Theoretical Estimation of Optical Gain in Tin-incorporated Group IV Transistor Laser

Mukul K Das[1], *Senior Member, IEEE*, Ravi Ranjan[2]
[1]Associate Professor, Department of Electronics Engineering, Indian School of Mines, Dhanbad, India
[2]Research Scholar, UGC-SAP Research Laboratory, Department of Electronics Engineering, Indian School of Mines, Dhanbad, India
Email: das_mkdas@yahoo.co.in, ranjan275@gmail.com

***Abstract*-We have calculated the electronic band structure and polarization dependent optical gain of a Si-$Si_{0.12}Ge_{0.73}Sn_{0.15}$-$Si_{0.11}Ge_{0.73}Sn_{0.14}$ based transistor laser (TL) with strain-balanced Ge_zSn_{1-z} single quantum well (QW) in the base. A direct bandgap Ge_zSn_{1-z} alloy can be achieved by incorporating a proper amount of α-Sn into Ge. The calculated optical gain in the QW is helpful to predict optical characteristics of Tin (Sn) incorporated group IV material based TL.**

I. Introduction

The group IV semiconducting materials like Silicon (Si) and Germanium (Ge) have widely been used in microelectronics but the constraint of their indirect bandgap nature prevents them to be used as active devices in optoelectronics. The direct Γ valley of the Ge conduction band is only 134 meV higher than the indirect L valley, suggesting that with band-structure engineering, Ge has the potential to become a direct band gap material and an efficient light emitter [1, 2]. Several research papers on semiconductor optoelectronic devices based on SiGeSn materials such as lasers [3], modulators [4], detectors [5] etc. have been reported in last few years.

TL is a new optoelectronic device invented by M.Feng and N. Holonyak and it is the combination of transistor and laser that can take an electrical input and can simultaneously give both electrical and optical output [7]. TL has attracted a lot of interests among researchers in recent years. III-V based materials have only been used for the device till now as reported by several researchers in the last decade [6]. In this paper we propose a simple theoretical model for TL based on Tin incorporated group IV material. We estimated optical gain spectra for different values of injected carrier densities to evaluate threshold current density and other optical parameters.

II. Theoretical Analysis & Results

The schematic diagram of the TL considered in our model is shown in figure 1. The n-type Si material forms an emitter layer, the p-type $Si_{0.12}Ge_{0.73}Sn_{0.15}$ as a base and n-type $Si_{0.11}Ge_{0.73}Sn_{0.14}$ as collector layer. For lasing action a $Ge_{0.85}Sn_{0.15}$ QW is inserted in the $Si_{0.12}Ge_{0.73}Sn_{0.15}$ base which acts as barrier. The collector layer is lattice matched with strain-relaxed $Ge_{0.87}Sn_{0.13}$ buffer layer which is used for subsequent growth of barrier and well. Due to lattice mismatch well and barrier layer we get a tensile strained $Si_{0.09}Ge_{0.73}Sn_{0.16}$ barrier and compressive strained $Ge_{0.85}Sn_{0.15}$ well. 80 Å barrier width is calculated for 100 Å well width using strain balanced condition for a cubic based multilayer system grown along (001) axis [9].

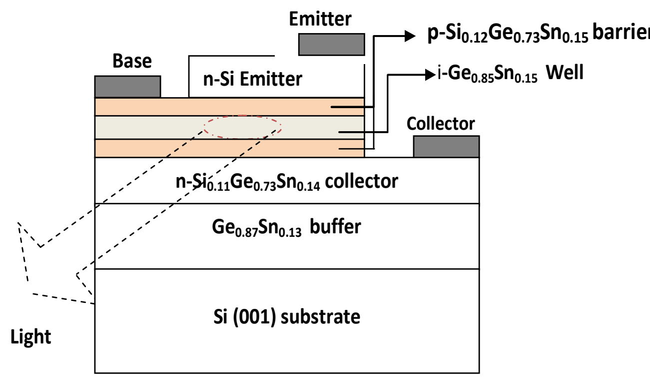

Fig. 1. Schematic structure of SiGeSn/GeSn based Transistor Laser

Band-structure of strained QW is calculated using model solid theory [10]. Material parameters of SiGeSn alloy used in this calculation is taken from [3]. Band gap energies between valence band [Heavy Hole (HH) and Light Hole (LH) both] and conduction band (L valley and Γ valley both) for different Sn concentrations in the well are shown in Fig. 2. Direct band gap GeSn well can be obtained by choosing Sn concentration corresponds to the point A or higher. But at this point LH is higher that HH and the transition between LH and Γ valley is less significant and the gain is TM mode. Dominant HH to Γ valley transition can be obtained by choosing Sn concentration corresponds to the point B or higher. Following this guideline, concentration of Sn in the well and barrier of the device, considered in our analysis, is selected. Now the calculated band profile is used to find Eigen energies and corresponding wave functions in Γ conduction band, HH band and LH band by solving the following Schrödinger equation with effective mass approximation [10].

