Hole Injection Enhancement in InGaN Laser Diodes

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Abstract: Performance of blue laser diode improved by adding 5 nm p-GaN layer prior to electron blocking layer. Decreased polarization discontinuity reduces band bending, which enhances hole transport from 7.698 kA-cm^{-2} to 8.961 kA-cm^{-2}, reduces electron leakage from 2.546 kA-cm^{-2} to 0.842 kA-cm^{-2} and laser power improves from 146.54 mW to 204.8 mW at 10 kA-cm^{-2}.

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1. Introduction

InGaN laser diodes (LDs) have wide range of applications in under-water communication, free space visible light communication, LiDAR, bathymetric imaging, spectroscopy etc. However, the performance of LDs is limited due to various carrier and photon loss mechanisms. Efficient carrier injection is required to improve the performance of the device. Also, carrier leakage should be suppressed to improve radiative recombinations in Quantum Wells (QWs).

In this work, we have employed a 5 nm p-GaN layer prior to EBL to enhance the hole injection into the active region of LD. The reasons of enhanced hole injection are investigated in detail. With the additional GaN layer, electron leakage from the active region reduced significantly.

2. Device Structure

In this numerical simulation study, we have employed a LD structure, which was experimentally grown, fabricated and characterized by Muziol et al. [1] referred as reference LD. Figure 1 depicts, reference LD structure and the modified structure. Bottom cladding is 700 nm n-$Al_{0.065}Ga_{0.935}N$, top cladding is 400 nm p-$Al_{0.065}Ga_{0.935}N$. Lower core of the waveguide is 100 nm n-GaN + 80 nm undoped-$In_{0.08}Ga_{0.92}N$. Active region consists of 2.6 nm u-$In_{0.17}Ga_{0.83}N$ 3 QWs optimized for 450 nm emission each separated by 8 nm u-$In_{0.08}Ga_{0.92}N$ barriers. Upper core of waveguide is 60 nm u-$In_{0.08}Ga_{0.92}N$ + 100 nm p-GaN. EBL is 30 nm p-$Al_{0.15}Ga_{0.85}N$ layer which is inserted between InGaN and GaN layers of upper core layers. In this work, we have inserted a 5 nm p-GaN layer prior to EBL in the reference LD structure.

The numerical simulations are carried out in commercially available, SiLENSe 5.12 Laser edition tool. This recent version of the tool employs the Schrödinger equations for electron and holes with the potential energy determined from a self-consistent solution of the Poisson and drift-diffusion transport equations [2]. It also calculates waveguide modes and optical confinement in QWs. Band structure parameters and material properties can be found in Ref. [3].

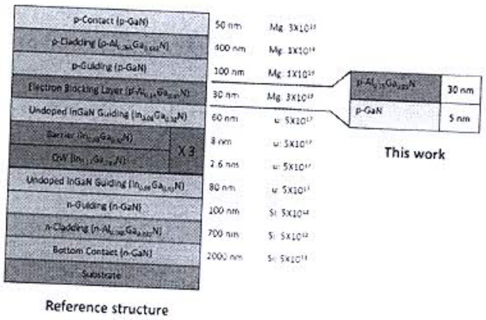

Figure 1 Reference and modified LD device structure

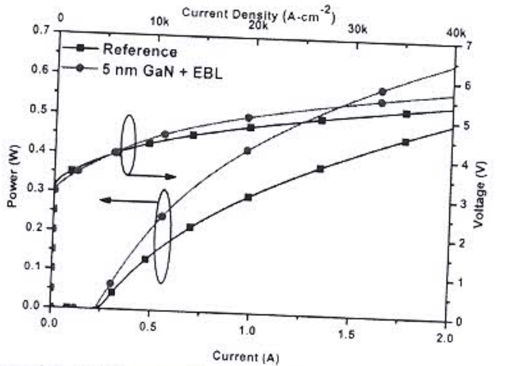

Figure 2 L-I-V characteristic of reference and modified LD.

3. Results and Discussion

Figure 2 shows the L-I-V characteristic of reference LD as well as the LD under investigation. Threshold current density of reference and 5 nm GaN + EBL LD are 4.905 kA-cm^{-2} and 4.511 kA-cm^{-2} respectively. Light output power increases from 146.54 mW to 204.8 mW at injected current density of 10 kA-cm^{-2}. Slope efficiency of LD improves from 0.548 W/A to 0.774 W/A. Dynamic resistance increases from 816 mΩ to 959 mΩ due to additional p-GaN layer. Injection efficiency at the threshold current increased from 0.78 to 0.83.

