Numerical Analysis of Tin Incorporated Group IV Alloy Based MQWIP

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***Abstract*—This work investigates performance of strain balanced SiGeSn/GeSn multi quantum well infrared photodetector by numerical analysis. Expression of responsivity is obtained by solving rate equation and continuity equation at steady state considering carrier transport mechanism across multiple well-barrier interfaces. The result shows a significant responsivity is achieved in mid-IR wavelength region which further increase on with no. of wells. Responsivity is also studied under variation of Sn content in quantum well.**

I. INTRODUCTION

In last few years, quantum well infrared photodetectors (QWIP) have attracted many researchers due to their potential applications like spectroscopic sensing, security, surveillance etc [1]. Group III-V based materials which are the dominant materials in these QWIPs are not compatible with Si platform, which is required for realizing integrable QWIP. Integrable QWIP offer several advantages like its cheap cost due to CMOS technology and also in mid-IR based optical interconnects [2]. Due to their compatibility to CMOS technology, Silicon photonics based materials like Si/Ge could be a better alternative to take the place of III-V based materials in these detectors. Unfortunately, poor response of Si/Ge based detectors in IR region restrict them to be used in integrable QWIPs [2]. Recently, incorporation of Sn into Ge matrix emerges as one of the promising solution which extend its response to IR region and convert it into direct band gap material [3]. Moreover, SiGeSn/GeSn technology provided a viable solution for mid-IR optical interconnects [4]. Successful growth of GeSn/SiGeSn based photodetectors has been reported in recent times [5,6]. However, most of these detectors are either operate at 1550 nm of wavelength or employed in bulk scale. Therefore modeling of GeSn based QWIPs is crucial and demanding in present scenario before their actual fabrication. But due to large lattice mismatch between α-Sn and Ge, excessive strain produces which can be minimized by using strain balanced designs. Ghetmiri et. al. pointed out recently that SiGeSn/GeSn/GeSn strain balanced quantum well structure can be used as a building block in optoelectronic devices [7].

In this context, authors had already reported a high absorption coefficient in strain balanced SiGeSn/GeSn/SiGeSn single quantum well infrared detector (SQWIP)[8].But multiple quantum well structure is required to enhance the performance of QWIP. In present work, numerical analysis has been done in SiGeSn/GeSn MQWIP to obtain responsivity by solving rate equation and continuity equation in quantum well considering charge transport phenomena across multiple well-barrier interfaces. Further, responsivity is also investigated under variation in no. of wells and Sn content in active QW layer.

II. DEVICE STRUCTURE AND THEORETICAL FORMULATION

The proposed device schematic is shown in Fig.1. It consists of n intrinsic $Si_{0.09}Ge_{0.8}Sn_{0.11}/Ge_{0.83}Sn_{0.17}/Si_{0.09}Ge_{0.8}Sn_{0.11}$ QW periods. This n period stack is further grown in strain balance condition via $Ge_{0.872}Sn_{0.128}$ relaxed buffer. Sn content of well, barrier and buffer are optimized to obtain type I direct band gap quantum well as well as strain balanced structure. The thickness of quantum well in each period is 7.6 Å to facilitate single bound state. The thickness of barrier is obtained as 50 Å according to condition of strain balance structure. This QW structure of n number of periods is further sandwiched between p and n SiGeSn to form a p-i-n photodetector. Light is incident from top and assumed as TE polarized to cause dominant heavy hole band (HH)- Γ conduction band (Γ CB) interband transition in compressive strained QWIP [8].

