Analysis of static response of tin incorporated group –IV alloy based mid-infrared transistor laser

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***Abstract:*-In this work we present an analysis of static response 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 $Ge_{0.85}Sn_{0.15}$ single quantum well (QW) in the base. Laser rate equation and continuity equation are used to obtain the static response. The estimated results illustrate that design of group IV material based TL is feasible that has a potential application in mid-infrared optoelectronics integrated circuit.**

I. INTRODUCTION

In recent years group IV materials (Si and Ge) grab the attention of many researchers to work on low cost mid-infrared (2-5 μm) device [1]. However, the indirect bandgap nature of these materials prevents them to be used as an active optoelectronic device. Recently, the experimental evidence shows that GeSn alloy can be utilize as a direct bandgap semiconductor material [2] and it is used to design different optoelectronic devices such as lasers, detectors etc. [3,4]. But, the proper design and performance analysis of GeSn alloy based TL is still unavailable in literature. Recently, authors reported a theoretical model of group IV TL that works in mid-infrared region (2.68 μm) and calculated its optical parameters [5].

The analytical modeling and performance analysis of III-V TL is done by several researchers using rate equation and continuity equation for both minority carrier and photon [6, 7]. Most of the modeling parameters used in these analyses can be easily extracted from literature as III-V photonics is well established. However, GeSn which is Group IV based direct bandgap semiconductor material is recently developed, therefore modeling parameters and experimental reported articles on optical device (electrically pumped laser) are very limited in literature. It is main bottleneck to modeling of group IV optical devices like laser, photo-detector and transistor laser. But the advantages offers by group IV photonics [1] motivate researchers to look for appropriate solution. In this paper, authors present a static analysis for proposed GeSn/SiGeSn based TL by solving the laser rate equation and continuity equation which includes the effect of capture and escape lifetime in QW [6]. Static response of TL is required to determine the threshold base current density (J_{Bth}) which largely influences current gain, photon density and minority carrier density.

II. THEORITICAL ANALYSIS & RESULTS

Schematic structure of the group IV TL considered in our analysis is shown in Fig.1. The n-type (10^{19} cm^{-3}) Ge material forms an emitter layer, the p-type (10^{19} cm^{-3}) $Si_{0.12}Ge_{0.73}Sn_{0.15}$ as a base and n-type $Si_{0.11}Ge_{0.73}Sn_{0.16}$ as collector layer. Intrinsic $Ge_{0.85}Sn_{0.15}$ QW is inserted in the $Si_{0.12}Ge_{0.73}Sn_{0.15}$ base which acts as barrier. In $Ge_{0.85}Sn_{0.15}$ QW, Γ-conduction band is direct band gap for lasing action, as reported in our previous work [5]. The width of QW and barrier is 10 nm to ensure strain balanced condition [8]. The band-structure of Γ and L valley in conduction band and heavy hole (HH), light hole (LH) valence band in well and

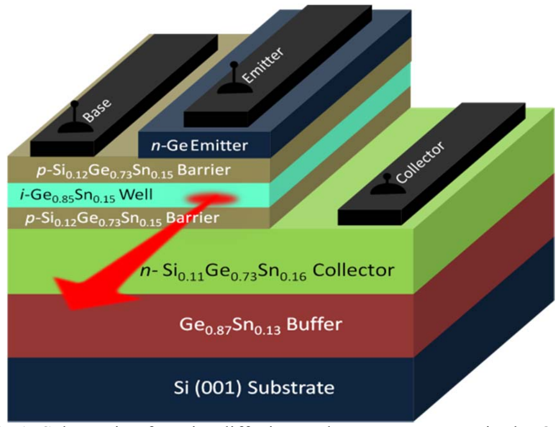

Fig.1: Schematic of carrier diffusion and quantum capture in the QW and the Γ-conduction band energy in the base region.

barrier is calculated using model solid theory [8]. The calculated band profile is used to find Eigen energies and corresponding wave functions in Γ conduction band, and HH valance band by solving Schrödinger equation with effective mass approximation [9]. Optical gain is estimated [6] at the band edge in the QW with the help of Fermi golden rule [10]. The material gain is obtained in mid-infrared region, and shown in figure 2. In the calculation of gain we assume that

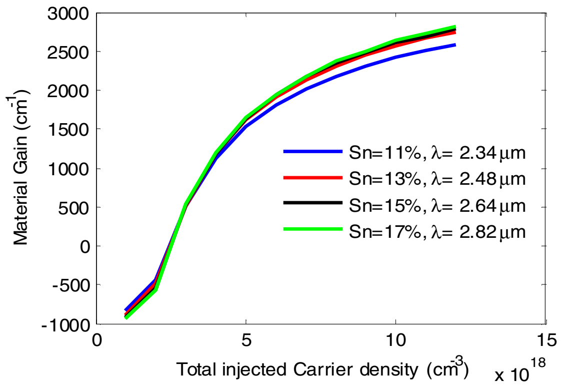

Fig.2: Material Gain as a function of total injected carrier density for different Sn concentration in well region

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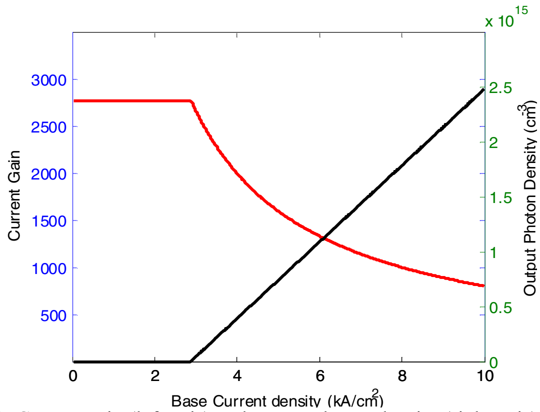