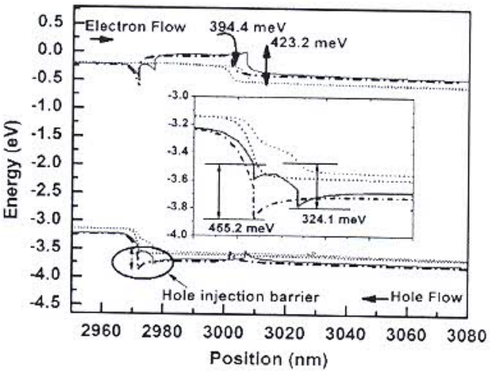

Figure 3 Energy band diagram showing enhanced hole injection and electron leakage suppression

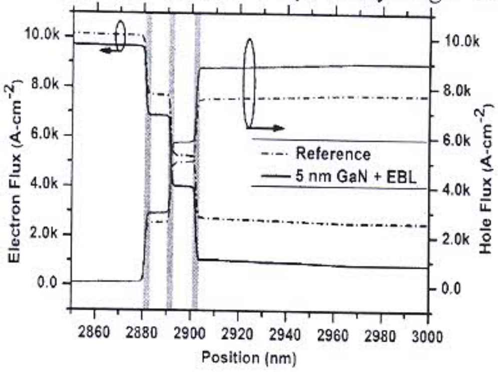

Figure 4 Carrier flux showing the enhanced hole transport and reduced electron leakage

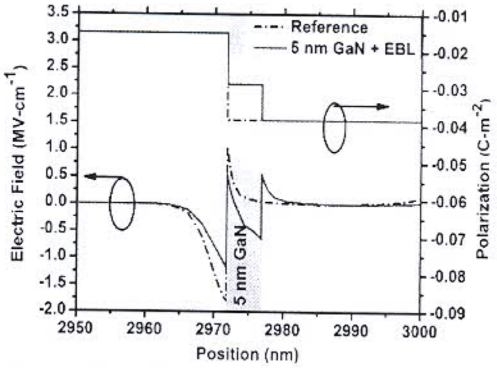

Figure 5 Polarization discontinuity and electric field at the interface of EBL

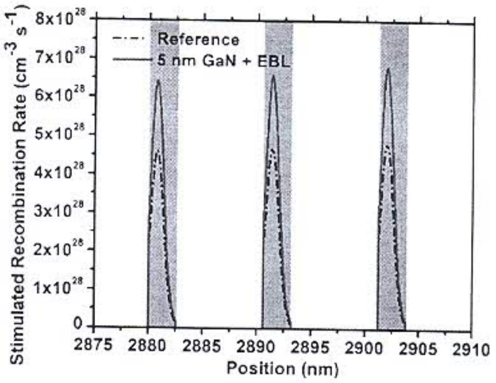

Figure 6 Stimulated recombination rate in QWs

Figure 3 compares the band diagram for both the LDs. The enlarged view of valence band discontinuity at the EBL interface is shown in the inset graph. Energy bandgap difference at the interface layers is accommodated with the band bending. Large lattice mismatch between these layers results into piezoelectric polarization in addition to spontaneous polarization. Electric field induced by total polarization leads to band bending at the interface. In reference LD, the energy barrier induced at the interface for the hole transport is 455.2 meV which reduces to 324.1 meV with additional 5 nm p-GaN layer. Also, the barrier for electron leakage increased from 394.4 meV to 423.2 meV. It is clear from Figure 4, the hole flux enhanced from 7.698 kA-cm^{-2} to 8.961 kA-cm^{-2} and electron leakage flux reduced from 2.546 kA-cm^{-2} to 0.842 kA-cm^{-2} at the injected current density of ~10 kA-cm^{-2}. From Figure 5, it shows that, the polarization discontinuity at the interface have reduced from 0.0235 to 0.014 C-m^{-2} which have reduced electric field at the interface and reduced band bending to enhance the hole injection. Figure 6 shows the stimulated recombination rate in the QWs. Increase in light output power is attributed to the increased stimulated recombinations due to enhanced hole injection in to the active region.

4. Conclusion

Hole injection to the active region has been enhanced by inserting a 5 nm thin p-GaN layer. Reduction in polarization discontinuity reduced the induced electric field. Stimulated recombinations are increased in QWs, which resulted into decreased threshold current density and increased LD output power and slope efficiency.

5. Acknowledgement

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