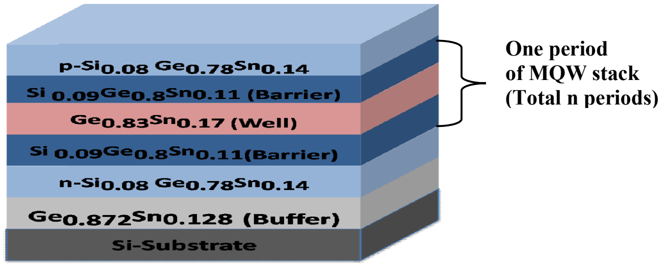

Fig.1 Schematic structure of strain balanced MQWIP

Now, after incident of light electron hole pairs generated and captured in Γ-CB and HH of QW. After capturing, carriers may escape mainly by two mechanisms from QW and cause photo current. First one is thermionic emission which is due to its operation at room temperature and existence of first bound state in well near the top of conduction band (valence band)[9]. Second escape process of the carrier which is quite evident due to thin barriers, is tunneling [9]. Apart from escape, photogenerated carriers can also recombine through ban to band recombination. We assume 10 ps as the recombination time of the carriers (electrons or holes). Responsivity is most important performance parameter which indicate photocurrent per unit input optical power at steady state. Before deriving general expression of responsivity for

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MQWIP structure, a general expression of same in term of position coordinate x is derived for SQWIP for electrons in following manner. Rate equation in QW is written in case of generation of carriers due to interband transition as:

$$\frac{dn_{QW}}{dt} = \frac{J_i}{q} + G(x,t).w_d - n_{QW}.R_e \qquad (1)$$

where , n_{QW} is concentration of electrons in quantum well, R_e is total escape rate and recombination rate of electrons in quantum well; $G(x,t)$= generation rate of carriers, I_0 is intensity of light, w_d is well width, α is absorption coefficient of QW layer which was obtained from our previous work [8]. J_i is injected current density due to captured electrons in quantum well. At steady state $dn_{QW}/dt = 0$

$$J_i = (I_0 \exp(\,(-\alpha x).w_d - n_{QW}.R_e).q \qquad (2)$$

Now, continuity equation over quantum well is given by

$$\frac{\partial n}{\partial t} = -\frac{n_b - n_0}{\tau} + v_e \frac{\partial n}{\partial x} \qquad (3)$$

where n_b is electron density in continuum state, v_e is saturation velocity due to small dimension of QW. At steady state $n_b(x)$ can be solved after applying appropriate boundary condition, x=0 to w_d(well width) and $n_b(0)=J_i/qv_e$.

Thus the position dependent electron density is given by:

$$n_b(x) = \frac{I_0.\alpha \exp(-\alpha x).w_d - n_{QW}.R_e}{v_e}.\exp\left(\frac{x}{\tau v_e}\right) \qquad (4)$$

The above expression of $n_b(x)$ is electron density for single quantum well. In case of multiple quantum well this expression can be changed to

$$n_b(x') = n_r.\exp\left(\frac{x'}{\tau v_e}\right) + \left(\frac{\alpha w_d I_o \exp(-\alpha x')\exp\left(\frac{x'}{\tau v_e}\right) - n_{QW} R_e \exp\left(\frac{x'}{\tau v_e}\right)}{v_e}\right) \qquad (5)$$

n_r=contribution due to previous r^{th} quantum well; x'=distance traversed by light for r^{th} no. of Q.W.expression of n_r can be obtained for r^{th} stage of N quantum well and written as:

$$n_r = \left[\frac{P}{v_e}\right]\sum_{i=1}^{n-r+1} f_e^{(i-1)} \exp\left(\frac{(i-1)w_d}{\tau v_e}\right) \qquad (6)$$

$$P = \left[\alpha w_d I_0 \exp\left(w_d\left(\frac{1}{\tau v_e} - \alpha\right) - n_{QW} R_e \exp\left(\frac{w_d}{\tau v_e}\right)\right)\right]$$

f_e is a factor (n/n_{QW}) which is obtained from rate equation. It multiply with carrier density each time when electron crosses appropriate interface of well and barrier. Substituting the expression of n_r, in eqn.(5), n_b can be written after averaging over width of n quantum well as:

$$n_b = \frac{1}{w_d v_e} P \sum_{i=1}^{n-r+1} f_e^{i-1} \exp\left((i-1)\frac{w_d}{\tau v_e}\right)\left(\frac{1-\exp\left(\frac{w_d}{\tau v_e}\right)}{(\tau v_e)^{-1}}\right) +$$

$$\frac{1}{w_d v_e}\left[\frac{I_0 w_d \alpha\left(1-\exp\left(w_d\left(\frac{1}{\tau v_e} - \alpha\right)\right)\right)}{\left(\alpha - \frac{1}{\tau v_e}\right)} + n_{QW} R_e \frac{\left(1-\exp\left(\frac{w_d}{\tau v_e}\right)\right)}{(\tau v_e)^{-1}}\right] \qquad (7)$$

