Numerical Analysis of Electrically Pumped Si-GeSn/GeSn Quantum Well Transistor Laser

Ravi Ranjan[1], Prakash Pareek[2] and Nishit Malviya[3]
[1]Department of EEE, Darbhanga College of Engineering, Darbhanga, Bihar, India, [2]Department of ECE, Vishnu Institute of Technology (A), Bhimavaram, W.G., A.P., India [3]Department of ECE, Indian Institute of Information Technology, Ranchi, Jharkhand, India, Email: ranjan275@gmail.com

***Abstract:*- The threshold current density of electrically pumped Sn incorporated group IV alloy based transistor laser (TL) is analyzed by proposing and designing a theoretical model for the same. Active region for the lasing action is formed by strain compensated GeSn single quantum well (QW) in the base of the transistor. The threshold current density for lasing action is determined with the help of obtained modal and other losses, and calculated material gain. The obtained threshold current density in the range of 2-3 kA/cm2 indicates that design of purely group-IV material based TL is viable and realistic.**

I. Introduction

Optical interconnects have become potential solutions to overcome the limitation of its electrical counterpart, widely used in multi module and system on chips [1]. Design of suitable optical source is very important to make this technology successful. Group-IV material based optical source is always desirable due to its CMOS integrability [2]. Several efforts in designing and fabricating Gr-IV based optical sources have already been given in the last few decades [3]-[4]. These Gr-IV alloys can be used as active materials for integrated photosensitive devices [5]-[6]. But, the direct band gap is obtained in near and mid infra-red (IR) regions. However, Mid-IR has now become a region of interest for toxic gas sensing, chemical process monitoring and other significant applications. Group four photonics (GFP) based device design is always preferred for these applications due to mature growth technology. The analysis and design of GeSn based Transistor Laser (TL) with QW in its base will create a value addition into the GFP based research. In this article, an electrically pumped transistor laser, based on active GeSn well layer, is proposed and its performance is analyzed. Authors have already reported a theoretical model for optical gain in a GeSn based TL earlier [6]. In this report, a complete analysis and design of Gr-IV material based TL is discussed by developing a theoretical model for the device considering the optical gain. Model also includes the effect of Sn concentration in active layer, contact layer material, device dimensions etc. on the performance of the laser.

II. THEORITICAL ANALYSIS & RESULTS

Schematic diagram of the proposed structure for Gr.-IV TL is shown in Fig.1. The structure is considered on the basis of some reported III-V based TLs [7] but with necessary modification concerning the Gr-IV material. The n-type (10^{19} cm^{-3}) Ge and $Si_{0.11}Ge_{0.73}Sn_{0.16}$ (10^{17} cm^{-3}) forms respectively the emitter and the collector of the device. Thin intrinsic $Ge_{0.85}Sn_{0.15}$ layer is inserted into the p-type (10^{19} cm^{-3}) $Si_{0.12}Ge_{0.73}Sn_{0.15}$ base (barrier) region to form quantum well. The whole structure is considered to be grown on Si substrate after developing a strain-relaxed $Ge_{0.87}Sn_{0.13}$ buffer

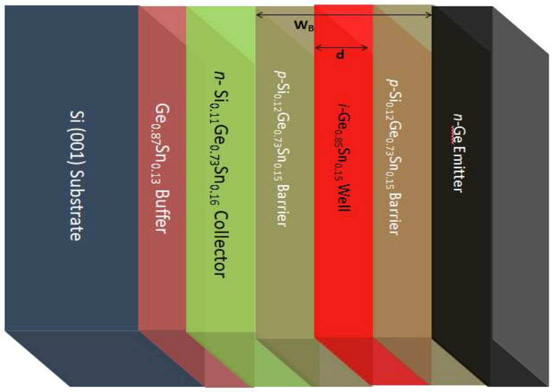

Fig.1: Schematic structure of *npn* Ge-$Si_{0.12}Ge_{0.73}Sn_{0.15}$-$Si_{0.11}Ge_{0.73}Sn_{0.16}$ based transistor laser (TL)

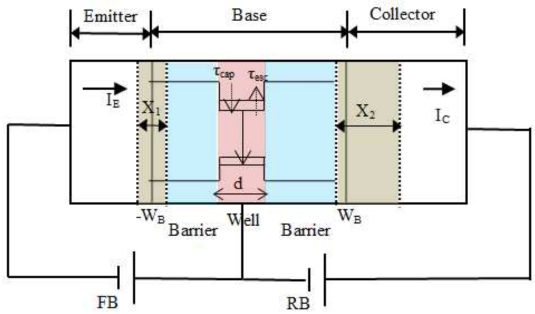

Fig.2: Schematic of carrier diffusion and quantum capture in the QW and the Γ-conduction band energy in the base region.

layer as shown in the figure. The collector layer is lattice matched with buffer layer which supports subsequent growth of barrier and well. Barrier and well layers are respectively considered as tensile and compressively strained with almost equal value with respect to the buffer layer [8]. The well width is chosen in such a way that single Eigen energy state exists within the QW and also fulfills the condition of strain balancing. Widths of well and barrier layers are calculated to be 10 nm each.

