Optimization of the Gain Curve of the InGaN Blue Light Laser Diode

Yen-Chang Chen, Te-Jen Kung, and Yuh-Renn Wu
Graduate Institute of Photonics and Optoelectronics and Department of Electrical Engineering,
National Taiwan University, Taipei 10617, Taiwan
Corresponding email:yrwu@ntu.edu.tw

***Abstract*—A laser diode(LD) structure is simulated by the Poisson, drift-diffusion, and Schrodinger equation solver and the Hemholtz equation solver. The gain curve has been optimized by optimizing the comparisons for different numbers of quantum well(QW), different indium composition in the QW and different size of the guiding layer.**

***Keywords*—GaN, laser diode, composition, InGaN, guiding layer, quantum well, gain, gamma**

I. Introduction

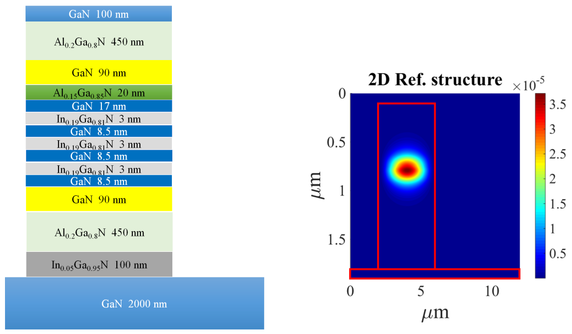
The invention of GaN-based blue light laser diode has brought the dawn of a new era to the illumination technology. For a laser diode, the most important thing is to increase the gain peak[1] especially under electrical pumping. Therefore, it is important to understand the limiting factor and make a suitable adjustment to improve the gain curve of laser diodes (LDs). As we know, a LD structure often use a high refractive index structure as a guiding layer with a low refractive index structure as a cladding layer, and the light can be confined at the guiding layer like a resonator. The different designs of the guiding layer and the cladding layer can make the different optical confinement factor and have different gain curves.

In addition, quantum well (QW) numbers are critical to a LD. If there are too many QWs with unbalanced carrier distribution, some QW's gain might be negative. On the other hand, if the QWs' number is insufficient, the total gain can't be large. In our simulation, we simulate the different QW numbers and different thickness of the guiding layer to a LD structure, and we try to find the optimize structure of a GaN laser diode.

II. Methodology and Structure

Fig.1(a) shows the LD structure[2] (ref structure) for simulation which consists of 2μm n-GaN, 100nm n-$In_{0.05}Ga_{0.95}N$ buffer layer, 450nm n-$Al_{0.2}Ga_{0.8}N$ cladding layer, 90nm n-GaN guiding layer, 3 pairs of quantum wells, 20nm p-$Al_{0.15}Ga_{0.85}N$ electron blocking layer, 90nm p-GaN guiding layer, 450nm p-$Al_{0.2}Ga_{0.8}N$ cladding layer, and 100nm p-GaN. Fig.1(b) shows the calculated optical field[3] of the reference structure, which is calculated by solving Helmholtz equations

$$\left(\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}+\mu\varepsilon-\beta^2\right)E\left(x,y\right)=0 \quad (1)$$



(a) (b)

Fig. 1: (a) the laser diode structure in the simulation. (b) is the cavity mode of 2D optical field of the LD structure.

μ and ε are the magnetic permeability and Permittivity respectively. By calculating eigenvalue β, we can get the normalized optical field E(x,y). The definition of the optical confinement factor Γ is

$$\Gamma_i=\frac{\int\mid E_i\left(x,y\right)\mid^2dxdy}{\int\mid E\left(x,y\right)\mid^2dxdy} \quad (2)$$

The Γ is about 0.0108 in the reference structure.

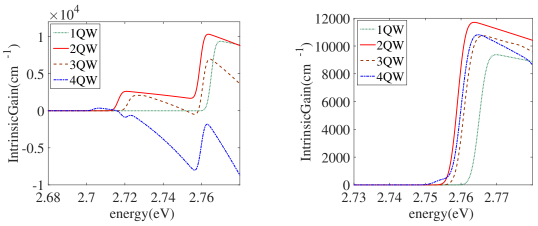
To calculate gain curve, we use a program our lab developed to calculate Poisson, drift-diffusion, and Schrodinger solver and calculate gain curve. The equation of the gain curve is

$$g\left(\hbar w\right)=\sum\frac{\pi e^2\hbar}{cm_e\epsilon\left(\hbar w\right)}\frac{E_p}{2}\frac{N_{2d}}{W}f_{nm}\Gamma_i \times erf\left(\hbar w-E_{nm}\right)\left[f_e\left(E\right)+f_h\left(E\right)-1\right] \quad (3)$$

c, m, N_{2d}, W, f_{nm}, f_e, f_h, and erf($\hbar w$-E_{nm}) are the light of speed, the mass of electron, carrier density, the length of the laser diode structure,the overlap of each conduction band and valance band, Fermi-Dirac distribution of electron and hole, and the error function, respectively.

