Small signal analysis of tin-incorporated group-IV alloys based multiple quantum well Transistor Laser

Ravi Ranjan
Department of Electrical and Electronics Engineering
Darbhanga College of Engineering
Darbhanga, India
ranjan275@gmail.com

Paraksh Pareek
Department of Electronics and Communication Engineering
Vaagdevi Engineering College
Warangal, India

S. S. Anwer Askari & Mukul K. Das
Department of Electronics Engineering
Indian Institute of Technology (Indian School of Mines)
Dhanbad, India

Abstract—**In this work we present a small signal analysis of Ge-$Si_{0.12}Ge_{0.73}Sn_{0.15}$/$Si_{0.11}Ge_{0.73}Sn_{0.16}$ n-p-n mid-infrared transistor laser (TL) with strain-balanced $Ge_{0.85}Sn_{0.15}$ multiple quantum well (QW) in the base. The frequency response of TL for common base (CB) configuration is calculated from small signal relationship between the photon density and emitter current density by solving laser rate equation and continuity equation considering the virtual states as a conversion mechanism. The result shows that modulation bandwidth initially increases then decreases with number of QW.**

I. INTRODUCTION

The main limitation to achieve the ultimate goal of monolithic integration with the current silicon platform is all group-IV optical sources [1]. In recent years the light sources based on silicon photonics have been developed - silicon Raman lasers [2] and Ge lasers [3] but never became a proficient alternative of III-V material based light source. The Group IV Photonics (GFP) which include an alloy of Si, Ge & Sn that gives a direct band gap material (GeSn, SiGeSn) [4] in the near and mid-IR region used as active materials in Photonics devices [5]. In this context, authors have already proposed a theoretical model of such alloy based single QW transistor Laser (TL) for the mid-infrared region [6],[7], where authors calculate the material gain and other performance parameters. The value of optical confinement factor is main limitation with single quantum well transistor laser (SQWTL), therefore multiple quantum well (MQW) structure is considered and performance parameters like threshold current density, current gain and output photon density are evaluated for SiGeSn/GeSn MQW transistor laser [8] .In this paper, authors present a small analysis for proposed GeSn/SiGeSn based MQW TL by solving the laser rate equation and continuity equation simultaneously which includes the virtual states as a conversion mechanism [9]. The Coupling between two nearby wells is not considered which may affect its material gain and thus other characteristics

II. THEORETICAL ANALYSIS AND RESULTS

The Schematic structure of $Si_{0.12}Ge_{0.73}Sn_{0.15}$/$Ge_{0.85}Sn_{0.15}$ MQWTL, considered in our analysis, is shown in Fig.1. The n-type (10^{19} cm-3) Ge, p-type (10^{19} cm-3) $Si_{0.12}Ge_{0.73}Sn_{0.15}$ and n-type (10^{17} cm-3) $Si_{0.11}Ge_{0.73}Sn_{0.16}$ respectively form emitter, base and collector of the device. The multiple (N) number of intrinsic $Ge_{0.85}Sn_{0.15}$ layers is inserted in the base at a regular spacing to form the alternate barrier and well layers in the base. This N number of compressively strained GeSn well is strain-balanced with the tensile strained SiGeSn barrier with respect to the relaxed GeSn buffer layer. The collector layer is lattice matched with buffer layer and placed in between the base and the buffer layer. The growth axis is assumed to be along the z-direction. The widths of the barrier and the well are taken 10 nm to ensure single bound state in each quantum well as well as the strain balanced condition.

The schematic diagram of the carrier diffusion and energy band diagram of Γ-conduction band and HH-valence band under bias is shown in Fig. 2. In the diagram, W_B is the width of the base and the x= $-W_B/2$, x= $W_B/2$ is the position

