Analysis and Simulation of AlGaN/GaN Single Quantum Well Transistor Laser in Ultra-Violet Band

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Abstract—— **The performance and characteristics of an AlGaN/GaN Single Quantum Well Transistor Laser with 336 nm wavelength at room temperature has been analyzed in this paper for the first time. A charge control model which is based on coupled rate equations has been used for modeling. Using simulation, The Optical Frequency Response of this device has been exploited and the bandwidth of 25 GHz and Resonance Peak of 4 dB at 15 GHz has been achieved for this device. The base width in this work is 225 nm with 15 nm Quantum Well width.**

Keywords-component: GaN Transistor Laser, Single Quantum Well Transistor Laser, Optical Frequency Response, Bandwidth

I. INTRUDOCTION

For briefly, Transistor Laser is a semiconductor device (a double hetero structure Transistor) that combines the functions of Laser and Transistor. It performs this operation by converting electrical input signals into two output signals that are electrical (from the collector region) and optical (from the quantum well in base region) [1].

For Transistor Lasers with emission wavelength at 1 µm (near infrared region) and 1.56 µm (long wavelength) many studies have been done ever. Thus we need to a Transistor Laser with operation at Ultra-Violet bands or Short wavelength bands. But the studies of Ultra Violet Transistor Laser have been done in this work for the first time. Our proposed structure for transistor laser is similar to a laser diode that fabricated before [2,3]. Also fabrication of heterojunction bipolar ultra violet light-emitting transistors has been reported [4].

In this work for first time we introduce and analyze the AlGaN/GaN Single Quantum Well Transistor Laser (SQW-TL) and simulated it using a charge control model for our Transistor Laser structure that has been reported before [5].

Fig. 1 shows the epitaxial structure of the n- $Al_{0.3}Ga_{0.7}N$/ p-$Al_xGa_{1-x}N$/ n- $Al_{0.3}Ga_{0.7}N$ with the emission wavelength of 0.336 µm which is analyzed in this work. In this structure the substrate is the Sapphire. Other layers material is the AlGaN alloys. After deposition of a sub-collector layer with thickness of 280 nm on the sapphire substrate a 600 nm collector, 210 nm base with 15 nm quantum well and finally 500 nm emitter and with 25 nm emitter contact are proposed to be grown. The $Al_{0.3}Ga_{0.7}N$ Emitter and Collector layer acts as cladding layers. The waveguides are $Al_{0.16}Ga_{0.84}N$ and quantum well in the middle of base region is $Al_{0.06}Ga_{0.94}N$.

Under active biasing process the electron injects from emitter into the base. Some of injected electrons capture in quantum well but most of them recombine with base region holes. Result the emitting light.

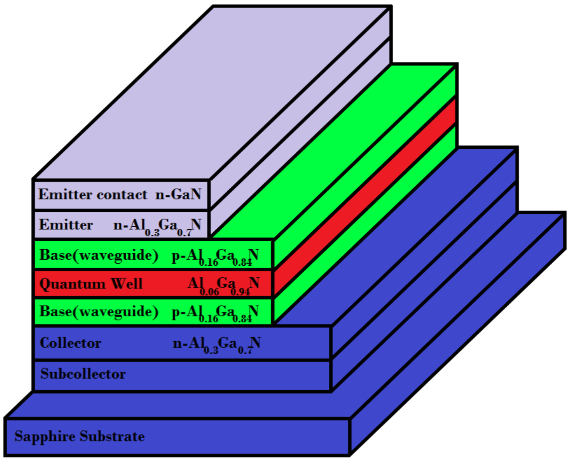

Fig. 1 The proposed epitaxial structure of the short wavelength transistor laser that have been analyzed

The light is reflected by mirrors which are placed in both sides of the quantum well to form a resonant cavity. Light is increasingly stimulating until the beam of laser light emits. Electrons which do not recombine with holes reach the collector region and make the electrical output of transistor laser which make the transistor current gain (β). This process is shown in fig. 2.