Fig.3. Current gain (left axis) and output photon density (right axis) as a function of base current density.

the amount of carrier injected in Γ valley in well region is same as injected carrier reach in Γ valley of barrier. So, the value of gain increases due to increment in JDOS which again depends on Sn content in QW. Using laser rate equations and continuity equation with appropriate boundary condition [6] the static carrier concentrations in the base region before QW (*δN1*) and after QW (*δN2)* are calculated and given below as:

$$\delta N_1 = \frac{N_{V.S}e^{W_B/2L_D} - \left(L_D/qD_n\right)J_E}{2\cosh(W_B/2L_D)}e^{x/L_D} + \frac{N_{V.S}e^{-W_B/2L_D} + \left(L_D/qD_n\right)J_E}{2\cosh(W_B/2L_D)}e^{-x/L_D} \quad (1)$$

$$\delta N_2 = \frac{n_{CB0} - N_{V.S}e^{-W_B/2L_D}}{2\sinh(W_B/2L_D)}e^{x/L_D} + \frac{N_{V.S}e^{W_B/2L_D} - n_{CB0}}{2\sinh(W_B/2L_D)}e^{-x/L_D} \quad (2)$$

The emitter and collector current density is derived as:

$$J_E = J_{V.S}\cosh\left(\frac{W_B}{2L_D}\right) + N_{V.S}\frac{qD_n}{L_D}\left(\sinh\left(\frac{W_B}{2L_D}\right) + \frac{\cos^2 h(W_B/2L_D)}{\sinh(W_B/2L_D)}\right) - n_{CB0}\frac{qD_n}{L_D}\frac{\cosh(W_B/2L_D)}{\sinh(W_B/2L_D)} \quad (3)$$

$$J_C = \frac{qD_n}{L_D}\left(\frac{N_{V.S}}{\sinh(W_B/2L_D)} - n_{CB0}\frac{\cosh(W_B/2L_D)}{\sinh(W_B/2L_D)}\right) \quad (4)$$

where $N_{v.s}$ and $J_{v.s}$ is virtual state carrier concentration and current density respectively, W_B (30 nm) is base width, L_D is diffusion length, D_n (9.3 cm^2s^{-1}) is diffusion constant, n_{CB0} is excess carrier concentration at the edge of collector side and

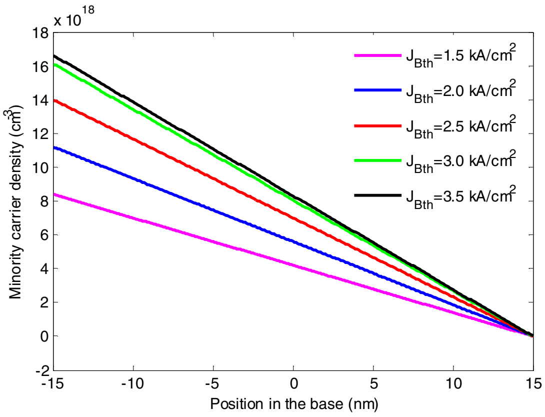

Fig.4: Minority carrier density in the base region for different base current density

J_E and J_C is emitter and collector current densities respectively. Due to non availability of recombination life time of GeSn in literature, we choose carrier life time in QW (τ_s) and base (τ_B) as per conventional direct band gap and indirect band gap material respectively. Hence, τ_s = 1 ns and τ_B=100 ns [11].Values of τ_{esc} and τ_{cap} are depends on structure of TL and material used in base region so, it is calculated for given model [12]. The chosen values of other relevant TL parameters like QW width (d), transparency (N_{tr}) and threshold (N_{th}) carrier density are 10 nm, 2.4x10^{18} cm^{-3} and 9.7x10^{18} cm^{-3} respectively. The differential optical gain (G_0), photon lifetime (τ_p) and optical confinement factor (Γ_t) are 2.45x10^{-12} $m^{-3}s^{-1}$, 2.35ps and 0.024 respectively. The Optical confinemet is calculated using finite element method. The model loss is (63.3 cm^{-1}) which include effect of free carrier obserbtion.

The variation of current gain (β) and output photon density (N_p) with base current density (J_B) shown in figure 3. Above J_{Bth}, lasing action starts and due to significant recombination of carriers in QW, current gain starts to decrease sharply and output photon density starts to increase. Here the value of current gain is very high (β=2771), it is because of structure of TL where base width is only 30 nm. In simulation we have neglected the effect of spontaneous emission so the output photon density is zero till the base current reaches to its threshold value as shown in figure. The minority carrier density distribution before and after the QW in the base region with different base current density (J_{Bth}) shown in figure 4. For uniformly spaced base current density (ΔJ_{Bth}=0.5 kA/cm^2), the minority carrier density increases at a constant rate with J_B. And as J_B reached to J_{Bth} the minority carrier density saturates with J_B because current gain decreases rapidly due to lasing action.

In this study threshold base current density (2.84 kA/cm^2), current gain (2771) and photon density are calculated for Group IV GeSn alloy based TL. The proposed TL works in mid infrared region (2-3 μm).The lower value of J_{Bth} is obtained due to QW structure and alloying of Sn in Ge material. The performance of device can be improved by selecting appropriate physical dimension and Sn composition in base of TL This result can be helpful for designing the low cost group IV mid-infrared TL.

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