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Enhancement of Deep Violet InGaN Double Quantum Wells Laser Diodes Performance Characteristics Using Superlattice Last Quantum Barrier

Maryam Amirhoseiny [*,1], Ghasem Alahyarizadeh [2]

[1] Imam Khomeini International University- Buin Zahra Higher Education Center of Engineering and Technology , 3451745346, Buein Zahra, Qazvin, Iran

[2] Engineering Department, Shahid Beheshti University, G.C., P.O. Box 1983969411, Tehran, Iran

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Abstract: The performance characteristics of InGaN double-quantum-well (DQW) laser diodes (LDs) with different last barrier structures are analyzed numerically by Integrated System Engineering Technical Computer Aided Design (ISE TCAD) software. Three different kind of structures for last quantum barrier including doped- GaN, doped- AlGaN and GaN/AlGaN superlattice last barrier are used and compared with conventional GaN last barrier in InGaN-based laser diodes. Replacing the conventional GaN last barrier with p-AlGaN increased hole flowing in the active region and consequently the radiative recombination which results in the enhancement of output power. However it caused increasing the threshold current due electron overflowing. For solving this problem, the last barrier structure altered with GaN/AlGaN superlattice. The simulation indicates that the electrical and optical characteristics of LDs with the superlattice last barrier, like output power, differential quantum efficiency (DQE) and slope efficiency, has significantly improved, besides the threshold current decreased. The enhancement is mainly attributed to the improvement of hole injection and the blocking electron overflowing which are caused by the reduction of polarization charges at the interface between the barrier and well, and electron blocking layer (EBL).

Keywords: InGaN Quantum Well Laser, Superlattice Last Barrier, Electrical And Optical Properties, Numerical Simulation.

[*] Corresponding author. Email: **amirhoseiny_m@yahoo.com**

1. INTRODUCTION

In recent decades, InGaN multi-quantum-well (MQW) laser diodes (LDs) have made great progress in applications such as full-color displays, optical storage, chemical sensors, printing and medical applications [1-5]. III-nitride materials have attracted significant interest because of their specific properties including wide bandgap energy, broad coverage of the electromagnetic spectrum, and high thermal stability, as well as their wide application especially in optoelectronics. InGaN based LDs are one of the most applied devices in commercial products, benefiting its emission wavelength coverage and great performance. In addition, They can be used in various applications for high density optical disc systems [6-9]. However, there are various fundamental properties in LDs structures which necessitate further evaluation.

Although laser action takes place in the wells, the barrier layer is used to prevent coupling between adjacent wells. Therefore, barrier thickness and composition are among the important structural parameters that affect optical and electrical properties of InGaN MQW devices [10-12]. It can be attributed to effects of radiative recombination and nonradiative recombination in the active region with a different barrier structures. Among the various effective parameters for enhancing the LDs performance, the poor hole injection efficiency and the electron leakage are observed as a key factors [13-15]. So, many structural designs have been employed by different research groups to overcome the problems as mentioned above, and improve the performance of GaN-based lighting devices. Using the AlGaN electron blocking layer (EBL) after the last barrier, just before the p-side layers, reduces electron overflow considerably [16-19]. AlInGaN quaternary EBL [20,21], Strain-free GaN-InAlN SLS EBL [20], Wedge-shaped EBL [23], step graded and linearly graded EBL [25], tapered and graded AlGaN EBL [25], quaternary InAlGaN/GaN SLS EBL[26], and quaternary AlInGaN multi quantum-barrier EBL [27] are the other proposed EBL structures to overcome electron overflow. They also significantly decreased built-in polarization. Replacing conventional cladding and waveguide layers by SLS cladding [28] and waveguide layers [29] enhances OCF that results in higher output power. Furthermore, many approaches have been proposed to increase the overlapping of electron and hole wave functions in active region including quantum wells and barriers.

