Extended Abstracts of the 2022 International Conference on Solid State Devices and Materials, Makuhari, 2022, pp27-28

Significant Improvement of Injection Efficiency in Deep-UV LD Structures by Light Mg Doping in p-Core Layer

Yuri Itokazu [1, 2], Noritoshi Maeda [1], Hiroyuki Yaguchi [2], and Hideki Hirayama [1]

[1] RIKEN
2-1 Hirosawa, Wako, Saitama, 351- 0198, Japan
Phone: +81-80-4802-0822 E-mail: yuuri.itokazu@riken.jp
[2] Univ. of Saitama
255 Shimo-Okubo, Sakura-ku, Saitama, Saitama, 338-857, Japan

Abstract

Improvement of injection efficiency is essential to achieve lower threshold and shorter wavelength LDs. We have confirmed that the introduction of electron blocking layer and Mg doping layer into the core layer significantly improves the injection efficiency. In this study, we show that optimizing the Mg doping level in the core layer improves the external quantum efficiency by a factor of about 10 compared to the non-doped sample. This is because the dip in the conduction band due to polarization charge at the core/cladding layer interface is suppressed by ionized Mg activated by the Poole-Frenkel effect.

1. Introduction

Laser diodes (LDs) have advantages such as compactness, long life, and low power consumption. Hence, they are expected to be realized in a variety of wavelength bands. Recently, laser oscillation in the UVC[1] and UVB[2] regions has been reported; the shortest wavelength of LDs is 271.8 nm. The injection efficiency of deep-ultraviolet (DUV) LDs is low, and this trend will become more pronounced at shorter wavelengths. Improvement of injection efficiency is essential to achieve lower threshold and shorter wavelength LDs.

We have shown that the introduction of electron blocking layer (EBL) and Mg doping layer into the core layer significantly improves the injection efficiency[3]. In this study, we investigate the dependence of the external quantum efficiency (EQE) on the core layer Mg doping level experimentally. The effect of Mg is also investigated using the simulation software SiLENSe.

2. General Instructions

Samples were grown by MOCVD on c-plane sapphire substrates. Figure 1 shows the Al composition profile of the fabricated LD structures. For the n-cladding layer, n-AlGaN with an Al composition of 70 % was used, and for the p-cladding layer, a polarization doped layer with an Al composition continuously varying from 100 % to 70 % was used. The Al composition of the core layer was 63 %, and an EBL was placed within the core layer (near the MQW). In this experiment, only the Mg flow rate in the p-core layer sandwiched between the EBL and p-cladding layer was varied. The Mg flow rate ranged from 0 to 90 sccm. The output power was measured on-wafer using a Si photodetector calibrated to give the output power of a flip-chip LED.

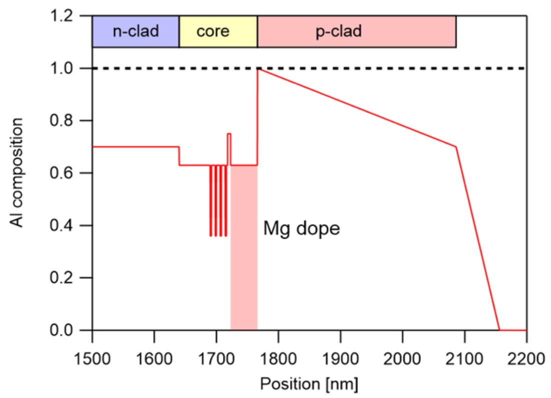

Fig. 1 Al composition profile of the fabricated LD structures.

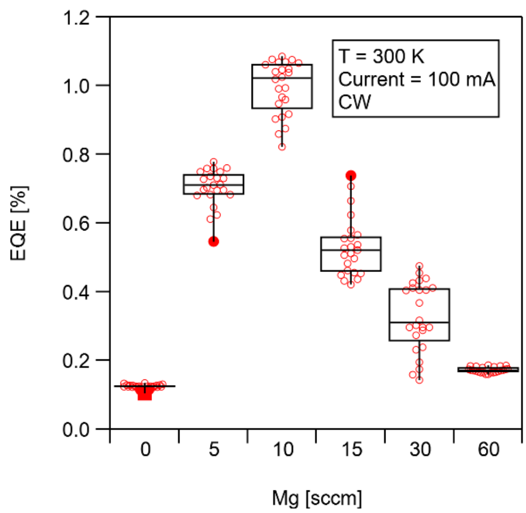

Fig. 2 Measured EQE at 100 mA as a function of Mg flow rate.

Figure 2 shows the measured EQE of the fabricated LD structures as a function of Mg flow rate. The EQE increased with increasing Mg flow rate up to 10 sccm and then decreased. For the undoped sample, the EQE at 100 mA was 0.12 %, whereas for the sample with Mg flow rate of 10 sccm, the EQE was 1.0 %. At the optimum doping level, an EQE of approximately ten times that of the non-doped sample was observed.

