Greatly Improved Carrier Injection in GaN-based VCSEL by Multiple Quantum Barrier Electron Blocking Layer

Dan-Hua Hsieh[1], An-Jye Tzou[1,2], Da-Wei Lin[1], Tsung-Sheng Kao[1], Chien-Chung Lin[1,3], Chun-Yen Chang[2], Hao-Chung Kuo[1,*]

[1]*Department of Photonic & Institute of Electro-Optical Engineering, National Chiao Tung University, Hsinchu 30010, Taiwan*
[2]*Department of Electrophysics, National Chiao Tung University, Hsinchu 30010, Taiwan*
[3]*Institute of Photonics System, National Chiao Tung University, Tainan, Taiwan*

[*]hckuo@faculty.nctu.edu.tw

***Abstract*—In this report, the fabrication and characteristics of III-nitride based vertical-cavity surface-emitting laser (VCSEL) with bulk AlGaN and AlGaN/GaN superlattice electron blocking layer (EBL) are observed experimentally and theoretically. The results have been revealed that laser performance is improved by using superlattice EBL. The output power and the slope efficiency are enhanced by the improvement of carrier injection into active region. And the reduction of threshold current density from 10 to 8 kA/cm2 is also observed. Theoretical calculation results suggest that the improved carrier injection efficiency can be mainly attributed to the partial release of the strain at the interface of last quantum barrier and superlattice EBL and hence the increase of electrons and holes effective barrier height.**

***Index Terms*—GaN-based VCSELs, Multiple-quantum-barrier electron blocking layer**

I. INTRODUCTION

Recently, III-nitride based materials have attracted intensive attention due to its potential application in visible and ultraviolet light emitting, which cover the region from ultraviolet to green. The development of III-nitride based blue laser diodes (LD) is thus a result of the improved quality of III-nitride based materials , which provides important application in high-density optical storage [1,2]. Compared with LD, the development of III-nitride based vertical-cavity surface-emitting laser (VCSEL) could provide several advantages over LD, such as circular beam shape, on-wafer testing, low threshold current. However, because of large lattice mismatch between AlN and GaN, the in-situ growth of AlN/GaN DBR becomes a critical issue. Secondly, the large difference between electron and hole mobility, and significant polarization field within III-nitride based materials, which can cause electron leakage from active region to the p-side, and the low injection efficiency of holes from the p-side [3]. To solve this problem, the common method is to insert a p-doped bulk AlGaN EBL between the last quantum barrier and p-GaN. However, such type of EBL has been reported that the downward band-bending induced by the serious polarization at the interface between the last quantum barrier and EBL can reduces the effective potential height for electrons. In addition to the conventional bulk AlGaN EBL, several EBL structures had been proposed, such as graded composition bulk p-AlGaN EBL, ternary p-InAlN EBL and p-AlGaN/GaN multiple quantum barrier (MQB) EBL [4]. In this report, we report the fabrication of GaN-based VCSELs with AlGaN/GaN MQB EBL. With the use of MQB EBL, the threshold current density and the output power show significant improvement compared with the use of conventional bulk EBL.

II. EXPERIMENT DETAILS

The devices are grown by MOCVD on the sapphire substrate, the structure consists 25 pairs un-doped AlN/GaN DBR as bottom reflector. A 880 nm n-doped GaN, 5 pair InGaN/GaN MQWs, and then 20 nm Mg-doped p-type $Al_{0.2}Ga_{0.8}N$ is directly grown on the last quantum barrier as the EBL, followed by a 100 nm p-doped GaN. After the growth of optical cavity and bottom DBR, SiNx is deposited by PECVD and a 10 um aperture is defined. ITO current spreading layer is deposited sequentially on the aperture. Finally, 10 pairs Ta_2O_5/SiO_2 dielectric top DBR is deposited onto ITO layer. For GaN-VCSEL with MQB EBL, bulk EBL is replaced by 5 pairs $Al_{0.2}Ga_{0.8}N$ (2nm)/GaN (2 nm) MQB. The device after fabrication are shown in Figure 1, which shows the GaN-based VCSEL structure, device A and B denote VCSELs with bulk EBL and MQB EBL, respectively.