Staggered quantum well is one of the structural designs that submitted as an improved active region for LDs and LEDs [30]. prior studies indicate that replacing the conventional GaN barriers by the InGaN barriers could be effectively reduce the polarization effects between the well and barrier and decrease electron current overflow [31]. Khan et al. and PARK et al. showed that optical properties of InGaN MQWs can be enhanced with quaternary AlInGaN barriers [32]. Using quaternary AlInGaN provide an environment to control the lattice constant and band gap. Employing the InGaN-delta-InN, AlGaN-delta-GaN, and AlInN-Delta-GaN QW is another approach to enhance electron-hole wave function overlap and radiative recombination [33]. Triangular shaped QWs [34], type-II QWs [35], W-shaped QWs [36,37], quaternary AlInGaN barriers [38,39] and InGaN/GaN/InGaN multilayer barriers[40] are the other structural designs in the active region to enrich electron-hole wave function overlap. However, improvement of InGaN- based LDs performance is still under process.

In this paper, we numerically compared the electrical and optical characteristics of InGaN MQW LDs with four different last barrier structures. To enhance the emission efficiency of laser, we proposed the SLS structure on the last barrier. The performance of the InGaN LDs are studied by analyzing the light- current characteristics, DQE, energy band diagram, electron and hole carrier densities, radiative recombination, and LD efficiency.

2. LASER STRUCTURE AND SIMULATION PARAMETERS

The LD original structure used in this study as a reference consists of a 0.4µm n-GaN, a 0.1 µm n-$In_{0.05}Ga_{0.95}N$ compliance layer, a 0.42µm n-$Al_{0.07}Ga_{0.93}N$ cladding layer and a 0.1µm n-GaN waveguiding layer. The double quantum well active region consists of two 2.5 nm $In_{0.082}Ga_{0.918}N$ wells that are sandwiched between 8.5nm of GaN barriers. A 15 nm p-$Al_{0.22}Ga_{0.78}N$ EBL is used to reduce electron leakage on the top of the active region. Next layers consist of a 0.1 µm p-GaN waveguiding layer, a 0.42µm p-$Al_{0.07}Ga_{0.93}N$ cladding layer and a 0. 1µm p-GaN layer, respectively. All three other LD structures consist of an identical layer structure to that of the original structure except for the last quantum barrier. The last quantum barrier of LDs structure are replaced by a p-doped AlGaN layer(structure B), p-doped GaN layer (structure C) and a $Al_{0.15}Ga_{0.85}N$/GaN superlattice (structure D), respectively. The schematic diagrams of the LD structures are shown in Fig. 1.

The laser simulation process was carried out using Integrated Systems Engineering Technology Computer Aided Design (ISE-TCAD) software. The simulation parameters are the same as those used in our previous studies [41].

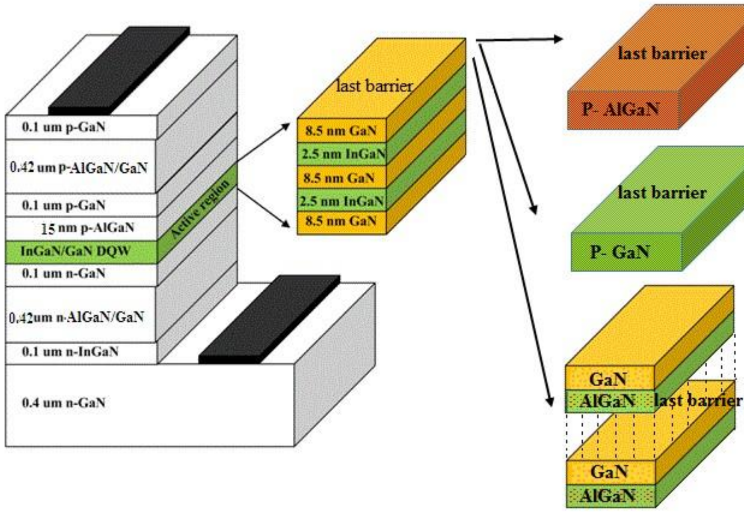

Figure 1 : Schematic diagram of InGaN MQW LDs with GaN (original structure), p-AlGaN barrier, p-GaN barrier, and AlGaN/GaN superlattice Last barrier.

