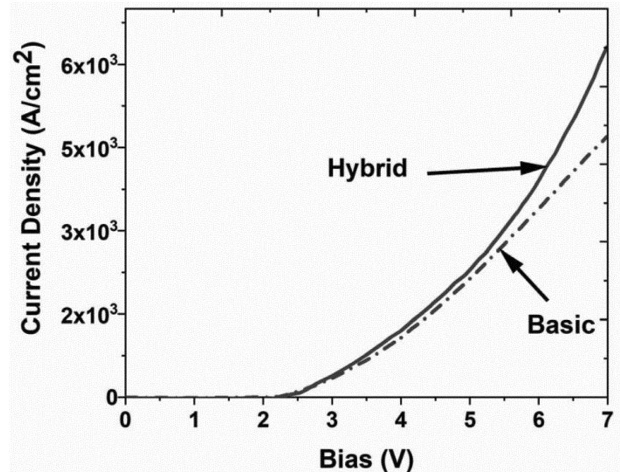

Fig. 2 — I-V curves of hybrid and basic p-n hetero-junction structures

exponential current dependency. The turn-on voltages on both LED structures are nearly the same (~2.2 V). Both LEDs show very high shunt resistances (slope of I-V graph at 0 V) and low series resistances (slope of I-V curve at turn-on potential). The basic In GaN/GaN LED structure show slightly higher series resistance due to multiple quantum well layers and thickness.

Figure 3 shows the emission intensity vs. photon energy curves for hybrid and basic LED structures. The emission intensity of the hybrid LED structure is better than the basic LED structure. This is because of less non-radiative recombination contribution from SRH & Auger. Moreover, in hybrid LED structure emission exists for the large range of wavelengths which in turn produce a wider spectrum and light. In both the LED structures the emission intensity is maximum at 2.35 eV (527.5 nm). Fig 4 shows the normalized internal quantum efficiency (IQE) curves for hybrid and basic LED structures Basic LED shows a large efficiency drop at a higher injection level called as “efficiency droop” problem in GaN LEDs. This is because of a large number of non-radiative recombination’s generally from auger and deep level defects. In basic LED structure the IQE starts decreasing at higher injection level and reduced to 75 % of the initial level at a current density of 1000 A/cm^2 whereas, in hybrid LED structure no efficiency droop is seen up to current density 6500 A/cm^2. Moreover, in a hybrid LED structure the IQE current density increases with current density.

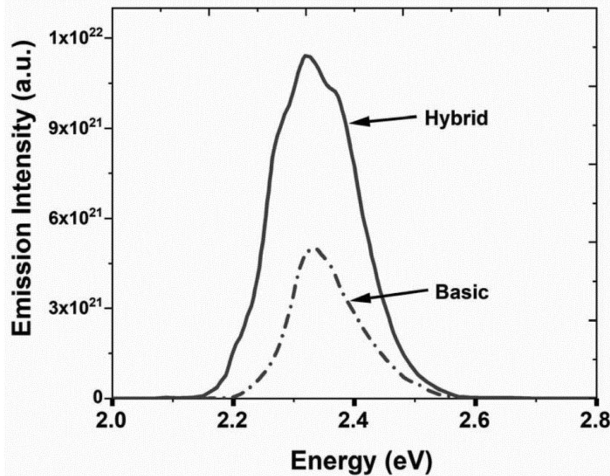

Fig. 3 — Emission Intensity curves of basic and hybrid LED

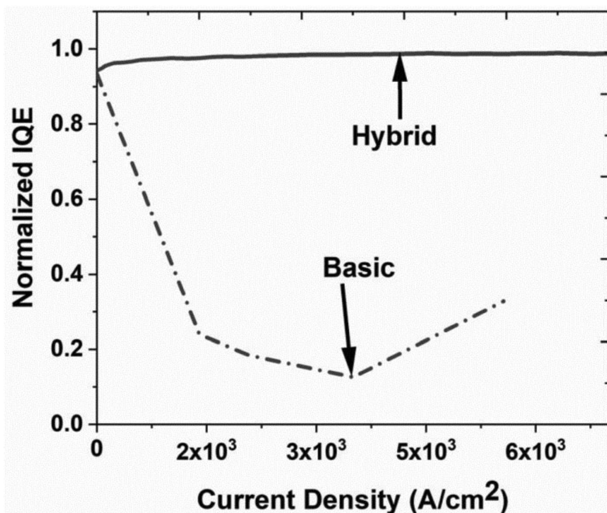

Fig. 4 — Normalized internal quantum efficiency vs. current density of hybrid and basic LED structures

3.2 Hybrid LED structure with different thickness

Further, we studied the effect of quantum well thickness on the efficiency and emission intensity of hybrid LED structure. Fig. 5 shows the variation of IQE with different active layer thickness. For the same current density, the internal quantum efficiency of the hybrid LED structure decreases as layer thickness increases. This is because of the higher resistance of layers. Moreover, in the wider wells, charges are distributed over large distances thus reduces effective carrier density and thus reduces the radiative recombinations and overall IQE decreases. Fig. 6 shows the maximum possible emission for different quantum well thickness. Maximum emission is obtained for layers with higher thickness because with an increase in layer thickness the stress and electric field are relaxed at the interface. Moreover, with increasing layer thickness the emission pattern shifts slightly toward a higher energy level. For 1 nm

