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Theoretical Analysis of Optical Gain in GaN / Al$_x$Ga$_{1-x}$N Quantum Well Lasers

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In this study, we investigated numerically the effect of aluminum concentration, temperature and well width on optical gain GaN / Al$_x$Ga$_{1-x}$N quantum well lasers, taken into account effective mass approximation. The numerical results clearly show that the increasing of well width, and decreasing of temperature and Aluminum concentration, the optical gain increases.

Keywords: III-Nitride, AlGaN / GaN quantum wells (QWs), Optical gain, Laser diodes.

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1. INTRODUCTION

Recently, there has been great interest in short wavelength light-emitting diodes (LEDs) and laser diodes (LDs) fabricated from III-V nitride compound semiconductors [1-6], which emit light in the UV to red region [7].

These laser diodes have potential in a number of applications such as optical storage, printing, full-color isplays, chemical sensors, medical applications [8-9], and high-density optical data storage [10].

In all previous work, the effect of structures on optical gain is investigated and by controlling the thickness of barrier, electron density and hole wave functions [11-13]. In this study, we present a theoretical analysis of the optical gain by variation of Al concentration, temperature, and well width in GaN /Al$_x$Ga$_{1-x}$N quantum well (QW) laser. The outline of the paper is as follows: Hamiltonian, the relevant eigenvalues and eigenfunctions of an electron confined in a quantum well laser are described in Section II. In section III analytical expressions for optical gain is obtained. Our numerical results and a brief conclusion are presented in Section IV and V, respectively.

2. QUNATIEZD ENERGY LEVELS

A schema energy band diagram for a typical QW structure is shown in Fig. 1. ΔE_c and ΔE_v are the discontinuities of the band edges of conduction and valence bands at the heterojunction, respectively. E_{cn} and E_{vn} are the quantized energy levels in the conduction band and valence band, respectively. E_g is the bandgap energy, and E_{tr} is the transition energy between the two quantized energy levels. E_{fc} and E_{fv} are the quasi-Fermi levels for electron and holes in the well.

Using the parabolic band model [14], E_{cn} can be obtained by solving the eigenvalue equations

$$\frac{m_{cb}}{m_{cw}}\sqrt{\frac{\Delta E_c - E_{cn}}{E_{cn}}} = \begin{Bmatrix}\tan \\ -\cot\end{Bmatrix}\left[\frac{L\sqrt{2m_{cn}E_{cn}}}{2\hbar}\right]\begin{Bmatrix}n: \ even \\ n: \ odd\end{Bmatrix} \quad (1)$$

where $\hbar = h/2\pi$ is Planck's constant, L is the well width,

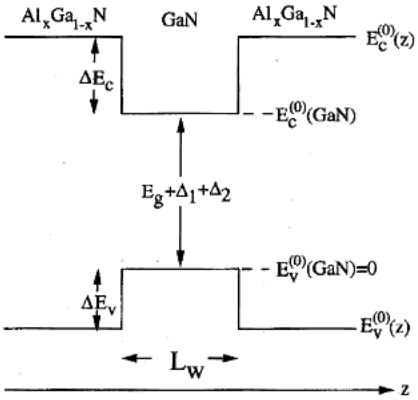

Fig. 1 – The conduction- and valence-band energy profiles of a GaN-A1$_x$Ga$_{1-x}$N quantum well with a well width L_w

and m_{cw} and m_{cb} are the effective masses of electrons inside of the well, and barrier respectively. The energy levels E_{vn} for the valence band can be expressed by

$$E_{vn} = \frac{\left[\frac{(n+1)\pi}{2}\frac{a_v}{L+\Delta W_v}\right]^2}{\left[1+\left\{\frac{(n+1)\pi}{2}\right\}^2 b_v\left(\frac{\Delta W_v}{W+\Delta W_v}\right)^3\right]} \quad (2)$$

with

$$\Delta W_v = \frac{a_v}{\sqrt{b_v \Delta E_v}} \quad (3)$$

where

$$a_v = \frac{2\hbar}{\sqrt{2m_{vw}}}, \qquad b_v = \frac{m_{vw}}{m_{vw}}. \quad (4)$$

3. OPTICAL GAIN

After the subband structures are obtained, we calculate the optical gain of the QW laser. The propagation direction of the generated photon is parallel to the QW layers, and the gain spectrum is calculated by the density matrix approach[15-16]. The gain spectrum due to the transition between the conduction subband and the valence subband is given by

$$g(\omega)=\omega\sqrt{\frac{\mu}{\varepsilon}}\sum_{n=0}\left(\frac{m_r}{\pi\hbar^2 L}\right)\int_{E_{cn}+E_{hn}+E_g}^{\infty} .<R_{cv}^2>(f_c-f_h)F_\tau(E_{cv})dE_{cv} \qquad (5)$$

Where ω the angular frequency of light is, μ is the permeability, ε is the dielectric constant, m_r is the reduced effective mass given by $m_{cw}^* m_{hw}^*/(m_{cw}^*+m_{hw}^*)$, E_{cv} is the transition energy, and $<R_{cv}^2>$ is the matrix element of the dipole element formed by an electron in subband n in the conduction band and a holein subband n in the valence band. In eq.(2), the light-hole band is neglected, and heavy-holes are considered. This is a reasonable approximation for most of lattice matched Qw's [17]. $F_\tau(E_{cv})$ is function expressing the transition broadening. Used the Lorentzian function based on the density matrix formalism as follows:

$$F_\tau(E_{cv})=\frac{\dfrac{h}{\tau_{in}}}{(E_{ch}-\hbar\omega)^2+(\dfrac{h}{\tau_{in}})^2} \qquad (6)$$

where τ_{in} is the intraband relaxation time.

