Effect of Parabolic Quantum Well on Internal Quantum Efficiency of InGaN/GaN based Micro-LED at low current density

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Abstract— **The quantum cascade stark effect (QCSE) in rectangular shaped quantum well (QW) poses a hindrance to increase the internal quantum efficiency (IQE) of nitride based LEDs. To circumvent the said problem for micro-LEDs operating at low current density, a parabolic QW structure has been proposed which is found to be useful to alleviate the QCSE and to increase the IQE. To emit around 500 nm, it has been observed that use of parabolic QW(instead of rectangular QWs) in the active region of micro-LED results in 10% less applied voltage to reach 0.1 A/cm² current at which ~50% more IQE is obtained. Further a variation in the number of parabolic QWs indicates that a two quantum well structure in the active region of the designed micro-LED will result in maximum IQE at a low current density of 0.1 A/cm². However, the performance of the parabolic QWs are inferior to the rectangular QWs at high current densities where the conventional LED works.**

Keywords—Parabolic quantum well, InGaN, µ-LED, Internal quantum efficiency, Radiative recombination

I. Introduction

III-Nitride-based light-emitting diodes have a wide range of spectrum which can cover the visible spectrum and penetrate deep into the ultraviolet region [1]. LED can be used in various applications including the fabrication of the display, optical communication, storage of information, and solid-state lighting [2,3]. Compared to conventional LEDs, micro-LEDs are smaller in size and have higher resolution, higher colour saturation, longer life, faster response, lower power dissipation, and becoming popular for micro-emitter array applications [4,5,6]. The electron blocking layer (EBL) is used to block the leakage of the majority carrier electron at a high current density [7,8]. Micro-LED is generally operated at a lower current density (<2 A/cm²) [9]. In this article, we have engineered QW in order to minimize the quantum cascade stark effect QCSE at a lower current density and also analysed the effect of the numbers of QW in the active region using One Dimensional Poisson, Drift-Diffusion, and Schrodinger Solver (1D-DDCC) software [10].

II. Device Structure and Parameters

The design of InGaN/GaN-based micro-LED is shown in Fig. 1 which is composed of a 200 nm thick n-GaN layer having a doping concentration of 2 x 10^{18} /cm³, a multiple quantum well (MQW) in active region, and a 150 nm thick p-GaN having a doping concentration of 2 x 10^{19} /cm³. The quantum barrier is 10 nm thick while the quantum well is 5 nm thick. The wavelength of emission depends upon the Indium composition in the active region. The considered value of the Auger recombination coefficient is 1 x 10^{19} cm^6 /s and the other parameters remain the same as the default values set in the software for InGaN material system. We have numerically investigated the optical and electrical properties of InGaN/GaN-based micro-LED using One Dimensional Poisson, Drift-Diffusion, and Schrodinger Solver (1D-DDCC) software.

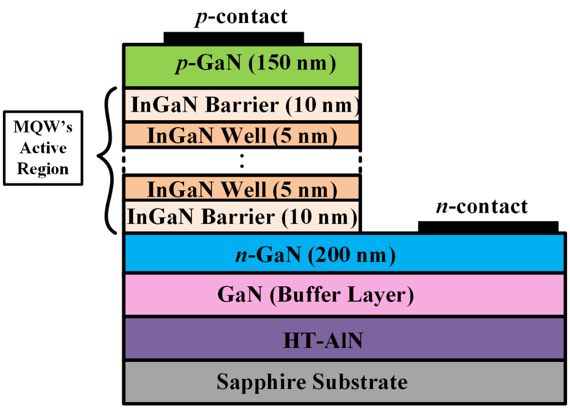

Fig. 1. Device structure.

III. Result and Discussion

The IQE (η_{IQE}) of LED can be written as [11],

$$\eta_{IQE} = R_{rad} / (R_{rad} + R_{non\text{-}rad}) \quad (1)$$

where, is R_{rad} the radiative recombination rate and $R_{non\text{-}rad}$ is the non-radiative recombination rate which is the combination of auger recombination and Shockley-Read-Hall recombination [11]. For increasing the η_{IQE} we needed to maximize the value of R_{rad} and minimize the value of $R_{non\text{-}rad}$. Due to the internal polarization field, QCSE limits the IQE in micro-LED at a lower current density [12]. From the schematic shown in Fig. 2a and 2b the effect of QCSE, i.e., the separation of electron and hole wave functions in rectangular QW and parabolic well can be understood. We designed 2-QW based micro-LED strcture to emit at ~500 nm, both for rectangular (Fig. 2a) and parabolic well (Fig. 2b) shapes. According to our simulation results, in case of rectangular QW, the said separation is ~ 5 Å whereas the same for the parabolic QW is ~ 1 Å at a lower current density of 0.1 A/cm². As a result it has been observed that the radiative recombination for rectangular QW is ~ 1/6 of non-radiative recombination (Fig. 2c) whereas in case of parabolic well the radiative recombination is almost 5 times of non-radiative recombination (Fig. 2d). Thus it is expected that the parabolic QW based LED structure will be more efficient. In Fig. 2e the plot of IQE with applied current