II. MODELING AND SIMULATIONS

Leburton and Zhang were developed a charge control model for transient analysis of the Transistor Laser in forward active mode, to describe the dynamics of photon, electron and charge densities [5]. Their model is based on coupled rate equations. We used this model to simulate our transistor laser. Results of this modeling are:

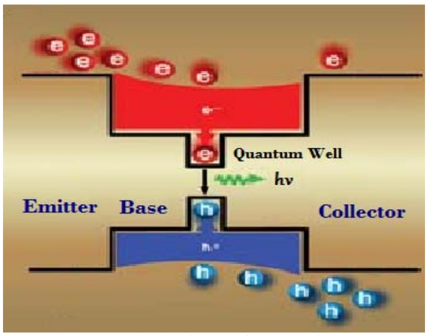

Fig. 2: electron transport in the base of a Transistor Laser

$$n_0 = n_{nom} + \frac{1}{\Omega t_p} \qquad (1)$$

$$N_{p0} = n_0 \frac{t_p}{t_{qw}}\left(\frac{J_0}{J_{th}} - 1\right) \qquad (2)$$

$$\frac{1}{t_{rb}} = \frac{1-v}{t_{rb0}} + \frac{v}{t_{cap}} \qquad (3)$$

$$J_{th} = \frac{qn_0}{t_{qw}}\left(1 + \left(\frac{1}{v} - 1\right)\frac{t_{cap}}{t_{rb0}}\right) \qquad (4)$$

where n_0 is steady state electron density, n_{nom} is the transparency electron density, Ω is differential gain factor, t_p is photon lifetime in quantum well and t_{qw} is recombination lifetime with spontaneous emission in the quantum well. N_{p0} is steady electron density and J_0 and J_{th} are the base current density and threshold base current density. v is the geometry factor and t_{cap} is the electron capture time in quantum well.

Values of the physical quantities and parameters that used in simulation are summarized in Table1 [2,6,7].

In equation (3) geometry factor v is defined as:

$$v = \frac{W_{qw}}{W_b}\left(1 - \frac{x_{qw}}{W_b}\right) \qquad (5)$$

W_{qw} is the quantum well width, x_{qw} is the distance from B-E junction to the quantum well and W_b. The geometry factor depends on position of quantum well in the base region.

For more exact simulation we used previous work [8] to calculate t_{qw}, t_{rb0}, Ω and t_p that supposed to be constant in [5]. These parameters are calculated here:

1. Recombination lifetime with spontaneous emission in the quantum well, t_{qw}:

$$t_{qw} = \frac{4\varepsilon m^* c^2 W_{qw}}{\omega q^2} O_{if} \qquad (6)$$

In this equation C is the speed of light in vacuum, ε is permittivity and equals to $\varepsilon_0\varepsilon_r$, q is free electron charge and O_{if} is the oscillator strength and equals to:

$$O_{if} = \frac{2m^*\omega}{\hbar}\left|<\psi_i|z|\psi_f>\right|^2 \qquad (7)$$

In above equations m^* is the effective mass and we can write:

$$\frac{1}{m^*} = \frac{1}{m_e} + \frac{1}{m_h} \qquad (8)$$

m_h and m_e are the hole and electron masses in $Al_xGa_{1-x}N$ alloy obtained with:

$$m_h = m_{hGaN} + x(m_{hAlN} - m_{hGaN}) \qquad (9)$$

$$m_e = m_{eGaN} + x(m_{eAlN} - m_{eGaN}) \qquad (10)$$

That x is mole fraction of aluminum in AlGaN alloy. We used [9] to calculate hole and electron masses.

Symbol	Value	Unit
n_{nom}	10^{12}	m^{-2}
W_{qw}	15	nm
W_{wg}	105	nm
Γ_{qw}	0.04	Unitless
Γ_{wg}	0.6	Unitless
ε_r	8.78	Unitless
k_p	4×10^{-17}	cm^2
n_{qw}	2.48	Unitless
λ	336	nm
L	500	µm
R_1,R_2	0.19	Unitless
t_{cap}	0.4	ps
β_{rad}	1.5×10^{-9}	cm^3s^{-1}
N_b	2×10^{18}	cm^{-3}
T	300	K

Table1: Physical parameter values of this work structure

2. Photon lifetime in quantum well, t_p:

$$t_p = \frac{n_{qw}}{c\left(\alpha_i + \frac{1}{2L}Ln\left(\frac{1}{R_1R_2}\right)\right)} \qquad (11)$$

$$\alpha_i = (\Gamma_{qw} + \Gamma_{wg})k_pN_b \qquad (12)$$

n_{qw} is the refractive index in quantum well , R_1 and R_2 are facet reflectivities, L is the cavity length in quantum well, Γ_{qw} and Γ_{wg} are quantum well and waveguides optical confinement factor. For calculating them we used ref [10] results. The k_p is intervalence band absorption and N_b is the base region doping.