The observed Mg-flow dependence can be interpreted in terms of the decreased potential dip at the p-core/cladding interface. A huge positive polarization charge is formed at the core/cladding layer interface, where the composition difference is large, and deep dip is formed in the conduction band. Figure 3 shows the conduction band and electric field near the interface between the p-core and p-cladding layers at 30 kA/cm^2. It is confirmed that a deep dip is formed due to the polarization charge at the core/cladding layer interface. The existence of this dip reduces the barrier height to electrons, resulting in significant decrease in injection efficiency. To suppress dip formation, a charge of opposite sign to the polarization charge (ionized Mg) can be placed at the core/cladding layer interface.

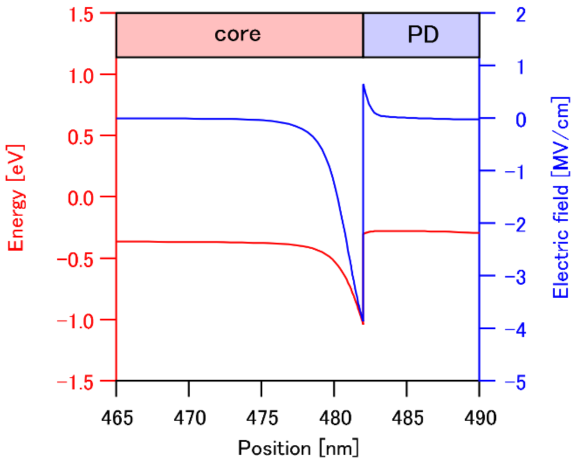

Fig. 3 Conduction band and electric field near the p-core/cladding layer interface at 30 kA/cm^2.

To test this idea, simulation calculations were performed using simulation software SiLENSe. In the simulation, the injection efficiency was calculated when ionized acceptors were placed in a 5 nm range near the core/cladding layer interface. Figure 4 shows the calculated injection efficiency at 30 kA/cm^2 as a function of ionized Mg concentration. The injection efficiency increases significantly with increasing ionized Mg concentration near the core/cladding layer interface. This is due to the suppression of conduction band dip by the negative charge (ionized Mg) placed near the core/cladding layer interface. Therefore, if sufficient ionized Mg concentration can be obtained near the core/cladding layer interface, a marked improvement in injection efficiency is expected.

However, because of the large thermal ionization energy of Mg acceptor[4], it is usually difficult to obtain a sufficient concentration of ionized Mg to suppress dip formation. Note that simulation calculations show that a strong electric field of up to 3.9 MV/cm is formed at the core/cladding layer interface. It has been reported that the activation energy of Mg is reduced by the electric field in high Al composition p-AlGaN[5]. Using the Poole-Frenkel model, we confirmed that

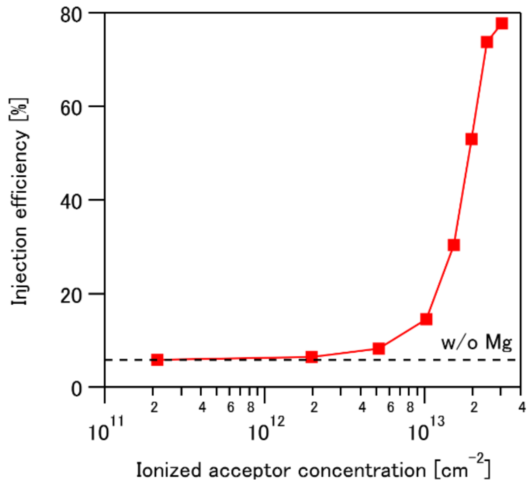

Fig. 4 Calculated injection efficiency as a function of ionized Mg concentration at 30 kA/cm^2.

the strong electric field at the core/cladding layer interface reduces the effective activation energy of Mg and may suppress dip formation due to polarization charge. The suppression of dip enhances the barrier height to electrons and contributes to the improvement of the injection efficiency. This finding is applicable to LEDs as well as LDs.

3. Conclusions

LD structures with different Mg doping levels in the p-side core layer were fabricated. At the optimum doping level, an EQE of approximately ten times that of the non-doped sample was observed. The observed Mg-flow dependence can be interpreted in terms of the decreased potential dip at the p-core/cladding interface. A huge positive polarization charge is formed at the core/cladding layer interface. The dip in the conduction band formed by the polarized charge significantly reduces the injection efficiency. Therefore, suppression of dip formation is important, and ionized Mg activated by the Poole-Frenkel effect suppresses dip formation and thus improves injection efficiency.

Acknowledgements

This work was supported by RIKEN Junior Research Associate Program

References

[1] Z. Zhang et al, Appl. Phys. Express **12**, 124003 (2019)
[2] K. Sato et al, Appl. Phys. Express **13**, 031004 (2020)
[3] N. Maeda et al, ICMOVPE XX, Stuttgart, Germany, July (2022)
[4] M. Nakarmi et al, Appl. Phys. Lett. 94, 091903 (2009).
[5] A. Muhin et al, Appl. Phys. Lett. **117**, 252101 (2020)