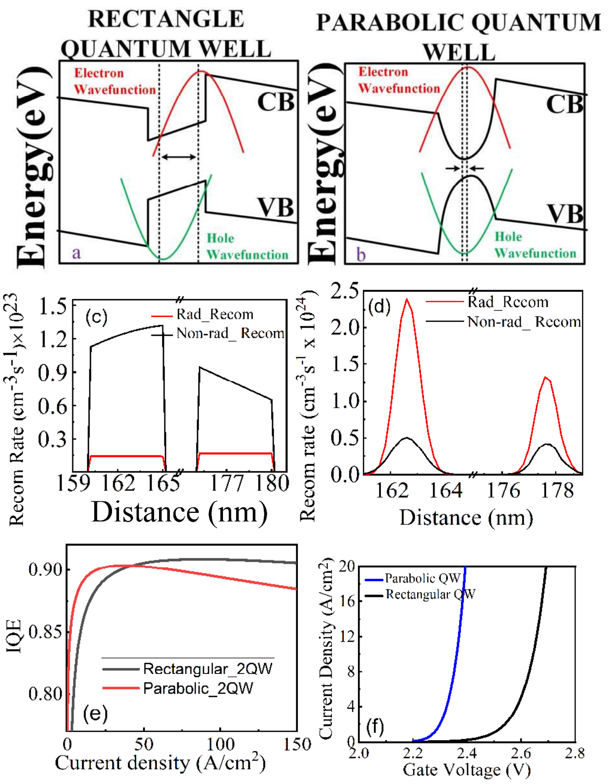

Fig. 2. Schematic diagram of (a) rectangular quantum well and (b) parabolic quantum well. (c) Recombination rate at QWs for rectangular and (d) parabolic wells. (e) IQE vs input current density for both rectangular and parabolic QWs. (f) J-V plot for LEDs containing both rectangular and parabolic QWs

density reveals that indeed the IQE of parablic QW based LED is much more than that of rectangular QW based LED. We have calculated that at 0.1 A/cm^2 input current density the IQE of parabolic QW based LED is ~50% more than its counterpart. Whereas for higher current densities (more than than 50 A/cm^2), the IQE of rectangular QW LED is higher compared to the parabolic QW LED. Therefore for micro-LED, parabolic QW in the active region may be considered to be much more suitable and for conventional LED the rectangular QW has the advantage in performance. Further, from Fig. 2f, it is observed that the micro-LED engineered with parabolic QW relatively possesses a higher current density at a lower voltage compared to the micro-LED with rectangular QW. This results in a reduction in operating

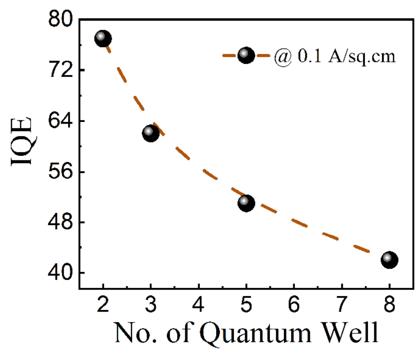

Figure 3. Variation of IQE with number of parabolic QWs in the active region of the micro-LED structure

voltage by ~10% for micro-LED with parabolic QW @ 0.1 A/cm^2 input current density .

Also, simulations were performed with varying number of parabolic QW in the active region of the LED structure. As shown in fig. 3, IQE drastically decreases with increasing number of QW. Therefore, it is concluded that 2 parabolic QWs in the active region for micro-LEDs should produce the optimum results.

IV. Conclusion

In summary, in case of polarization induced in InGaN/GaN QW based micro-LED structure, parabolic QWs are found to be highly beneficial since ~50% more IQE can be obtained with ~10% less input voltage at a standard operating condition (@ 0.1 A/cm^2 input current density). Thus the simulation results show that for the micro-LED operation, the employment of the parabolic QW engineered active region may improve the IQE (and thus External QE) significantly.

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