3. Recombination lifetime of carriers in the waveguides in base region, t_{rb0}:

$$t_{rb0} = \frac{1}{\beta_{rad} N_b} \tag{13}$$

The bimolecular radiative recombination coefficient β_{rad} for GaN is reported to be 1.5 ×$10^{-9}$$cm^3s^{-1}$ [7]. We can assume the same value for quantum well that is $Al_{0.06}Ga_{0.94}N$.

In equation (4) practically $t_{cap} \approx t_{rb0}$, so we can rewrite the threshold current density that:

$$J_{th} = \frac{qn_0}{t_{qw}}\left(1 + \frac{t_{cap}}{v\, t_{rb0}}\right) \tag{14}$$

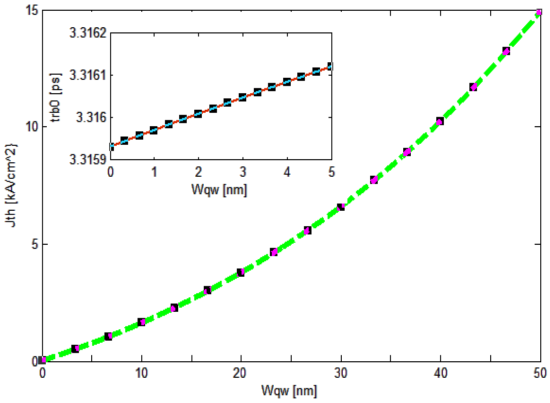

Fig. 3 main panel: Threshold current density variation due to quantum well width. Inset: variations of bulk charge lifetime

According to Fig. 3 threshold current density has exponential variation with quantum well width and also t_{rb0} increases with quantum well width, because result of increasing quantum well width is increasing base width.

III. OPTICAL FREQUENCY RESPONCE

Small signal analysis equations of our transistor laser can be obtained from coupled rated equations by superimposing a small sinusoidal to the DC current and we have:

$$S(\omega) = \frac{1}{1 + j\omega t_{rb}} \frac{A}{\omega_r^2 - \omega^2 + j\omega\gamma} \tag{15}$$

where $S(\omega)$ is the small signal modulation response, $\omega = 2\pi f$ that f is frequency of light and:

$$A = \frac{\Omega v N_{p0} t_{rb}}{q t_{cap}} \tag{16}$$

$$\omega_r = \sqrt{\frac{\Omega N_{p0}}{t_p}} \tag{17}$$

$$\gamma = \frac{1}{t_{qw}} + \Omega N_{p0} \tag{18}$$

In the equation (17) ω_r is resonance frequency and other parameters that used were explained before. The first term of (15), $1/1+j\omega t_{rb}$ shows that the optical frequency response consists of a low pass filter with a resonance because of last term or $A/(\omega_r^2-\omega^2+j\omega\gamma)$.

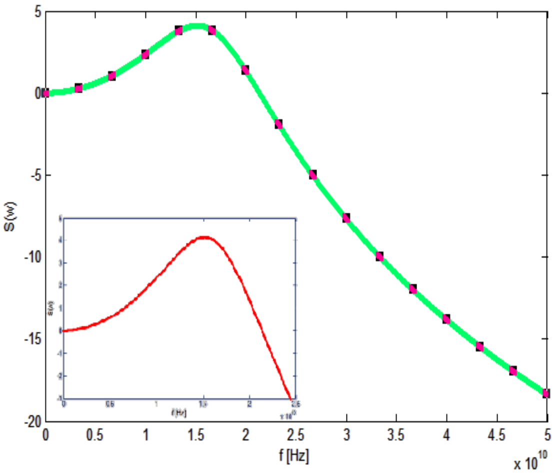

Fig. 4 main panel: optical frequency response of transistor laser as a function of f. the inset figure shows the half power frequency or f-3dB in our structure for transistor laser.

Fig. 4 shows the optical frequency response as a function of frequency for 15 nm width quantum well. Also figures show that we have less than 5 dB resonance peak at 15 GHz frequency. We know that lower resonance peak improve the frequency response of low pass filter, and also increase the stability in this wavelength (15 GHz).

According to inset panel we obtain 25GHz bandwidth for AlGaN/GaN single quantum well transistor laser. The above values for Bandwidth and resonance peak are optimum values for this device which we reached in this work.

In the final step we compare the optical frequency response of a 1550 nm long wavelength transistor laser which has been reported before [8], with our proposed device. Results have been illustrated in Fig. 5. According to it we observe that the resonance peak for long wavelength is about 25 dB, while this value for our transistor laser (short wavelength) is less than 5 dB. Since the lower resonance peak increases the stability of device, our device is more stable than long wavelength transistor laser.