III. Results And Discussion

Figs.2(a) shows the gain curve of four different QW numbers structure at current density of 5 kA/cm^2. The indium composition is $In_{0.19}Ga_{0.81}N$, for each QW. To understand the reason for the negative gain, we show the gain curve of each single QW in the device. As shown in Fig.3(d), the gain becomes negative in the fourth QW. It is due to poor

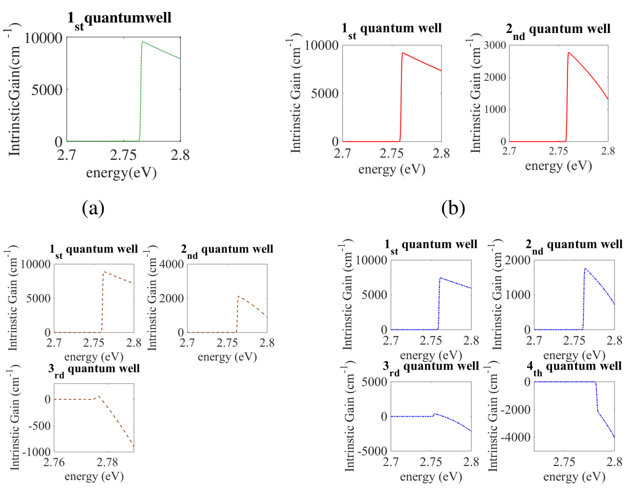


(a) (b)

Fig. 2: The gain curve of different quantum well numbers structure. 2(a) All the structures' gain does not rise at the same energy level due to different screen of QCSE. 2(b) After adjust the indium composition, the gain rise at the same energy level.

hole injection to the bottom QW that the parameter [f_e(E)+ f_h(E)]is smaller than 1. In addition, we can also see all the structures' gain do not rise at the same energy level. It is due to different degree of carrier screening in QW. The electron are concentrated at the first quantum well and the energy gap between the conduction band and valence band become high. Therefore, the gain does not rise at the same energy level.

To solve the problem, we can adjust the indium composition in the QW area. The 4-QW structure's indium compositions are $In_{0.206}Ga_{0.794}N$, $In_{0.199}Ga_{0.801}N$, $In_{0.197}Ga_{0.803}N$, and $In_{0.195}Ga_{0.805}N$ in each QW. For the small QW cases, the QW is eliminated from the bottom. Fig.2(b) shows the gain curve, after we adjust the indium composition, the gain rise at the same energy level and we can also find that the 2-QW structure's gain curve is the highest.



(a) (b) (c) (d)

Fig. 3: (a), (b), (c), and (d) are the gain curves in each QW of the 1,2,3 and 4 quantum wells structure. The gain of each single QW is plot separately to investigate the reason of the negative gain.

Next we adjust the thickness of the guiding layer to optimize the gain and as shown in Fig.4. There would have different Γs when we adjust the guiding layer. In this comparison we consider the optical properties Γ, cavity loss and the optical loss to calculate the total gain curve. For our simulation setting, the absorption coefficient of α_{GaN} is about 50∼150cm^{-1} and the α_{AlGaN} is about 200∼500cm^{-1} and We have four cases: (1)α_{GaN}=50cm^{-1},α_{AlGaN}=200cm^{-1}, (2)α_{GaN}=150cm^{-1},α_{AlGaN}=200cm^{-1}, (3)α_{GaN}=50cm^{-1}, α_{AlGaN}=500cm^{-1}and (4)α_{GaN}=150cm^{-1},α_{AlGaN}=500cm^{-1}. In the table I, we can see that when we adjust the thickness of the guiding layer the Γ would be different at each areas and it would influence the threshold current density for the LD structure. With different cases, the suitable thickness of the guiding layer is about 90nm to 180nm.

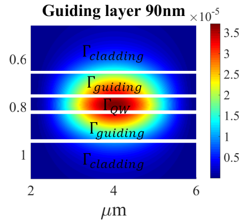


Fig. 4: The optical confinement Γ for different areas

TABLE I: Threshold current density for different size of guiding layer, Γ.

guiding layer thickness (nm)	Γ_{QW}	$\Gamma_{guiding}$	$\Gamma_{cladding}$	J_{sc} (kA/cm^2) for case 1	J_{sc} (kA/cm^2) for case 2	J_{sc} (kA/cm^2) for case 3	J_{sc} (kA/cm^2) for case 4
60	0.0105	0.4864	0.4202	6.3	10.4	20.8	33.1
90	0.0107	0.6205	0.2891	4.4	9.31	11.5	18.8
120	0.0104	0.7215	0.2018	4.7	11.3	10.2	19.3
150	0.0097	0.7748	0.1452	3.7	10.6	7.1	15.8
180	0.009	0.8182	0.1074	4.2	12.3	6.7	16.7

IV. CONCLUSION

The gain curve of InGaN laser diode is simulated and optimized by solving the Poisson, drift-diffusion, and Schrodinger equations and Helmholtz equation for the cavity mode. The optimized quantum well number of laser diodes is limited to be less than 4 due to imbalance of carrier injection. In addition, the indium composition in the quantum well should be different because of the band bending effect. By consider the loss in the laser diodes the thickness of the guiding layer is suggested to be at the range of 90 to 180nm.

V. ACKNOWLEDGMENTS

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