Modeling and Design of Tin Doped Group IV Alloy Based QWEAM

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Abstract—**This work investigates vital characteristics of Tin doped group IV based quantum well for its potential as electroabsorption modulator (EAM). Figure of merit and refractive index variation in proposed EAM structure is evaluated and studied under variation of electric field. The result depicted that this proposed structure can be a potential candidate for mid-infrared wavelength range applications on Si platform.**

I. INTRODUCTION

In last few years, electroabsorption modulators (EAMs) emerges as one of the indispensable component of fiber-optical communication network and systems, because of their small size, low driving voltage, low chirp, high extinction ratio, high modulation efficiency, and wide modulation bandwidth [1]. Moreover, they become very popular than their conventional LiNbO3 counterpart due to their ability to integrate with semiconductor lasers, semiconductor optical amplifiers, and attenuators [2]. Therefore EAMs are said to be one of the most viable path to realize on-chip optical interconnect which can overcome the hindrances of traditional large scale communication system. However, there has been a long quest among researchers for suitable active material in integrable EAM. Silicon photonics based materials like Si, Ge etc. due to their CMOS compatibility, are the potential candidates to realize monolithic EAM[3]. The reporting of a strong quantum confined Stark effect (QCSE) in Ge quantum well (QW) has opened the door of implementation of CMOS compatible quantum well electroabsorption modulator (QWEAM) [4]. However the indirect bandgap nature and weak mid-infrared response of Ge hamper the real time implementation of Ge based EAM [5]. Fortunately, recent works which demonstrated the conversion of Ge into direct bandgap material by doping of Tin (Sn) into it [6-9], have paved the path of efficient group IV mid-IR QWEAM.

Thus, the theoretical modeling of GeSn based QWEAM is important before its actual fabrication. To the best of authors knowledge, in spite of its immense potential, GeSn based QWEAM is hardly investigated theoritally in detail by the researchers. Therefore, the present work in the paper devoted to the study of some of the important characteristics of proposed GeSn based QWEAM. The most critical issue associated with GeSn quantum well is its strain. Due to lager lattice mismatch between Ge and Sn, strain induce which can become uncontrollable and ultimately causes dislocations. Therfore to resolve this issue, it has been already reported by the authors to use GeSn quantum well structure under strain balance condition [10].

In this paper strain balanced SiGeSn/GeSn quantum well structure is studied for its potential as an EAM. Important parameters like figure of merit (FOM) and refractive index variation are evaluated for the purposed structure. After their evaluation, they are studied under variation of different applied electric field (biases) as a function of energy (wavelength).

II. PROPOSED STRUCTURE AND THEORETICAL FORMULATION

The schematic of proposed structure cross section is shown in Fig.1. It consists of intrinsic $Ge_{0.83}Sn_{0.17}$ QW of thickness 8.2 Å. This particular thickness of the well is taken to make sure that only single bound state exist in its conduction band and valence band. This QW is sandwiched between 50 Å thick $Si_{0.09}Ge_{0.8}Sn_{0.11}$ barriers. Further, this structure is grown on $Ge_{0.872}Sn_{0.128}$ relaxed buffer. The Sn contents of well and barrier are chosen to ensure strain balance condition. It may be relevant to mention here that the thickness of barrier is obtained by using mathematical expression under strain balance criteria [10]. Under this criteria, strain in well (compressive) and barrier (tensile) is made exactly opposite in nature and magnitude with respect to buffer. Moreover, Sn content in the well is selected such that quantum well become direct band gap as well as of type I in nature. Therefore SiGeSn/GeSn QW structure as shown in Fig.1 is considered in this work for gauging its potential to be an efficient EAM. The practical feasibility of this structure is already justified by a group of researchers recently [9]. The electric field is applied to the perpendicular of the quantum well layer in this work to

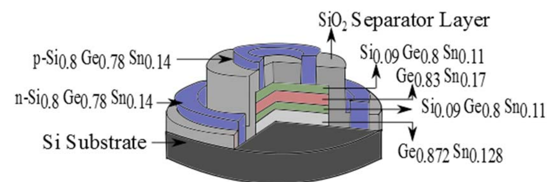

Fig.1.1 Cross section of purposed structure

obtain its electro absorption characteristic. Thus, TE mode of operation is considered in this work which observes a dominate heavy hole band -Γ conduction band transition [11].Initially, field dependent absorption characteristic of the considered quantum well structure is investigated. The main advantage of QWEAM is its ability to operate under low bias. Therefore, we evaluated absorption coefficient under different low biases for wavelength range typically in the range (2~4 μm). This wavelength range is most important from the point of view of spectroscopic sensing. To begin with, bounded states in Γ-conduction band, heavy hole band (HH) and light hole band(LH) of quantum well is calculated self consistently. Then absorption coefficient in presence of different electric fields (biases) considering excitonic effect (α_{EA}) is calculated by the following expression [10]

$$\alpha_{EA}(E) = \frac{\pi q^2}{n_{rw} c\varepsilon_0 \, m_0^2 \omega} \cdot \left|I_{c\Gamma 1}^{HH1}\right|^2 \cdot \left|\hat{e}.P_{cHH}\right|^2 .2\left|\varphi_{ex1}(\rho=0)\right|^2$$

$$\frac{1}{\sigma_{ex}\sqrt{2\pi}} \exp\left[-\frac{\left(E - E_{g\Gamma} + E_{c\Gamma 1F} - E_{HH1F} - E_{ex1}\right)^2}{(2\sigma_{ex})^2}\right] \qquad (1)$$

