Examination of Resonant Cavity Enhanced Strain Compensated SiGeSn/GeSn Interband MQWIP

Prakash Pareek[1], Lokendra Singh[2], Ravi Ranjan[3], Nishit Malviya[4], Vipul Agarwal[2]

[1]Dept. of Electronics and Communication Engineering, Vishnu Institute of Technology, Vishnupur, Bhimavaram, A.P., India
[2]Dept. of Electronics and Communication Engineering, Koneru Lakshmaiah Educational Foundation, Vaddeswaram, A.P.,India
[3] Dept.of Electrical and Electronics Engineering, Darbhanga College of Engineering,Darbhanga, Bihar, India
[4]Dept.of ECE, Indian Institute of Information Technology Ranchi, Ranchi, Jharkhand, India

***Abstract*—In this work, mathematical investigation is done for the potential of Group IV alloy based resonant cavity enhanced interband multiple quantum well photodetector (MQWIP). Strain balanced multiple quantum well structure is proposed to be configured between two Bragg reflectors(mirrors) to form a resonant cavity. Responsivity is calculated by solving the rate equation in each GeSn active well region of MQWIP considering interwell carrier transport mechanism and resonant cavity. The result reveals that peak responsivity is significantly higher than that of the MQWIP without resonant cavity at 3.8 μm.**

I. Introduction

Group IV photonics (GFP) introduces a new and diverse paradigm for the integration of optoelectronic and electronic devices [1]. Concurrently the field of mid-infrared sensing is also feeling the strong presence of GFP. In this context monolithic sensors are in high demand due to their affordability and compatibility with CMOS technology [1]. Researchers suggested Germanium (Ge), instead of Silicon (Si) as the active sensing material in monolithic photodetectors due to its higher absorption at 1550 nm [2]. However, indirect bandgap nature of Ge put a big question mark on the competency of Ge based photosensitive devices. The solution of this issue lies in the band gap attributes of Ge itself. There is only 140 meV difference between the direct and indirect bandgap of Ge [2]. Now the main focus of work was to overcome this small difference and transform Ge in a direct bandgap material. Many methodologies were suggested like high n-doping of Ge, inducing tensile strain in Ge and incorporating Sn in Ge. Among these techniques, incorporation of α-Sn into Ge was emerged as most popular and reliable technique [3].

In this context, few works have been reported regarding the design of GeSn based photosensitive devices particularly quantum well infrared photodetector (QWIP) [4]. However, several challenges were faced by the concerned workers. Firstly, there is very high lattice mismatch between Ge and Sn which can induce large amount of strain [3]. Next hurdle was the operating temperature of GeSn based monolithic detectors. In order to ensure its wider reach, integrable photodetectors need to be operate at room temperature. Most of the reported GeSn based QWIP were intersubband designed to be operated at lower temperature. Therefore, one of the authors reported the design of strain balanced GeSn interband QWIP and evaluation of its various performance parameters at room temperature [5,6]. However, responsivity of this group IV alloy based QWIP was not comparable to its III-V counterpart regardless of using the multiquantum well (MQW) structure in active region [7]. Moreover, number of well cannot be increased in MQWIP beyond a limit, because of responsivity bandwidth tradeoff [2].

In this context, introduction of resonant cavity in the device emerges as one of the potential solutions. To the best of our knowledge, detail study of resonant cavity enhanced (RCE) group IV alloy based strain balanced interband MQWIP is hardly reported in the literature. Therefore, in this work a theoretical model for the same is proposed. Responsivity is evaluated by solving the rate equation in the wells of RCE-MQWIP considering interwell carrier transport and illumination profile of resonant cavity.

II. Proposed Theoretical Model and Formulation

The schematic of proposed RCE strain balanced MQWIP is shown in Fig.1. The active region consists of undoped GeSn quantum well layer with Sn composition of 17%. Thickness of active layer (7.6 nm) and its composition is selected to facilitate direct interband transition between quantized state of Γ -conduction band and heavy hole valence band [5].