3. SIMULATION RESULTS AND DISCUSSION

The threshold current, output power, slope efficiency, and differential quantum efficiency (DQE) of the four different structure of deep violet $In_{0.082}Ga_{0.918}N/GaN$ DQW LDs are shown in Fig. 2. Using p-doped AlGaN barrier instead of the last GaN barrier layer of original structure presents higher values for the output power, slope efficiency, and DQE, compared with the original $In_{0.082}Ga_{0.918}N/GaN$ DQW LD while the threshold current is also increased. Another alternative to replace with conventional GaN last barrier is using p-GaN last barrier. P-GaN last barrier considerably decreases threshold current while other performance characteristics do not enhance remarkably. By replacing the last barrier structure with AlGaN/GaN SLS, LDs performance characteristics are improved remarkably compared with all other three structures besides the threshold current degraded which can be explained by exploring the energy diagrams of the four structures.

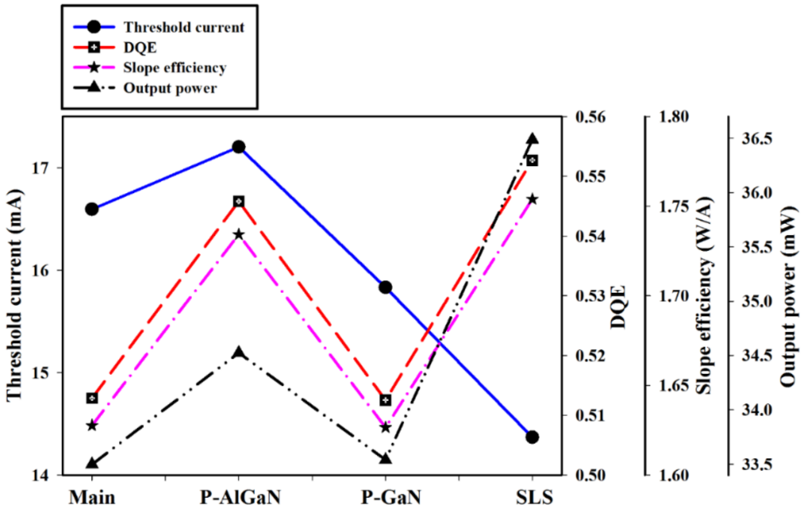

Figure 2: The threshold current, slope efficiency, output power and DQE of the four structures of deep violet InGaN DQW lasers

Fig. 3 shows the conduction and valence band energies and their quasi Fermi levels of the four different structure of deep violet $In_{0.082}Ga_{0.918}N/GaN$ DQW LDs. As shown in Fig. 3, the barrier structures are strongly affected on conduction, valance band and their Fermi levels of LDs. The differences between conduction band energies and their quasi Fermi levels can express the possibility of electron leaking to the EBL layer to flow in the p-typed layer. Finding a structure which can increase this difference, would help decreasing the electron leakage and so on reduction the threshold current. On the other hand, the differences between valance band energies and their quasi Fermi levels can define injection of holes to the active region and caused the increasing of radiative recombination which would enhance the output power. The best structure should have both of these factors to achieve improvement of output power, slope efficiency and DQE within the reduction of threshold current.

The energy band of the last quantum barrier is pulled down seriously by a strong electrostatic, which is caused by the compressive strain. Using the p-type doping in the last barrier is also helping holes to transfer across the EBL into the quantum well nearby the n-type layers. Results show that the effective potential height for electrons in the conduction band of the SLS barrier (565 meV) is much higher than that of the other three structures, and the effective potential height for holes in the valence band at the same part (129 meV) is much lower than that of the other three structures. The higher effective potential between conduction band and Fermi level decreased the threshold current in p-GaN and SLS barrier structures as discussed in Fig 2.

A strong piezoelectric polarization field can be generated due to the lattice mismatch between AlGaN layer and the GaN layer in the SLS structure. The piezoelectric polarization field and the spontaneous polarization field can pull down the GaN energy band and pull up the AlGaN energy band. Therefore the energy band of the AlGaN/GaN SlS last barrier is bent. Consequently, the height of effective potential barrier for electrons in the conduction band is enhanced and so the electron leakage can be effectively decreased. However, due to the declined band bending effect affected by the polarization field, the potential barrier for holes is reduced. This can strongly create the injection of holes into the active region which increase the overall hole concentration [42]. The same trend can be seen in the carrier current densities in Fig 4.