Also, comparison between two types of transistor lasers shows that f-3dB or bandwidth of our proposed device is higher than long wavelength transistor laser.

Thus, we predict that our proposed short wavelength structure can bring us a good bandwidth with minimum resonance peak that have been reported till now.

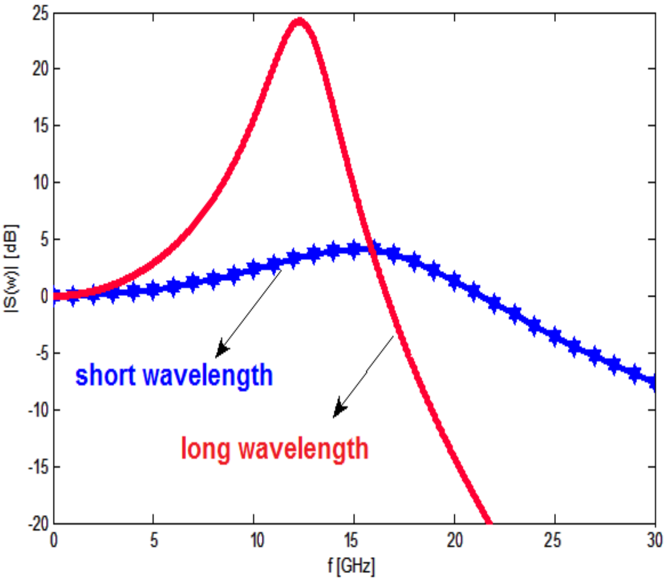

Fig. 5 comparison between long wavelength and short wavelength Transistor Laser.

IV. CONCLUSION

In this paper we used the charge control model based on rate equations for analyzing the optical frequency response of AlGaN/GaN single quantum well transistor laser. To achieve this goal, first we calculate exact values of used parameters in equations such as t_{qw}, t_{rb0} and t_p. Then we investigate the effect of quantum well on threshold current density (J_{th}) and bulk charge lifetime t_{rb0}. Results show that we can reach 25GHz bandwidth for AlGaN/GaN transistor lasers. Comparison between long and short wavelength transistor lasers demonstrate that our proposed structure have better characteristic performance respect to long wavelength transistor laser.

REFERENCES

[1] H. Kaatuzian, Photonics, vol 1,2 AmirKabir University of Technology press, .ISBN:978-964-463-273-7,2012. 978-964-463-319,2009.

[2] H. Yoshida, Y. Yamashita, M. Kuwabara, and H. kan, Demonstartion of an Ultraviolet 336 nm AlGan Multiple Quantum-Well Laser Diode, Applied Physics Letters, 93, 241106, 2008.

[3] H. Yoshida, Y. Yamashita, M. Kuwabara, and H. kan. A 342 nm Ultraviolet AlGaN Multiple Quantum Well laser diode, nature photonics,| vol 2, 2008.

[4] B. F. Chu-Kung,a_ M. Feng, G. Walter, and N. Holonyak, Jr. T. Chung, J.-H. Ryou, J. Limb, D. Yoo, S.-C. Shen, and R. D. Dupuis D. Keogh and P. M. Asbeck, Graded-base InGaN/GaN heterojunction bipolar light-emitting transistors, Applied Physics Letters , 89, 082108 _2006.

[5] L. Zhang and J. P. Leburton, Modeling of the Transient Characteristics of Heterojunction Bipolar Transistor Lasers, IEEE Jurnal of Quantum Electron, vol.45, no.4 , pp.359-366 ,2009.

[6] S. Nagahama, T. Yanamoto, M. Sano, and T. Mukai, Characteristics of Laser Diodes Composed of GaN-Based Semiconductor, phys. stat. sol. (a) 190, No. 1 ,2002.

[7] C.K. Sun, S. Keller, G. Wang, M. S. Minsky, J. E. Bowers, Radiative recombination lifetime measurements of InGaN single quantum well, Appl. Phys. Lett. 69 (13), 1996.

[8] H. R. Mojaver and H. Kaatuzian, Analysis and Improvmet of Optical Fequency Response in long wavelength Transistor Laser, Springer Science, DOI 10.1007/s11082-011-9531-2, 2011.

[9] S. M. Thahab, Characterization parameters of InGaN/InGaN and InGaN/GaN Quantum Well Laser Diode,INTECHOPEN, 2006.

[10] M. R. Farjadian, H. Kaatuzian, I. Taghavi, Theoretical Estimation of Optical Confinement Factor and its Effects on DC Characteristics of Long Wavelength Transistor, IEEE, 978-1-4673-5634-3/13, ICEE 2013.