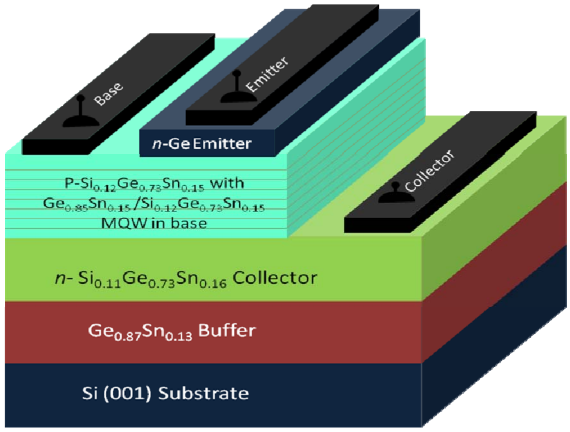

Fig.1. Schematic structure of *npn* Ge-$Si_{0.12}Ge_{0.73}Sn_{0.15}$-$Si_{0.11}Ge_{0.73}Sn_{0.16}$ based transistor laser (TL) with strain-balanced *i*-$Ge_{0.85}Sn_{0.15}$ multiple quantum wells (MQW) in the base.

of the emitter-base (EB) and the collector-base (CB) junction respectively, as shown in figure 2. The widths of well and barrier are d and W_b respectively. The total number of QWs is N and the position of an arbitrary n^{th} well can be expressed as: $x_n = -\frac{W_b}{2} + nW_b + (n-1)d + \frac{d}{2}$

The small signal analysis is required to obtained

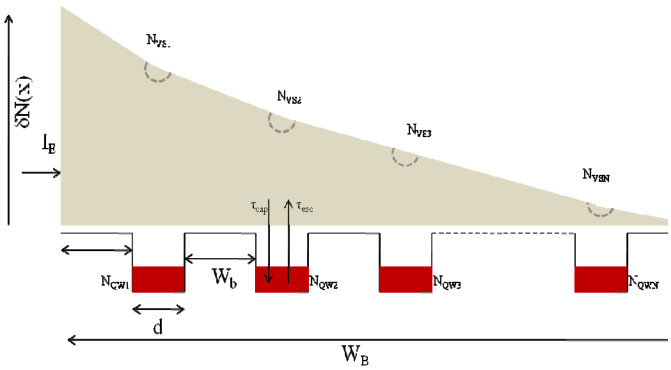

Fig.2: Schematic of carrier diffusion, quantum capture and escape in the MQW transistor laser

the frequency domain response and hence the modulation bandwidth of the device. The modulation bandwidth of MQW TL in the common base (CB) configuration is done by calculating the CB modulation transfer function $[s(j\omega)/j_e(j\omega)]$. Using laser rate equations and continuity equation with appropriate boundary condition the transfer function is obtained as:

$$H(j\omega)=\frac{1}{\dfrac{\cosh\left(\dfrac{x_1+\frac{W_B}{2}}{L_D}\right)}{H_2(j\omega)}+\dfrac{\left(\dfrac{qD_n}{L_D}\right)\sinh\left(\dfrac{x_1+\frac{W_B}{2}}{L_D}\right)}{H_3(j\omega)}-\dfrac{\left(\dfrac{qD_n}{L_D}\right)\cosh\left(\dfrac{x_1+\frac{W_B}{2}}{L_D}\right)\coth\left(\dfrac{x_1-x_2}{L_D}\right)}{H_3(j\omega)}+\dfrac{\left(\dfrac{qD_n}{L_D}\right)\left(\cosh\left(\dfrac{x_1+\frac{W_B}{2}}{L_D}\right)\Big/\sinh\left(\dfrac{x_1-x_2}{L_D}\right)\right)}{H_3(j\omega)}}$$

where, L_D is diffusion length, D_n is diffusion constant, $H_2(j\omega)$ and $H_3(j\omega)$ are the transfer function relating the photon and virtual state current and carrier concentration. The values of device parameters used in the calculation are taken from [7] and [8].

The small-signal modulation response for the CB configuration is shown in Fig. 3. It is observed that with increasing number of well (N), initially the modulation bandwidth increases with N and reaches to its maximum bandwidth and then starts to decrease. Since the optical confinement factor increases with N so, the modal gain increases with increasing N. Due to enhance modal gain, threshold base current density (J_{Bth}) decreases and consequently, a higher modulation bandwidth is obtained. However, the higher values of N lead to the transition from TL nature to DL nature. Thus after an optimized value of N, the modulation bandwidth, as well as resonance frequency, starts decreasing. The 3-dB modulation bandwidth with number of QWs is also plotted in Fig. 4. The figure, it shows that maximum modulation bandwidth is obtained as N=5. Thus the choice of N is very important to obtain enhanced performance of MQWTL.