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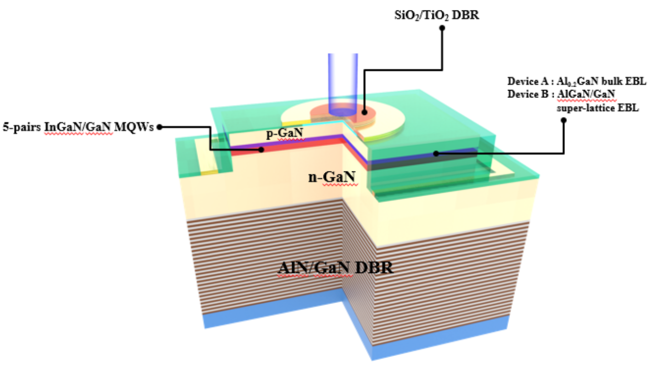

Fig. 1. Figure 1 device structure of the GaN-based VCSELs with bulk/MQB EBL.

III. RESULTS AND DISCUSSION

Figure 2 shows the simulated band diagram of device A and B by Photonic Integrated Circuit Simulator in 3D, (PICS3D) [5]. The results reveal a higher/lower potential barrier for electrons/holes in device B, which is due to the reduced polarization field by using superlattice structure.

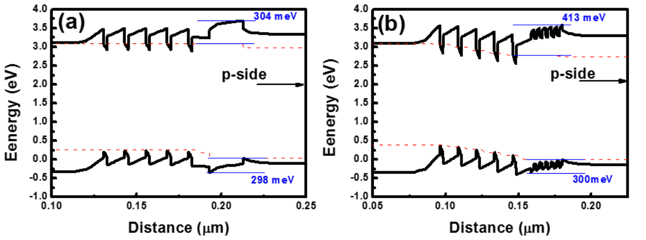

Figure 2 band diagram of the GaN-based VCSEL devices with (a) bulk and (b)MQB EBL.

In addition to the released polarization field, MQB structure can provide a virtual potential barrier higher than the bulk structure due to the effect of quantum interference [6], which can be seen in Figure 3. Figure 3 (a) and (b) are the simulated electron and hole reflectance spectrum induced by different EBLs, by using the MQB structure, it provides higher reflectance for electrons with higher energy (figure 3 (a)), but less holes will be reflected (figure 3 (b)). The dip in figure 3 (a) and (b) for device B is due to the quantum tunneling, however, only electrons with specific energy can tunneled through the MQB structure.

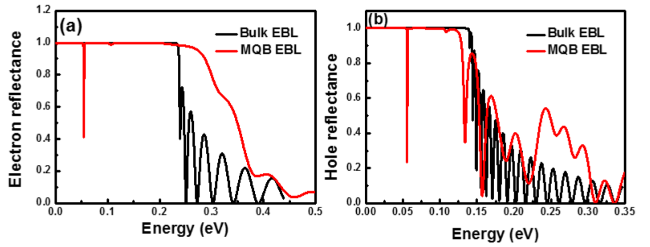

Figure 3 reflectance spectrum for (a) electrons and (b) holes with different EBL structures.

Figure 4 (a) and (b) show the 2-dimensional electron flow, from the result it can be seen that the electron leakage is much smaller in device B than in device A, especially near the aperture edge (labeled as white dashed rectangles). Such results are well related to the released polarization field and the higher virtual potential barrier for the use of MQB EBL in device B. Figure 4 (c) is the experimental and the simulated light-current density curves for both devices, the threshold current density is reduced from 12 kA/cm^2 (device A) to 10 kA/cm^2 (device B), and the output power is also increased by about 2.5 times with using MQB EBL.

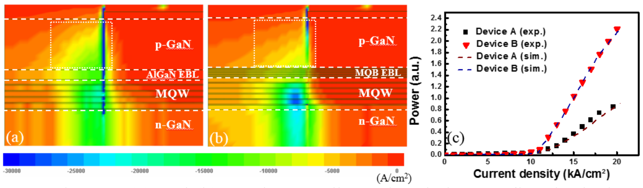

Figure 4 (a) and (b) are the two-dimensional electron flow in devices with different EBL structures, (c) experimental and simulated light-current density curves.

IV. CONCLUSION

In summary, the GaN-based VCSELs with bulk and MQB EBL are fabricated successfully. The GaN-based VCSEL with MQB EBL shows an improved performance with better electron confinement, the origin of such improvement is observed via the theoretical calculation, which reveals the higher potential barrier at conduction band due to the partial released strain by MQB structure, and larger virtual energy barrier induced by the quantum interference within MQB structure. The threshold current density shows a reduction from 12 kA/cm^2 to 10 kA/cm^2. In addition, the light output power of MQB-EBL VCSEL shows about 2.5 times enhancement as compared with conventional one.

ACKNOWLEDGMENT

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