In the above expression, $E_{c\Gamma 1F}$, E_{HH1F} are bound state Eigen energies in Γ- CB, and HH band respectively, in presence of electric field, F. E_{ex1} is bound state energy of 1s exciton, ϕ_{ex1} (ρ=0) is the corresponding wave function at origin, where ρ is position coordinate of exciton under Columbic interaction. P_{cHH} is a momentum matrix element between conduction band and HH band for Bloch states considering TE mode, σ_{ex} is exciton broadening,

A significant red shift in the peak of absorption coefficient is observed which depicted QCSE in quantum well. Figure of merit i.e effective change in peak absorption coefficient (Δα), is evaluated and plotted as a function of optical energy (E) for different electric fields in Fig.1. In figure 1, It can be clearly seen as F increases Δα decreases. Moreover, for 0.3-0.4 eV, the slope of Δα curve is positive.

After calculation of Δα, refractive index change (Δn) is calculated by using Kramers–Kronig relation which is given by following equation [1].

$$\Delta n(E,F)=\frac{ch}{\pi}\int_0^{\infty}\frac{\alpha(E',F)-\alpha(E',0)}{(E')^2-(E)^2}dE' \qquad (2)$$

Δn is plotted for different electric fields as a function of E in Fig.2. It can be clearly seen in the figure for higher electric field refractive index change increases in a negative manner.

The nature of Δα and Δn show opposite trends which becomes clear from figure 1 and figure 2. This is a significant observation which indicates the nature of chirp parameter which plays an significant role in the performance of QWEAM [1]. Chirp parameter obtained from the relation of refractive index change slope versus absorption coefficient slope. In this work, we can conclude that a negative chirp parameter is achieved which is highly desirable for QWEAM, due to opposite nature of refractive index change and absorption coefficient change. Hence the purposed structure in this work might be useful for realizing on-chip mid infrared based competent EAM.

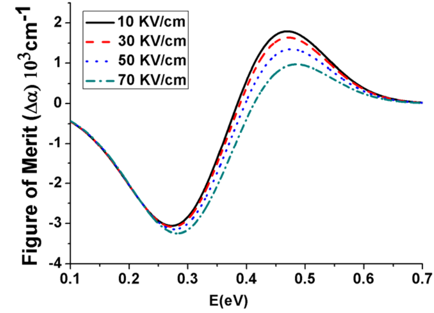

Fig.1. Plot of Δα versus E for different electric field

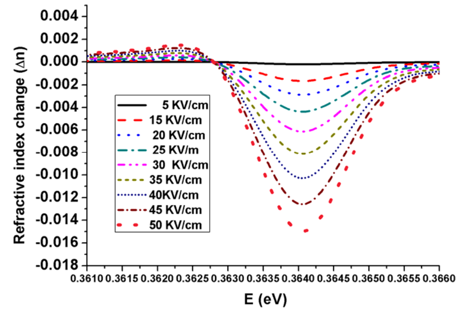

Fig.2. Plot of Δn as a function of E for different F

REFERENCES

[1] Kambiz Abedi, "The design of electroabsorption modulators with negative chirp and very low insertion loss", *Journal of Semiconductor*, Vol.33, No.6, p.064001,2012.

[2] J. F. Liu, et al. "Waveguide- integrated, ultralow-energy GeSi electro-absorption modulators", *Nature Photonics*, Vol. 2,no.7, pp.433–437, 2008.

[3] R. Soref, "Mid-infrared photonics in silicon and germanium," *Nature Photonics*, Vol. 4, pp. 495 – 497, Aug. 2010.

[4] Yu-Hsuan Kuo et. al., "Strong quantum-confined Stark effect in germanium quantum-well structures on silicon", *Nature*, Vol. 437, pp. 1334–1336, Oct. 2005.

[5] Pallab Bhattacharya, Semiconductor optoelectronic devices, *Pearson Education Inc.*, Second ed., New Jersey, 1994.

[6] 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.

[7] A. Gassenq et. al., "GeSn/Ge heterostructure short-wave infrared photodetectors on silicon," *Optics Express*, Vol. 20, pp. 27297-27303, 2012.

[8] Minami Akie et. al., "GeSn/SiGeSn Multiple-Quantum-Well Electroabsorption Modulator With Taper Coupler for Mid-Infrared Ge-on-Si Platform", *IEEE Journal Of Selected Topics In Quantum Electronics*, Vol.24, no. 6, p. 3400208, 2018.

[9] 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.

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

[11] Shuan Lien Chuang, Physics of optoelectronic devices, *John Wiley & Sons inc.*, New York, 1995.