In this study, an analysis of frequency response is observed for tin incorporated group-IV alloys based MQW TL. The modulation bandwidth of TL with respect to the number of QW is studied during the analysis. The maximum modulation bandwidth is obtained as 14.76 GHz for N=5. The proposed TL works in mid-infrared region (2-3 µm).

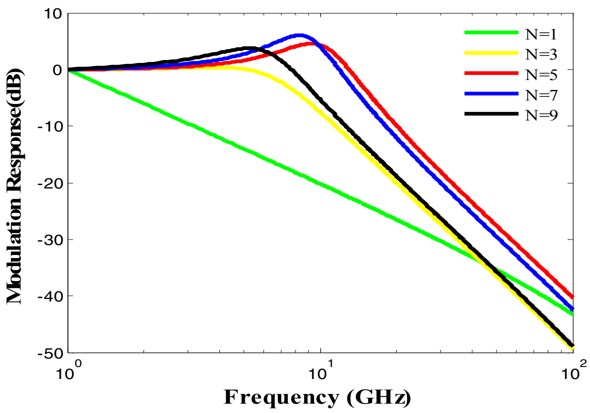

Fig.2. Modulation response with frequency for different number of QW

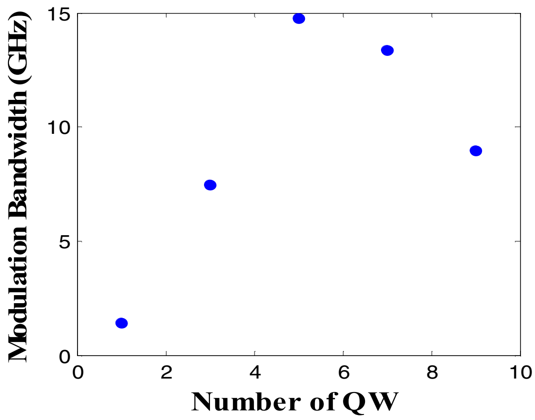

Fig.4. Modulation Bandwidth plotted with number of well

References

[1] D. Liang and J. E. Bowers, "Recent progress in lasers on silicon," Nature Photon., vol. 4, no. 8, pp. 511–517, Jul. 2010.

[2] H. Rong, S. Xu, O. Cohen, O. Raday, M. Lee, V. Sih, and M. Paniccia, "A cascaded silicon Raman laser," *Nature Photon.*, vol. 2, no. 3, pp. 170–174, Feb. 2008.

[3] R. E. Camacho-Aguilera, Y. Cai, N. Patel, J. T. Bessette, M. Romagnoli, L. C. Kimerling, and J. Michel, "An electrically pumped germanium laser," *Opt. Exp.*, vol. 20, no. 10, pp. 11316–11320, May 2012.

[4] R. Soref, "Mid-infrared photonics in silicon and germanium" Nat. Photonics 4, 495, 2010.

[5] R. Soref, D. Buca & S. Q. Yu," Group IV Photonics: Driving Integrated Optoelectronics", optics and photonics news, vol. 27, issue 1, pp-32-39,2016.

[6] Ravi Ranjan and Mukul K Das "Theoretical estimation of optical gain in Tin incorporated group IV alloy based transistor laser" Optical and Quantum Electronics, Vol.48, Article no. 201, March 2016.

[7] Ravi Ranjan, Mukul K Das and S Kumar, " Performance analysis of tin-incorporated group-IV alloy bsed transistor laser" optics and laser technology, Vol. 106, pp-228-233, Aprail 2018.

[8] Ravi Ranjan, Prakash Pareek, Syed Sadique Anwer Askari and Mukul Kumar Das, "Performance Analysis of GeSn Alloy Based Multiple Quantum Well Transistor Laser" *Proc. SPIE* 10526, Physics and Simulation of Optoelectronic Devices XXVI, 105262A, San Francisco, US, Jaunary 2018.

[9] B Faraji, W Shi, D L Pulfrey and L Chrostowski, "Analytical modeling of the Transistor Laser" IEEE J. Sel. Top. Quantum Electron. Vol.15 No.3 June 2009.