Modeling of Current Gain Compression in Tin-Incorporated Group-IV Alloy Based Transistor Laser

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Abstract: In this article, the modeling of current gain compression of SiGeSn/GeSn alloy based Transistor Laser (TL) is addressed to understand the characteristic of group IV TL. 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 $Si_{0.11}Ge_{0.73}Sn_{0.16}$ (10^{17} cm^{-3}) as a collector layer. Intrinsic strain-balanced $Ge_{0.85}Sn_{0.15}$ QW is inserted in the $Si_{0.12}Ge_{0.73}Sn_{0.15}$ base which acts as the barrier. In $Ge_{0.85}Sn_{0.15}$ material, Γ-conduction band is direct band gap for lasing action in the QW region. The collector layer is lattice matched with the strain-relaxed $Ge_{0.87}Sn_{0.13}$ buffer layer which is used for subsequent growth of barrier and well. The width of QW & barrier (10 nm) is calculated using strain-balanced condition for a cubic based multilayer system grown along (001) axis. The TE polarized optical gain is estimated [1] at the band edge in the QW with the help of Fermi golden rule. The modal gain and threshold modal gain that depends on optical confinement (2.5 %) and absorbtion loss in the different region are calculated using free carrier absorption mechanism and finite element method respectively. The total model loss which includes the mirror loss is equal to 61.77 cm^{-1} where cavity length of the waveguide is 500 μm and the reflectivity of both facet (R1 & R2) are 1 and 0.7 respectively. The transparency (N_{tr}) and threshold (N_{th}) carrier density is 2.51 x 10^{-18} cm^{-3} and 8.83 x 10^{-18} cm^{-3} respectively, so the differential optical gain (g) is 9.78 x 10^{-18} cm^2 . Using laser rate equations and continuity equation with appropriate boundary condition the base current density is calculated as:

$$J_B = 2N_{V.S}\frac{qD_n}{L_D}\sinh\left(\frac{W_B}{2L_D}\right) + J_{V.S}\cosh\left(\frac{W_B}{2L_D}\right) \quad (1)$$

where $N_{v.s}$ and $J_{v.s}$ are virtual state carrier concentration and current density respectively, W_B (30 nm) is the base width, L_D is diffusion length, D_n (9.3 cm^2s^{-1}) is the diffusion constant. In the calculation, the exact experimental value of τ_B and τ_s are not available in the literature for GeSn material. So, we take value of τ_B is 100 ns [2], because material used in base is indirect bandgap in nature and value of τ_s is 1 ns because QW is direct bandgap in nature. Values of τ_{esc} (0.63 ps) and τ_{cap} (0.5 ps) are calculated for given model using formula [3].The collector current density (J_C) as a function of collector-emitter voltage (V_{CE}) for different base current density (J_B) is shown in Fig. 2. It is observed from the figure that for J_B smaller than the threshold base current density (J_{Bth}=2.6 kA/cm^2) the current gain (β≈2722) is almost constant and it work as a normal transistor. When J_B exceeds J_{Bth}, current gain decreases due to the stimulated recombination process in the QW and hence J_C saturates.

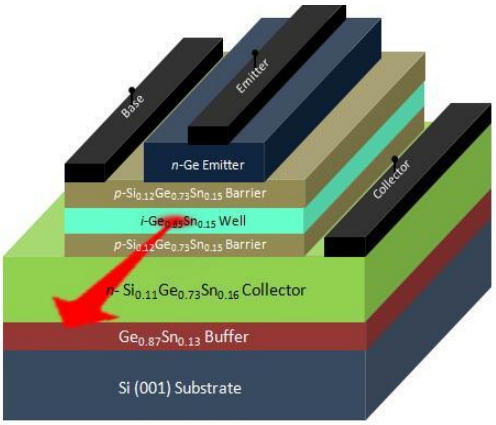

Fig.1. Schematic structure of *npn* Ge-$Si_{0.12}Ge_{0.73}Sn_{0.15}$-$Si_{0.11}Ge_{0.73}Sn_{0.16}$ based transistor laser (TL) with strain-balanced *i*-$Ge_{0.85}Sn_{0.15}$ single quantum well (QW) in the base.

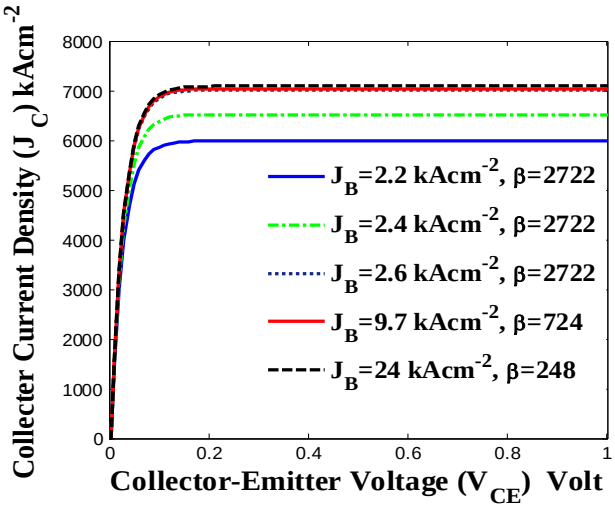

Fig. 2. Variation of collector current densityas a function of collector-emitter voltage for different injected base currents

References

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