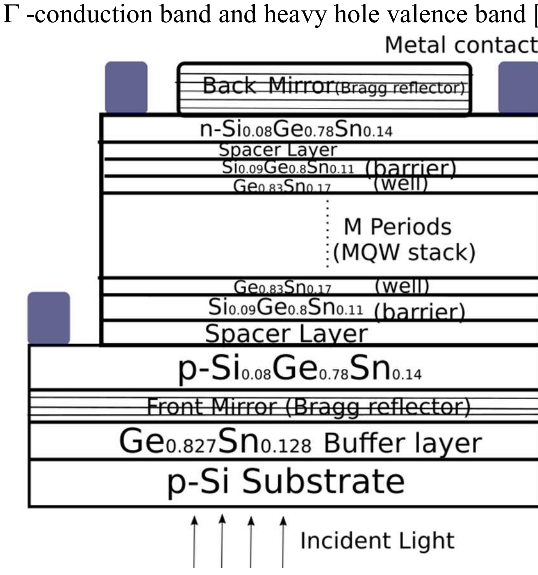

Fig. 1: Schematic of proposed GeSn based RCE-MQWIP

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Quantum well structure is formed by sandwiching this active region between SiGeSn barriers. A relaxed GeSn buffer layer is also included to tackle the issue of excessive strain and realize strain compensated structure. Hence, the thickness of each barrier (5 nm) and compositions of barrier and buffer layer ares considered to satisfy strain balancing criteria[5]. MQWIP structure is formed by alternative M periods of quantum well and barrier. Further, P and N heavily doped SiGeSn contact layers which are lattice matched with buffer are provided on either end of MQWIP to attain p-i-n structure. Now, in order to incorporate resonant cavity in this structure, two parallel mirrors (Bragg reflectors), are provided on the outside of contact layers as shown in figure 1. The theoretical modeling of this MQWIP is done with the help of model reported by Ryzhii with some modifications suited to interband RCE-MQWIP [8]. Light is assumed to be incident on the p-Si substrate and cause electron and hole pairs to be generated in active well regions. These carriers can escape either by thermionic emission or tunneling emission. Due to presence of multiple active layers, carrier of a particular well will interact with the carriers moving towards contact [7]. The generated photocurrent can be enhanced by the resonant cavity under favorable resonance conditions. Now responsivity can be calculated by solving rate equation for boundstate electrons and holes as interband transition is considered in this work. The position dependent rate equation for electrons is given as, where x is the position coordinate for MQWIP structure which directed from p to n side,

$$\frac{\partial n_{well}}{\partial t} = \frac{J_{i,e}P_c}{q} + K_g[(\exp(\alpha(L-x)) + R_b.\exp(-\alpha(L-x))] - n_{well}R_e \quad (1)$$

Where $J_{i,e}$ and P_c are injected current density and capture probability of electrons respectively[7], n_{well} is electron density in well, α is absorption coefficient of active region, R_e is total emission rate of electrons (tunneling and thermionic), L is the length of cavity, Rb (Rf) is reflectivity of back mirror (front mirror) in RCE-MQWIP, K_g is the photgeneration rate coefficient in resonant cavity which is given as [9]

$$K_g = \frac{(P_i\alpha(1-R_f)\exp(-\alpha w_d))}{\left[\begin{array}{l}1-2\sqrt{R_f R_b}\exp(-\alpha w_d). \\ \left(\mathrm{Cos}(2\beta L+\phi_f+\phi_b+R_f R_b\exp(-2\alpha w_d))\right)\end{array}\right]} \quad (2)$$

In eqn.(2), w_d is well width, P_i is input power, ϕ_f (ϕ_b) is phase shift due to front (back) mirror, β is propagation constant [9]. Interwell carrier transport mechanism is considered while calculating the effective number of photogenerated electrons. Similar equation can also be written and solved for holes to get the photogenerated hole current density. After solving the rate equations, responsivity, R can be calculated as follows

$$R = \frac{(J_e + J_h)}{P_i} \quad (3)$$

J_e and J_h are electron and hole current density respectively.

Relevant material parameters for barrier and well are calculated by linear interpolation and suitable approximations [6,7]. Absorption coefficient of the considered active region is already reported by one of the authors elsewhere [5]. R_f and R_b are considered to be as 0.49 and 0.99 respectively[9]. In this work L is considered in accordance with the satisfaction of resonant condition to obtain maximum K_g. Responsivity is calculated with the help of eqn.(3) and plotted as a function of wavelength for different number of quantum well (M) at fixed bias in Fig. 2. This figure clearly shows that with increase in quantum well number, responsivity increases. More importantly, the values of responsivities are higher (eg:0.41 A/W at 3.8 μm) as compared to the MQWIP without resonant cavity. This result further ushers the potential of RCE-MQWIP as a vital candidate for electronic photonic integrated circuits (EPIC). This work can be further extended by exploring the frequency response of the considered structure and thus evaluating the responsivity-bandwidth product.

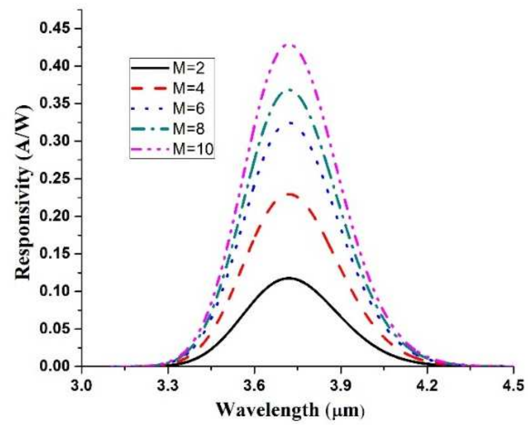

Fig.2 : Responsivity of RCE-MQWIP for different M

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