4. NUMERICAL RESULTS AND ANALYSIS

In this section, we present and discuss the numerical results of optical gain in symmetric QW laser for typical GaN / Al$_x$Ga$_{1-x}$N. The physical parameters used in our numerical work are: the effective mass is $m_{GaN}^*=0.19m_e$ for GaN,

$m_{Al_xGa_{1-x}}^*N=0.19(1-x)+0.33)m_e$ for $Al_xGa_{1-x}N$. The real part permittivity is chosen to be $\varepsilon=9.83\varepsilon_0$, here ε_0 is the permittivity of free space. The band-gap is $\Delta E_c=x6.13eV+(1-x)3.42eV-x(1-x)eV$.The conduction band offset is chosen $V_b=0.75(Eg(x)-E_g(0))$. The carrier density 4×10^{18} cm^{-3}.

The Al concentration in the GaN / Al$_x$Ga$_{1-x}$N quantum well has a great influence on many physical properties of the structure. In Fig. 2, we have plotted the optical gain as a function of photon energy for tree different concentration ratios as $x=0.1$, 0.2 and 0.38, in $T=300$ K. From this figure, it can be seen that the optical gain is related to the stoichiometric ratio. As the Al concentration in material rises, the optical gain have been reduced in magnitude and also shifted towards higher energies. The main reason for this resonance shift is the increment in energy interval of two different electronic states between which an optical transition occurs.

Fig. 3 shows plotted the optical gain as a function of photon energy for tree different value of temperature.

As seen clearly, both peak gain magnitude and gain peak frequency change with temperature. With increasing the temperature, shrinkages and the carrier can scatter another subband, and consequently the spectrum range and the optical gain decreases.

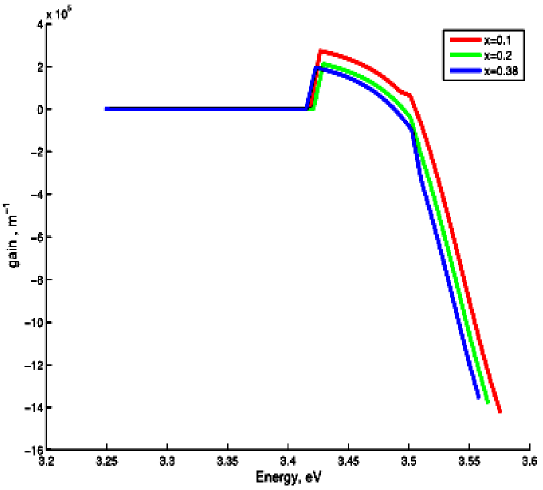

Fig. 2 – Optical Gain as function of wave length for GaN / Al$_x$Ga$_{1-x}$N quantum well Laser for $L_w=4$ nm with $x=0.1$, $x=0.2$, $x=0.38$.

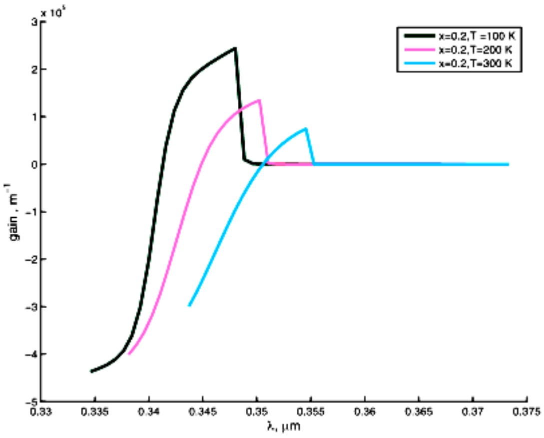

Fig. 3 – The dependence of the optical gain on temperature in Al$_{0.2}$Ga$_{0.8}$N/GaN QW Laser

We also calculated optical gain for GaAs / Al$_x$Ga$_{1-x}$As quantum well with $L_w=4$ nm, figure 4. As seen clearly, when temperature increases, the peak gain magnitude decreases, the same case of GaN / Al$_x$Ga$_{1-x}$N (figure 3) but the magnitude is highest than of case GaN / Al$_x$Ga$_{1-x}$N Qw's.

From Fig. 4, we deduced that Laser gain investigated for AlGaN wurtzite quantum-well structures emitting in the low wavelength relevant to the important application of bimolecular excitation.