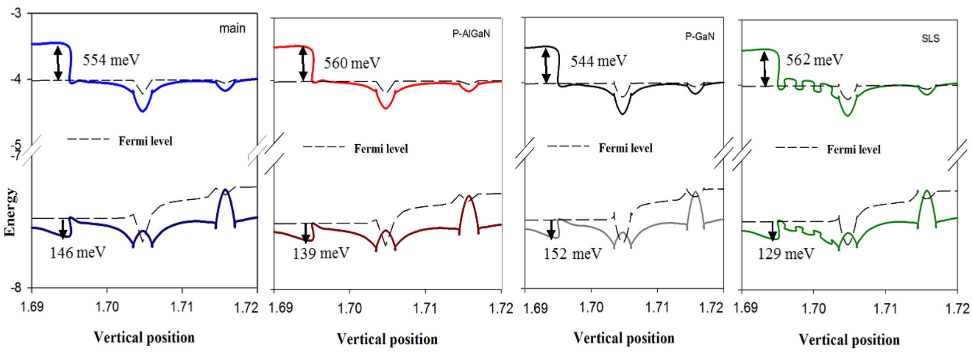

Figure 3: Energy band diagrams of the four structures of deep violet InGaN DQW lasers

It can be seen that the hole current density in the active region of SLS structure is the largest among the other structures, because the hole injection efficiency is effectively improved due to the lowest effective potential height as we explained before. Electron carrier density is another carrier which contribute in the radiative recombination. As mentioned before, electron leakage has main role in reduction of the radiative recombination. The SLS last barrier provide the lowest electron leakage among the four recommended structures.

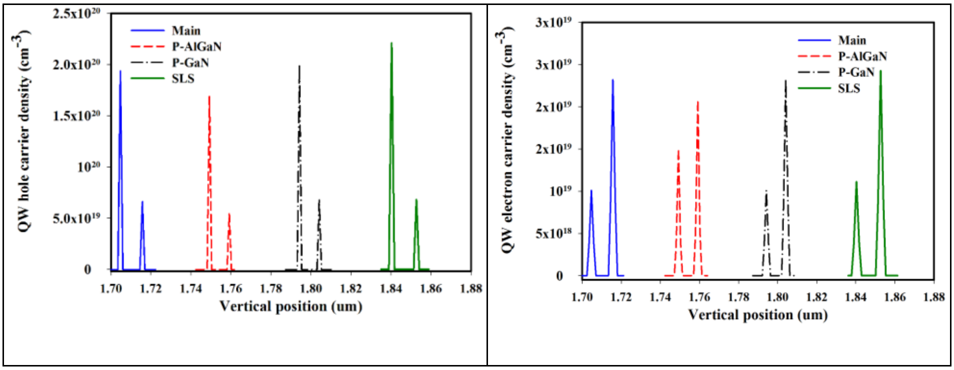

Figure 4: carrier current densities of the four structures of deep violet InGaN DQW lasers

The radiative recombination rates of the four structures are shown in Fig. 5. According to knowledge that by increasing the carrier concentration, more electrons can stay in the active region which would be recombined with holes. Therefore, the efficiency droop is reduced due to more quantum wells contribution to the radiative recombination. As a result, it can be seen that the radiative recombination rate in SLS structure, is higher than original and p-GaN structures due to the enhancement of electron confinement and hole injection efficiency.

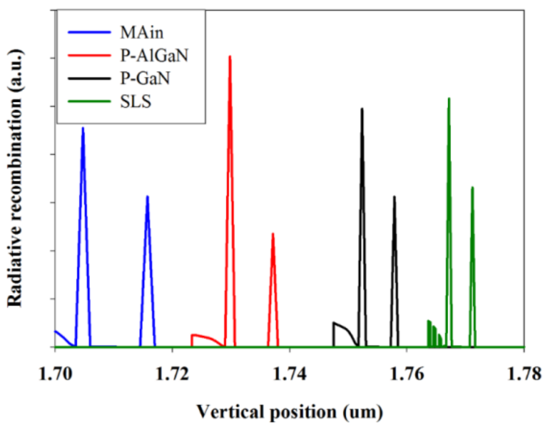

Figure 5: Radiative recombination rates of the four structures of deep violet InGaN DQW lasers

The optical intensity of the four of the InGaN DQW LDs with four different barrier structures are shown in Fig 6. Existance of more the carriers in LDs to be accumulate in the active region, improve the stimulated recombination rate in the active region and resulting enhancement of optical intensity of LDs. It is observed that the InGaN laser with SLS structure has highest carrire current density between all four structures and good radiative recombination in active region which caused the highest optical intensity of this LDs. Although, the results show that InGaN DQW laser with p-AlGaN last barrier structure has the highest radiative recombination, but it has lower optical intensity than the InGaN DQW laser with SLS structure may due to the higher leakage current.