Electrons Current density can be obtained by using $J_n = n_b q v_e$. Expression of hole current density (J_p) can be derived similarly. Now, expression of responsivity, R is obtained by expression $(J_n+J_p)A/p_{in}$, where p_{in} is input optical power and A is area of cross-section. The responsnivity is computed for different no of quantum well (n) and plotted versus wavelength as shown in Fig.2. It is clearly observed from figure a significant responsivity is achieved at wavelength of 3.55 µm and on increasing n, responsivity increases. Responsivity increases due to increment of well- barrier interfaces which further increased n_r. A maximum responsivity of 29 mA/W can be obtained for 5 quantum wells. However wavelength of operation can be changed by changing *x*. It can be observed from the inset of Fig. 1, that on increasing *x*, responsivity enhanced as well as get redshifted. This is due to reduction of energy band gap of $Ge_{1-x}Sn_x$ on addition of Sn, which also increases Joint density of states (JDOS) and overlap integral of interband HH-ΓCB transition. Thus the present study showed that proposed MQWIP can be utilized in mid-IR based optical interconnect.

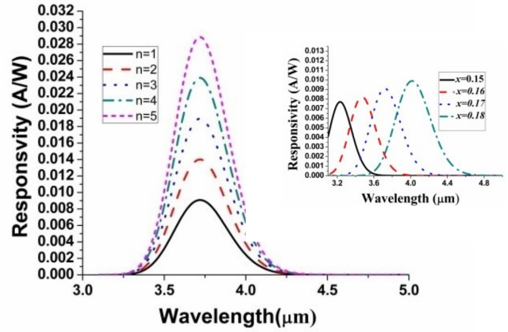

Fig.2 Plot of responsivity (R) as a function of wavelength for different no. of wells, plot of R for different *x* is also shown in inset.

REFERENCES

[1] V. Guériaux et al., "Quantum well infrared photodetectors:present and future," Optical Engineering vol. 50, p. 061013, 2011.

[2] G. Roelkens et. al., "Silicon-Based Photonic Integration Beyond the Telecommunication Wavelength Range", IEEE. Journal of Selected Topics in Quantum Electronics, vol. 20, no. 4, pp. 394-404,. 2014.

[3] J. Kouvetakis, J. Menedez, A.V.G. Chizmeshya., "Tin based group IV semiconductors: new platforms for opto and micro electronics and silicon," *Ann. Rev. of Mat. Res.*, Vol.36, pp.497-554, 2006

[4] R. Soref, "Emerging SiGeSn integrated-photonics technology", 2016 IEEE Photonics Society Summer Topical Meeting Series (SUM), CA, pp. 100-101. 2016. (doi: 10.1109/PHOSST.2016.7548747)

[5] J.Werner et al., "Germanium–tin p-i-n photodetecors integrated on integrated on silicon grown by molecular beam epitaxy," Applied Physics Letters, vol. 98, no. 6, Art no. 061108, 2011.

[6] J. Zheng et al., "GeSn p i n photodetectors with GeSn layer grown by magnetron sputtering epitaxy,"Applied Physics letters, vol. 108, no. 3, art. No. 033503, 2016.

[7] Seyed Amir Ghetmiri et. al., "Study of a SiGeSn/GeSn/SiGeSn structure toward direct bandgap type-I quantum well for all group-IV optoelectronics", Optics Letters, vol.42,no.3,pp.387-390, 2017.

[8] P. Pareek and M. K. Das, "Theoretical analysis of direct transition in SiGeSn/GeSn strain balanced QWIP," Optical and Quantum Electronics, vol. 48:228, pp. 1-11, 2016.

[9] G. Zhou and P. Runge, "Modeling of Multiple-Quantum-Well p-i-n Photodiodes," IEEE Journal of Quantum Electronics, vol. 50, no. 4, pp. 220-227, April 2014.