In Fig. 5, at $T=300$ K and the Al concentration $x=0.2$, we have shown the well width dependence of optical gain versus the photon energy. The optical gain is largely improved with increasing Al concentration. Hence, the increase in the optical gain can be explained by the fact that the quasi-Fermi level separation is increased when the well width decreased, consequently more level can contribute to optical gain and it increases. On the other hand, the matrix elements are not responsible for the increase in the optical gain.

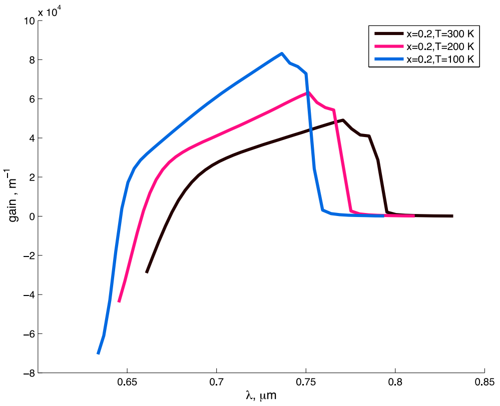

Fig. 4 – The dependence of the optical gain on temperature GaAs / $Al_{0.2}Ga_{0.8}As$ QW Laser

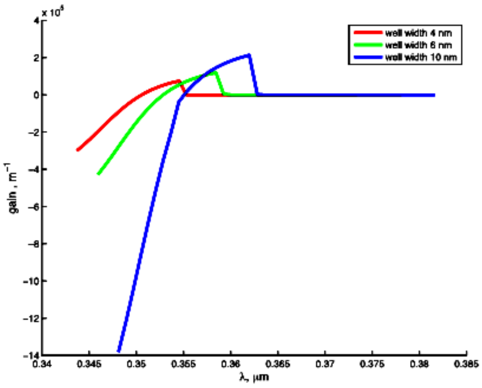

Fig. 5 – The dependence of the optical gain on quantum well thickness in $Al_{0.2}Ga_{0.8}N$ / GaN QW Laser

5. CONCLUSION

In conclusion, we have presented a theoretical analysis of the effect of concentration aluminum, temperature and width well on the optical gain of GaN / $Al_xGa_{1-x}N$ quantum well. For this purpose, the electronic band structure are calculate taking into account effective mass approximation. We have found that the width well has a significantly influence on optical gain. Comparing to optical gain of quantum well laser based GaAs / AlGaAs calculated too, we provided that GaN / AlGaN structure cab be used to bimolecular excitation.

We expect that this work will be of great help for the improvement of laser characteristics, as well as the introduction of new semiconductor optical devices.

REFERENCES

1. M.A. Haase, J. Qui, J.M. DePuydt, H. Cheng, *Appl. Phys. Lett.* **59**, 1272 (1991).
2. H. Jeon, J. Ding, A.V. Nurmikko, W. Xie, D.C. Grille, M. Kobayashi, R.L. Gunshor, G.C. Hua, N. Otsuka, *Appl. Phys. Lett.* **60**, 2045 (1992).
3. W. Xie, D.C. Grille, R.L. Gunshor, M. Kobayashi, H. Jeon, J. Ding, A.V. Nurmikko, G.C. Hua, N. Otsuka, *Appl. Phys. Lett.* **60**, 1999 (1992).
4. H. Zhao, G. Liu, R.A. Arif, N. Tansu, *Solid-State Electron.* **54**, 1119 (2010).
5. H. Zhao, J. Zhang, G. Liu, Tansu, *Appl. Phys. Lett.* **98**, 151115 (2011).
6. Y.K. Ee, J.M. Biser, W. Cao, H.M. Chan, R.P. Vinci, N. Tansu, *IEEE J. Sel. Top. Quantum Electron.* **15**, 1066 (2009).
7. S.N. Baby Dhanya, Sherin Thomas, *IJRET* **3**, 2319 (2014).
8. J.C. Carrano, A.J. Maltenfort, *Proc. SPIE* **4743**, 232 (2002).
9. Y.L. Pan, S. Holler, R.K. Chang, S.C. Hill, R.G. Pinnick, S. Niles, J.R. Bottiger, *Opt. Lett.* **24**, 116 (1999).
10. Akito Kuramata, Kazuhiko Horino, Kay Domen, Fujito *Sci. Tech. J.* **34**, 2 (1982).
11. Chin-Yi Tsai, *J. Appl. Phys.* **99**, 053506 (2006).
12. Emanuele Francesco Pecora, Wei Zhang, A.Yu. Nikiforov, Jian Yin, Roberto Paiella, Luca Dal Negro, Theodore D. Moustakas, *J. Appl. Phys.* **113**, 013106 (2013).
13. B.A. Mamedov, *Chinese Opt. Lett.* **12**, 081404 (2014).
14. Teparkson Pengpan, Chalongrat Daengngam, *Can. J. Phys.* **86**, 1327 (2008).
15. W.J. Fan, S.F. Yoon, M.F. Li, T.C. Chang, *Physica B* **328**, 264 (2003).
16. A. Aissat, S. Nacer, M. Bensebti, *Microelectron. J.* **39**, 63 (2008).
17. M. Asada, A. Kameyama, Y. Suematsu, *IEEE J. Quantum Electron.* **QE-20**, 477 (1994).