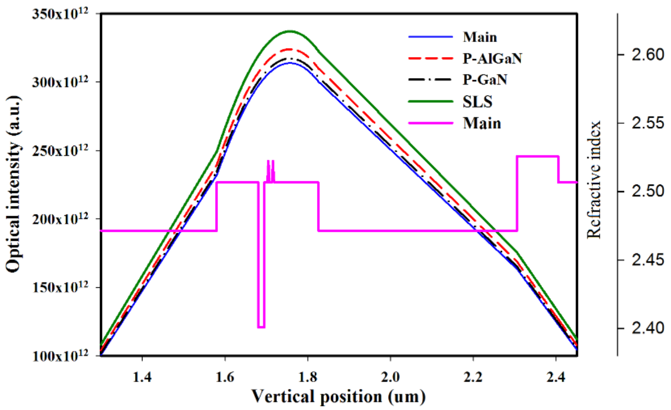

Figure 6: The optical intensity of the four structures of deep violet InGaN DQW lasers

The light output characteristics of the InGaN DQW LDs with four different barrier structures are shown in Fig. 7. As shown in this figure, the LD structure with AlGaN/GaN SLS last barrier has considerably higher output power compared to other LD structures. The output power strongly depend on the photon density inside the cavity. Based on the presented results (Fig. 3 and Fig.4), InGaN DQW LDs with SLS and p-AlGaN last barrier have the highest current density, respectively; which also have the highest output power too. The output power results are completely in good agreement with the previous discussed outcomes and also with the reported experimental results [43,44].

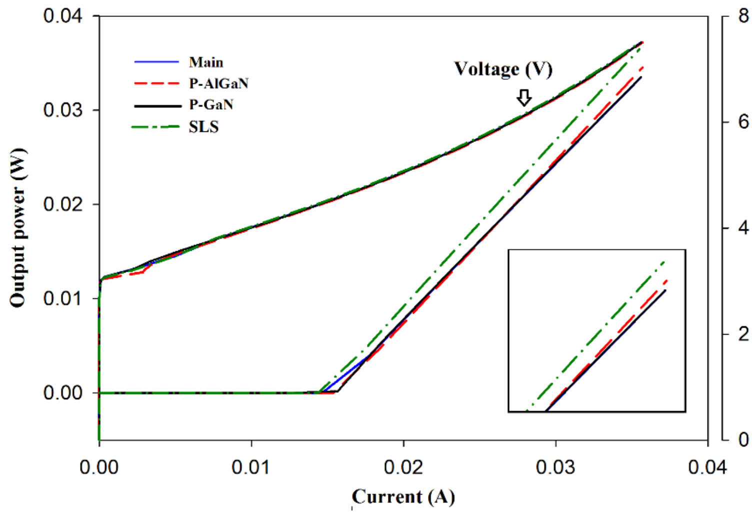

Figure 7: Light output characteristic (L-I) of the four structures of deep violet InGaN DQW lasers

4. CONCLUSION

To enhance of InGaN DQW LDs characteristics, a different designed LD is proposed with doped barrier and a AlGaN/GaN superlattice last quantum barrier. The simulation results indicates that the optical properties of the LDs are significantly enhanced owing to the increase of hole injection, the reduction of electron leakage, and the better radiative recombination in the QWs. Compared with the LDs using p-doped GaN, p-AlGaN barriers, the laser with AlGaN/GaN superlattice last quantum barrier exhibits the best characteristics. The reason could be effects of the generated strong piezoelectric polarization field due to the lattice mismatch between AlGaN layer and the GaN layer in the SLS structure. The best structure showed an improvement of output power, slope efficiency and DQE within the reduction of threshold current.

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