$$\left[\frac{-\hbar^2}{2}\frac{\partial}{\partial z}\frac{1}{m_p}\frac{\partial}{\partial z}+V_p(z)\right]\psi = E_p\psi \qquad (1)$$

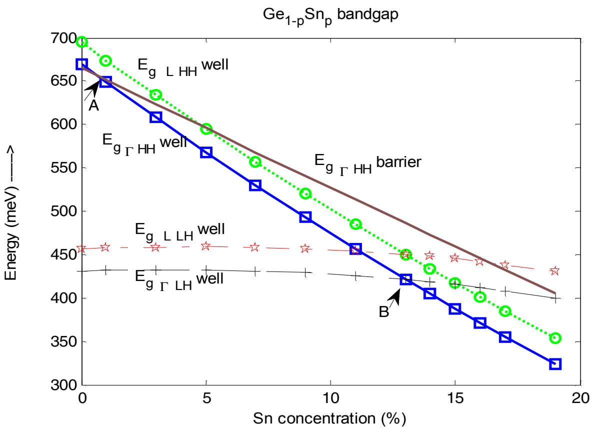

Fig. 2. Bandgap of strained GeSn as a function of Sn

where, z is position variable, ψ is wave function, E_p is Eigen energy, m_p is the effective mass where suffix p stands for type

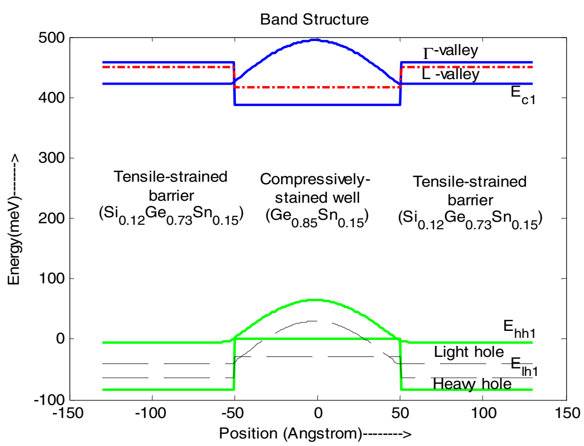

Fig. 3. Plot of energy band structure, Eigen energy and wave function in $Ge_{0.85}Sn_{0.15}$/ $Si_{0.12}Ge_{0.73}Sn_{0.15}$ QW

of band. V_p is the potential profiles of different bands. The equation is solved using Finite Difference Method (FDM) [11]. Calculated wave functions and Eigen energies are shown

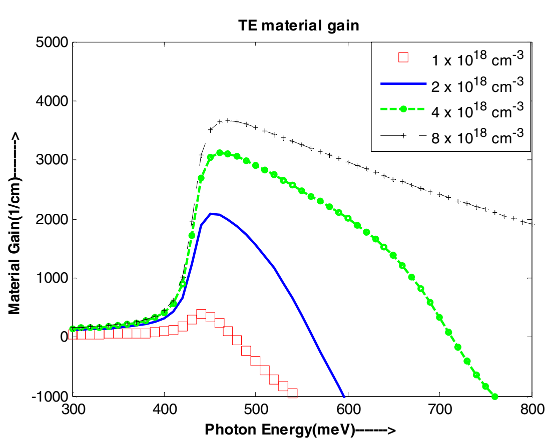

Fig. 4. TE mode gain spectra for different injected carrier densities.

in Fig.3. Dimension of well is chosen by taking critical thickness of GeSn layer into consideration. It is clear from figure that that single quantized level is present for the said dimension of well.

Optical gain is estimated in the strain-balanced QW with the help of Fermi golden rule and using Eigen energies in conduction band and HH band [10]. In calculation of gain, we have assumed no leakage of carrier in L-conduction valley. Optical gain for different carrier densities is plotted as a function of photon energy and is shown Fig. 4. It is clear from figure that, with increase in injected carrier densities the optical gain increases and peak value of gain shifts towards higher energy for larger carrier densities. In this plot, z is kept fixed at 0.85. However, the gain for different values of z are calculated and peak gains along with the other material parameters e.g. band gap are summarized in Table. 1 for quick reference.

In the present work we proposed analytical model for Tin incorporated n-p-n TL to predict its optical characteristics. The proposed TL operates in mid infra red region.

TABLE I: Values of some material parameters and maximum gain in SiGeSn/GeSn based TL for different composition of Sn.

Well composition	Barrier width (Å)	EgΓ,HH (meV)	EgL,HH (meV)	E_C (meV)	E_{hh1} (meV)	TE Gain (cm^{-1})
$Ge_{0.84}Sn_{0.16}$	110	371.2	401.1	407.8	-47.7	1902
$Ge_{0.85}Sn_{0.15}$	80	387.7	417.3	423.6	-4.64	2107
$Ge_{0.86}Sn_{0.14}$	40	404.5	433.8	443.4	-15.7	2052

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