On application of forward bias in the base emitter junction, carriers are injected from emitter into the base. Some of these carriers are captured into the QW and rest move towards collector to produce collector current. Now the captured carriers produce light through their radiative recombination with the holes in the valence band. Carrier diffusion and energy band diagram (Γ-conduction band and

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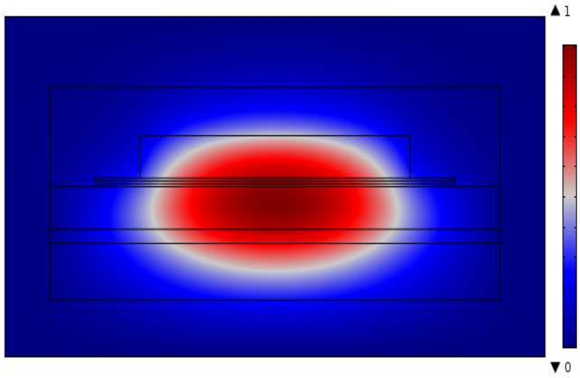

Fig.3. Field distribution of the TE field *Ex* for the quasi-TE fundamental mode at λ = 2.68 μm.

HH-valance band) in the base region of the device under bias is shown in Fig. 2. The threshold base current density (J_{Bth}) here, is very important to determine for analyzing the performance. Solving the continuity equation and rate equation with appropriate boundary condition, threshold base current density for lasing is obtained as,

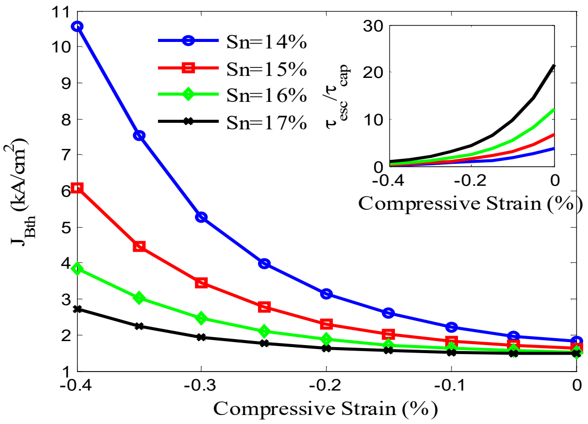

Fig.4. Plot of threshold base current density (J_{Bth}) as a function of compressive strain for different Sn concentration in the well. (-ve) sign indicates compressive. In inset quantum capture efficiency (τ_{esc}/τ_{cap}) variation is shown.

$$J_{Bth} = \frac{N_{th}}{\tau_s} qd \left[\frac{2D_n \tau_{cap} \tau_s}{L_D d \tau_{esc}} \sinh\left(\frac{W_B}{2L_D}\right) + \frac{\tau_{cap}}{\tau_{esc}} + 1 \right] \quad (1)$$

where, N_{th} is threshold carrier density, τ_s is carrier recombination lifetime in QW, D_n is diffusion coefficient, L_D is diffusion length, d is QW thickness, τ_{cap} and τ_{esc} are capture and escape life time of carriers respectively and W_B is the base width.

The threshold modal gain depends on the optical confinement factorand absorbtion loss. Optical confinemet is determined by using simulation of the structure by finite element method. The field distribution of the TE field, E_x for the quasi-TE fundamental mode at λ = 2.68 μm in waveguide is shown in Fig. 3. The peak transverse electrical field is located near the active region, providing optical confinement factor of 2.5% only for single QW. For better optical confinement in the well, silica (SiO_2) layer is considered to act as cladding layer.

In result, the calculated values of injected carrier densities, band offsets, overlap integrals for different strain in the well is summarized in Table-1 for quick reference. A particular compressive strain in the well can be achieved by changing Sn concentration in the well. But, in that case, composition of Sn in buffer layer needs to be changed accordingly. When Sn concentration in the well is increased, Γ valley band offset between well and barrier increases. Variation of J_{Bth} with compressive strain for different Sn concentrationin the well is shown in Fig. 4. It is seen from the figure that J_{Bth} increases with increasing compressive strain. This is due to the combined effect of N_{th} and quantum capture efficiency (τ_{esc}/τ_{cap}) variation with strain. As the strain in well is increased, differential gain (g) decreases and hence, N_{th} increases because more number of carriers is required to achieve the threshold modal gain. Quantum capture efficiency decreases when compressive strain increases which is shown in the inset of Fig. 5. This is mainly due to the effective band offset variation with the strain. Reduction in quantum capture efficiency means less number of carriers is captured into the well and so the high base current density (J_B) is required to achieve the threshold condition. However, the effect of quantum capture efficiency is dominant in this case because it varies exponentially with the strain and, thus, J_{Bth} increases with strain.

Table 1: Values of some material parameter with compressive strain at Sn=15% in well

Strain (%)	**Injected carrier in Γ& L valley (cm^{-3})**	**Barrier Eg(Γ), Eg(L) (eV)**	**well Eg(Γ), Eg(L) (eV)**	**Overlap Integral (I)**
0.0	6.30×10^{18}, 3.71×10^{18}	0.49, 0.46	0.37, 0.42	0.945
0.1	6.15×10^{18}, 3.86×10^{18}	0.48, 0.46	0.38, 0.42	0.938
0.2	6.01×10^{18}, 4.00×10^{18}	0.46, 0.45	0.38, 0.42	0.925
0.3	5.86×10^{18}, 4.15×10^{18}	0.44, 0.44	0.39, 0.42	0.904
0.4	5.72×10^{18}, 4.30×10^{18}	0.43, 0.45	0.40, 0.42	0.867

So, theoretical model is developed for electrically pumped GeSn based Gr.-IV transistor laser for analyzing its performance. Threshold base current density of 2.6 kA/cm^2 is obtained for a particular choice of some device and material parameters.

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