Investigating the Impact of Quantum Barriers on the Ideality Factor of InGaN/GaN Multi-quantum-well Light Emitting Diodes

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***Abstract*—Electrical Characteristics of InGaN/GaN multi-quantum-well (MQW) light emitting diodes (LED) were simulated for various well/barrier structures in the active region. The results showed that the values of ideality factors are heavily dependent on the properties of the quantum barriers (QB). For a single quantum well LED, the ideality factor (η) was found to be near unity ($\eta = 1.01$) and increased to a value of $\eta = 1.83$ for seven quantum wells separated by six QBs. The value of η also increased with the thickness of the QBs. Further investigation revealed a higher indium concentration in the quantum wells also increases η through an enhancement in the potential of the QBs.**

***Index Terms*—ideality factor, InGaN, light emitting diode, multi-quantum-well, simulation**

I. Introduction

Unlike regular p-n junction diodes, GaN-based LEDs have been reported to exhibit a higher ideality factor ($\eta > 2$) [1], [2]. Some studies link these higher values to factors like current crowding [3] and dominance of tunneling transport [4], [5]. Some works suggest that the rectifying nature of the MQWs results in the formation of multiple junctions within the overall LED heterostructure [6]. These studies indicated that the externally measured ideality factor of the device is a superposition of ideality factors of these individual junctions [7]. As per this theory, the height, width, and the no of quantum barriers in the heterostructure should be a critical determining factor behind these high values of η. Despite studies suggesting triangular band profiles in QBs to be a crucial factor behind high η [8], a comprehensive report on this topic is yet to emerge. However, such a report will provide critical insights, especially for developing higher wavelength InGaN LEDs.

In this work, we simulated the electrical characteristics of InGaN/GaN LEDs for different MQWs and obtained their ideality factor. The results were analyzed with the help of the simulated band diagrams. Theoretical predictions made earlier [7], [8] matched very well with the obtained results, as a clear relation between QBs and the higher ideality factor had been validated.

II. Methodology

The MQW LEDs have been simulated using a one-dimensional drift-diffusion charge control solver (1D-DDCC) [9]. The trap-assisted tunneling model has not been considered for this simulation to observe the effect of QBs explicitly. Also, the p-GaN, n-GaN, and electron-blocking layers were kept identical for this study. Only the MQWs were engineered for the simulation.

III. Results and Discussion

The initial investigation was done by varying the number of quantum wells (QW) in the device. For a single 3 nm QW, without the presence of any QBs, the value of the ideality factor was estimated to be quite close to unity ($\eta = 1.01$). This increased gradually with the inclusion of every new well/barrier pairs (3 nm QW and 10 nm QB) in the heterostructure. The estimated ideality factors are shown in figure 1(a). It can be clearly inferred from the results that the additional QW/QB pairs are causing the formation of additional junctions, increasing the ideality factor of the whole heterostructure. To study the impact of QBs individually, we fixed the no of quantum wells to 5 and varied the thickness of the QBs from 8 nm to 12 nm. The results are shown in figure 1(b). We observed that a gradual increase in the thickness of QBs corresponded to a gradual increase in the ideality factor of the diode. These results attested to a direct correlation between QBs and the ideality factors. A wider QB resists current conduction through the heterostructure, effectively bringing down the current density, which results in the increase of η.

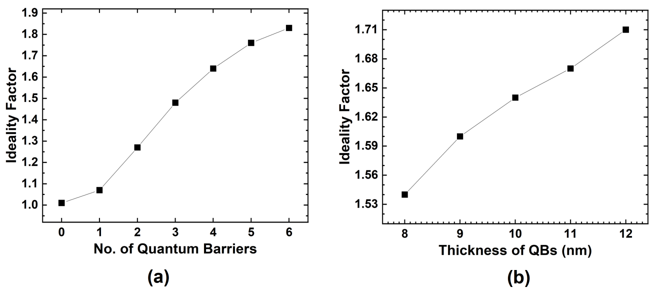

Fig. 1. Ideality factor of the simulated LEDs as a function of (a) No of QBs and (b) thickness of QBs in a 5 QW structure

To explore the ideality factor in higher wavelength regimes, further simulations were done varying Indium concentration in the quantum wells. A five-quantum well structure (3 nm QW and 10 nm QB) was used for this study, and the indium concentration in the QWs varied from 15% up to 45%. The extracted ideality factors (shown in figure 2(a)) increased significantly at higher In-concentrations, reaching $\eta = 3.18$ for sample C. The results suggested higher values of η to be a much more prominent issue for higher wavelength InGaN LEDs. The root of these values can also be traced back to the higher electric field in QBs, as can be seen in the simulated band diagrams in figures 2(b)-2(c).

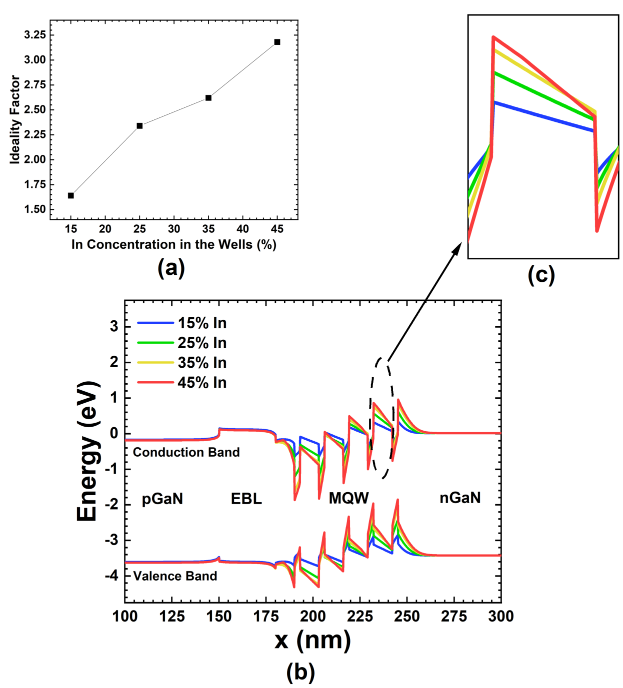

Fig. 2. (a) Ideality factor of the simulated LEDs as a function of Indium incorporation. (b) Simulated band diagram of the LEDs at a forward bias of 3.5 V with (c) an enlarged version of a QB suggesting higher potential barriers for structures with higher In-content

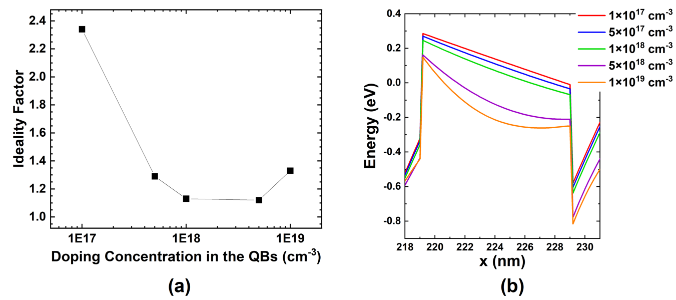

Fig. 3. (a) Ideality factor of the simulated LEDs as a function of doping of the QBs (b) Simulated band diagram of a QB showing doping-induced lowering of barrier potential

One potential solution to the challenge with these high values of η could be flattening the QBs through doping, as suggested in earlier works [8]. We implied this for our structure with 25% Indium and observed a significant reduction in η as shown in figure 3.

IV. Conclusion

Simulation results of different heterostructures showed that the junction formed at the QW/QB interface impacts the external ideality factor of the LEDs significantly, with higher potentials in QBs resulting in higher values of η.

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