Lateral Carrier Confinement and Threshold Current Reduction in GaN QW Lasers with Deeply Etched Mesa

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Abstract- **Shallow etch depths may contribute to a reduction in the optical gain of MQW lasers through the lateral diffusion of carriers away from the region of greatest optical intensity. Deeply etched mesas can prevent this lateral diffusion, but may themselves contribute to a degradation of optical gain if the sidewalls are not effectively passivated. Simulation results considering the effects of surface recombination velocity (SRV) at the edge of the etched active layers indicate that SRV must be reduced below approximately 10^5 cm/s in order for deep etch designs to provide benefit. Very few experimental studies quantify the efficiency of GaN surface passivation in terms of SRV. Further experimental studies are required to better assess the viability of deep etch MQW laser designs.**

I. INTRODUCTION

Pure blue-green LDs are promising light sources for mobile full color laser projection display [1]. Although green lasers based on second harmonic generation technologies are already available, semiconductor LDs have advantages in size, stability and efficiency. Unfortunately, there are several challenges to be solved until the growth of InGaN LDs emitting at longer wavelength can be successful. It has been demonstrated that the threshold current density of LDs increases with emission wavelength from violet to blue-green [2]. The probable reasons are polarization related electric field which degrades the quantum efficiency (QE), dissociation of InGaN well layer with high In content at high growth temperature, and In fluctuation which increases with In composition [3]. Optical confinement factor can also influence the threshold density of LDs. Zhang et al. showed that confinement factor can be increased and hence threshold current of relatively low QE UV and blue-green LDs can be reduced if the well layers in MQW are made thicker [4].

Lateral carrier diffusion and surface recombination current in mesa sidewalls can also increase threshold current. Once carriers enter the quantum wells (QWs), the large lateral concentration gradient forces them to diffuse laterally outwards inside the well. Consequently, a significant portion of the current does not provide useful gain to the optical modes and hence dissipates as heat. To alleviate the problem, carriers must be confined laterally inside the QWs. There are different ways to confine carriers laterally inside a QW. Sugawara *et al.* proposed quantum structure intermixing (QSI) from the lateral direction of the mesa sidewall to improve the performance of VCSELs [5]. Chen *et al.* presented a theoretical analysis for different active layer structures to minimize the laser threshold current of the ultraviolet GaN/AlGaN multiple-quantum-well laser diodes [6]. Although they have investigated different internal physical mechanisms to analyze laser threshold properties but issues like etch depth, electrical insulation layer properties, sidewall recombination current and surface passivation effects are not addressed in their article. One can laterally confine carriers and hence reduce threshold current with deeper etch depth to keep the active region inside the mesa bounded by insulator. But deeper etch depth can degrade device performance because of the formation surface states at the lateral edge of the QWs during fabrication unless the sidewalls are properly passivated.

In this article, we have theoretically investigated the possibility of lateral carrier confinement inside QWs of InGaN/GaN Edge Emitting Laser (EEL) by etching all the way down to the active region and below it. Simulation results show that if the surface recombination velocity (SRV) can be reduced below a certain level at the edge of the QWs, the laser structure can take the advantage of deeper etch to reduce threshold current.

II. DETAIL OF SIMULATION

Simulated Edge Emitting Laser structure contains 2 QW (GaN/$In_{0.27}Ga_{0.73}N$) where the barrier thickness is 8.8 nm and well thickness is 2.2 nm for both the QWs. Drift-diffusion simulation is coupled self-consistently with a scalar finite element optical mode solver in order to characterize our devices both electrically and optically. The optical and electronic parts of the equations are linked through the gain and optical generation and recombination calculations. To describe transport across the InGaN/GaN heterojunctions accurately, a thermionic emission model is employed. Electronic equations and photon generation rate are solved self-consistently with the wavelength calculation using an iterative gummel scheme.