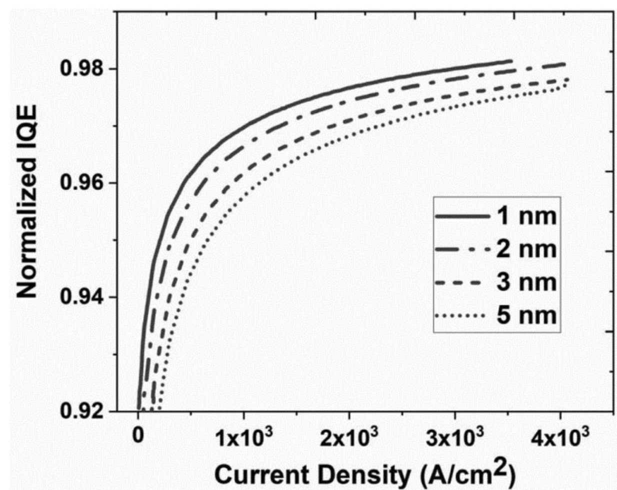

Fig. 5 — IQE Emission intensity of hybrid LEDs with different thickness

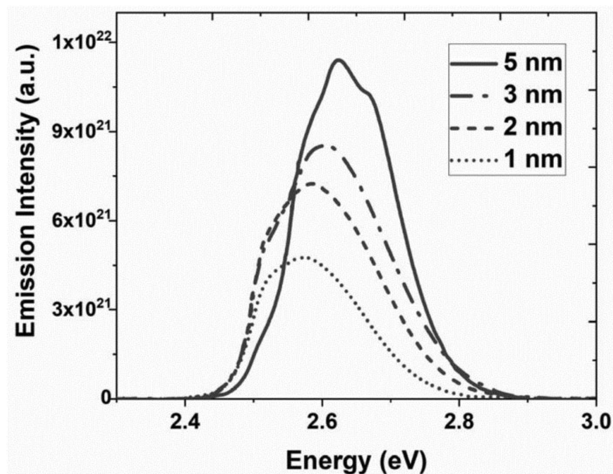

Fig. 6 — Emission intensity of hybrid LEDs with different thickness

well thickness the maximum peak is obtained at 2.57 eV (482 nm) and for 5 nm the peak is shifted towards 2.62 eV (472 nm). This blue shift in emission peak can be correlated with a reduction in internal stress of layers with thickness.

4 Conclusions

Basic LED structure with p-GaN as p-layer, n-GaN as n-layer, and InGaN/GaN quantum wells show large efficiency droop at higher injection level due to reduction in radiative transitions over non-radiative transitions. However, hybrid LED structures containing p-GaN as p-layer and n-ZnO as n-layer and CdZnO/ZnO as quantum wells show no efficiency droop at high injection level due to reduction in stress and strain at the interface. Further, the IQE and peak wavelength in a hybrid LED structure depend upon the layer thickness of the quantum well. Maximum efficiency improvement is obtained for lower quantum well thickness and emission intensity with higher thickness.

Acknowledgements

One of the author B.C. Joshiacknowledges CSIR-Central Electronics Engineering Research Institute, Pilani, India for their valuable support in the present research work.

References

1 Devi V & Joshi B C, *Optoelectron Adv Mater Rap Commun*, 10 (2016) 1.
2 Li X H, Song R, Ee Y K, Kumnorkaew P, Gilchrist J F & Tansu N, *IEEE Photon J*, 3 (2011) 489.
3 Ambacher, *J Phys D: Appl Phys*, 31 (1998) 2653.
4 Ortony J W & Foxonz C T, *Rep Prog Phys*, 61 (1998) 1.
5 Devi V, Kumar M, Shukla D K, Choudhary R J, Phase D M, Kumar R & Joshi B C, *Superlatt Microstruct*, 83 (2015) 431.
6 Pereira L S, Santos A M, Alves J L A, Alves H W L & Leite J R, *Microelectron J*, 34 (2003) 655.
7 Crawford M H, *IEEE J Select Top Quantum Electron*, 15 (2009) 4.
8 Devi Vanita, Kumar Ravinder & Joshi B C, *IEEE J Disp Technol*, 11 (2015) 30.
9 Chuang S L & Chang C S, *Semicond Sci Technol*, 12 (1996) 252.
10 Anderson R L, *IBM J Res Develop*, 4 (1960) 283.
11 Farahmand M, Garetto C, Bellotti E, Brennan K F, Goano M, Ghillino E, Ghione G, Albrecht J D & Ruden P, *IEEE Trans Electron Dev*, 48 (2001) 535.