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III. RESULTS

Due to the limitations of fabrication technology, it is known that etch depth cannot be controlled in nano meter precision range. Hence two cases are considered. One is when we etch down to the top surface of Electron Blocking Layer (EBL) and the other is when we etch down to n-wave guide region so that the active region is inside mesa. Simulation results show that threshold current decreases significantly and also slope (L-I curve) efficiency increases when we etch deep (See Fig. 1). Such a deeper etch-depth shuts off the lateral diffusion of active carriers inside the QWs and forces them to flow through the optical mode and remain there for longer period. Hence, for lower threshold current, the LASER gets turned on. In order to understand the effect of lateral diffusion only, we did not include any surface trap states in the well-oxide interface to simulate Fig. 1.

Unpassivated interface of deep etched active layer and electrical insulation material is rather poor with higher surface states density. So, injected current tends to flow near the interface and away from the optical mode profile due to higher surface recombination velocity. Hence threshold current increases and slope efficiency decreases in a deep etched EEL with unpassivated sidewall. In our device simulator, default value of surface Shockley-Read-Hall (SRH) recombination velocity is 10^3 cm/s. We have simulated deep etched EEL for different SRV to see its effect on threshold current and slope efficiency of L-I curve. Results are shown in Fig. 2. It is clearly evident that higher SRV (i.e. higher surface states density) increases threshold current and degrades slope efficiency. From Fig. 2, it can be concluded that if we can reduce SRV below 10^5 cm/s at the etched edges of the active region, then deep etched design of EEL will be meaningful to reduce threshold current and improve slope efficiency. Y. J. Lin *et al.* reported a reduced SRV of 4.7×10^4 cm/s when they treated n-GaN surface with $(NH_4)_2S_x$ [7]. They attributed the reason to the accumulation of majority carriers and repulsion of minority carriers near the n-GaN surface and also to the removal of the native oxide and sulfur passivation. Further experimental studies are required to better evaluate the feasibility of deep etch MQW laser designs.

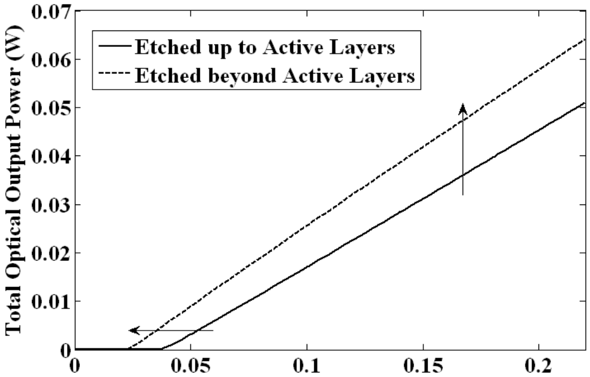

Fig. 1. Effect of etch depth on L-I curve. Higher etch depth decreases threshold current and increases slope efficiency as the active region is confined within the mesa width.

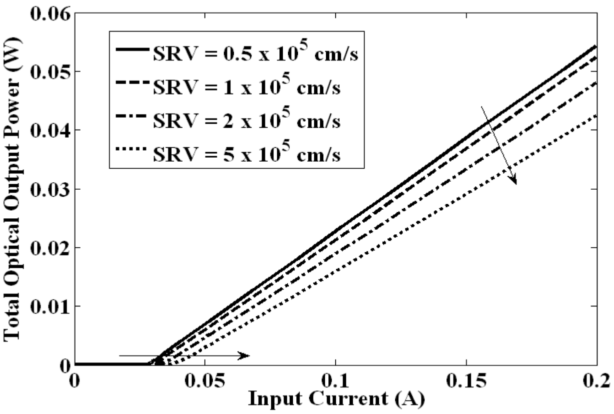

Fig. 2. Effect of surface recombination velocity (SRV) on L-I curve. Higher SRV increases threshold current and reduces slope efficiency as the injected carriers prefer to flow through the sidewall.

IV. CONCLUSION

We have investigated the influence of deeper etch depth on the threshold current of InGaN/GaN Edge Emitting QW laser. Simulation results show that deeply etched mesa can reduce threshold current and increase slope efficiency of L-I curve if the surface of the sidewall is properly passivated. Deep etch design will be useful for practical devices only if SRV can be reduced below 1×10^5 cm/s. So far, very few studies reported the effectiveness of the surface passivation technique for GaN in terms of SRV.

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