Impact of Sn content on frequency response of GeSn SQWIP

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Abstract. In this paper a detailed theoretical investigation of Sn content dependent frequency response in strain balanced SiGeSn/GeSn single quantum well infrared photodetector (SQWIP) is made. The rate equation in the quantum well is solved to obtain photo generated current density in frequency domain. Impact of Sn content in the well on the frequency response, and bandwidth is studied. The result show that a large bandwidth can be achieved at higher Sn content of active region i.e. quantum well in the device. This is mainly due to the consideration of strain balancing condition in the structure of proposed SQWIP. On using proper choice of Sn content in well, this structure may be used in CMOS compatible photonic integrated circuit.

1. Introduction

In last few years, III-V quantum well infrared photodetectors (QWIP) are used in ground and space-based applications such as night vision, temperature detection, early warning systems, navigation, flight control systems, weather monitoring, as well as security and surveillance [1]. However, the broad use of these III-V QWIPs is restricted due to their high cost and incompatibility to silicon which is very important to realize electronic photonic integrated circuit [2]. In recent years, emergence of genuine direct band gap group IV alloy i.e. GeSn, paved the path of monolithic QWIP [3,4]. Therefore study as well as modeling of GeSn QWIP is very crucial before its fabrication to reengineering its properties. In this process, strain also come into play obviously, due to a large lattice mismatch between Ge and Sn. Thus, strain balanced structure is used to protect the active GeSn well layer from excessive strain during fabrication [5]. In a strain balanced system, strain in well region can be minimized by adjustment of lattice constant of barrier and buffer layers. Due to its simple structure, a single quantum well structure is most appropriate for a better understanding of various physical aspects.

In this context, authors had already proposed a strain balanced GeSn based single QWIP (SQWIP) and reported a higher absorption coefficient for GeSn active layer [6]. Thus in present paper, extending our earlier work [6], effect of Sn content of well on frequency response in strain balanced Si$_{0.09}$Ge$_{0.8}$Sn$_{0.11}$/Ge$_{0.83}$Sn$_{0.17}$ QWIP is studied. In this work, we derived an analytical expression of frequency dependent current density in QWIP using rate equation in quantum well.
2. Model Description and theoretical formulation

The cross section of the model considered in our analysis is shown in Fig 1. It consists of Ge$_{0.83}$Sn$_{0.17}$ quantum well layer sandwiched between two wide bandgap Si$_{0.09}$Ge$_{0.8}$Sn$_{0.11}$ barriers. The Ge and Sn content of well and barrier are optimized to facilitate low direct bandgap well layer as well as wide bandgap barrier for quantum carrier confinement [6].

In this work, bias voltage is assumed to be large enough so that the carriers are drift across barriers at saturation velocity. Carrier transport mechanism is an important process which needs to be addressed in order to obtain frequency response in detector. Fig. 2 shows a simple schematic of GeSn QWIP for calculating the frequency dependent photocurrent. Let the light of appropriate wavelength incident from p-side of the P-i-N detector. After incident of light, electron hole pairs are generated. These photogenerated electrons and holes move in opposite direction under influence of electric field. Diffusion of photogenerated carriers can be neglected due to a large electric field across depleted region. This movement of photogenerated carriers induces a current density in the structure. Let this current density due to moving electron, $J_{em}$ (considering electron first). Actually, $J_{em}$ depends upon the distribution function of uncollected electrons in the active region of the QWIP structure [7]. The distribution function includes the effect of decaying nature of light intensity. So, from the figure 2, expression of current density due to moving electrons is given by[7],

$$J_{em} = K q v_e \left[1 - \exp(-\alpha w_d - v_e t)\right]$$  \hspace{1cm} (1)

where $K$ is a constant which depends upon the intensity of input light. $w_d$ is quantum well layer thickness, $v_e$ is saturation velocity of electron and $\alpha$ is absorption coefficient of active GeSn well layer as computed in our previous work [6].

The transport mechanism of photogenerated carriers in quantum well can be fully understood by using rate equation in quantum well. The rate equation for electrons in conduction band can be written as[7],

$$\frac{\partial n_{em}}{\partial t} = \frac{J_{em}}{q} - n_{em} R$$  \hspace{1cm} (2)
where, \( J_{em} \) = current density due to moving electron, \( n_{QW} \) = electron sheet concentration in quantum well in \( \text{cm}^{-2} \), \( J_{em} \) = Current density at quantum well due to moving carriers, \( r_{esc} \) = rate of thermionic emission in quantum well, \( r_r \) = rate of recombination of carrier in quantum well, \( R = r_{esc} + r_r \) i.e. total rate of thermionic escape, tunneling and recombination of carriers. The rate equation involves the processes of carrier capture and escape from quantum well. The two main mechanisms of carrier escape from quantum well are considered in our study which are tunneling emission and thermionic emission. Thus the carriers which are injected from the contact, some get captured in quantum well; some escape from quantum well due to thermionic emission and tunneling, reach the contact at the other end and extracted by strong electric field [8]. Now, the rate equation in quantum well can rewritten as:

\[
\frac{\partial n_{QW}}{\partial t} = K_v \left[ 1 - \exp(-\alpha \left( w - v \right) t) \right] - n_{QW} \left( r_{esc} + r_{tunneling} + r_{recombination} \right)
\]

(3)

On using Laplace transform to solve the above expression

\[
n(j \omega) = K_v \left[ \frac{1 - R \exp(-j \omega)}{\left( \frac{\alpha v}{R} + 1 \right)} \right] \left[ \frac{1}{\alpha v - R - j \omega} \right]
\]

(4)

Same calculation is done for obtaining hole current density i.e. \( p(s) \). Thus the frequency dependent current density in SQWIP can now be written as

\[
J(j \omega) = n(j \omega)q_v + p(j \omega)q_h
\]

(5)

3. Results and discussion

Before calculating frequency response, some appropriate approximations are made for material parameters like saturation velocity, recombination time for Sn for which exact values are not reported in the literature. To understand the effect of Sn content on the frequency response of GeSn QWIP, Fig. 3 is plotted. The figure shows the frequency response for different Sn content at zero bias. It is clearly observed from the plot, with increasing Sn content in quantum well layer, 3 dB bandwidth increases. The above statement become more clear when bandwidth is extracted from this figure and plotted as a function of applied bias and is shown in Fig. 4. In figure, bandwidth increases with bias due to decrement of effective band height which further increases thermionic emission [7]. Moreover, thermionic emission is more dominant here due to consideration of room temperature (300K). The figure also depicts a significant increase in the bandwidth on increasing Sn content. This is due to the strain balanced nature of the structure.

![Fig. 3. Plot of frequency response of SQWIP for different Sn content in the well](image-url)
When Sn content is increased then the barrier thickness is reduced due to strain balanced condition. Due to decrease of barrier thickness, transit time of the carriers reduces. This causes increase in 3 dB bandwidth. The increment is more for higher Sn content in well. It is worth to be mentioned here at this critical juncture that increasing Sn content beyond 20% causes serious fabrication dislocations [9]. Therefore proper optimization of Sn should be done before actual implementation of GeSn SQWIP.

4. Conclusion
In this work, we have theoretically studied the frequency response in strain balanced SiGeSn/GeSn QWIP. The alloy composition of well, barrier and buffer layers are chosen to ensure type I direct band gap quantum well as well as strain balanced structure. The frequency dependent photogenerated current density is obtained using rate equation in quantum well including various physical aspects involved in QWIP physics. The nature of frequency response is investigated under variation of Sn content in well. The 3dB bandwidth which is obtained from this frequency response is also plotted as a function of Sn content in active layer as well as applied bias. A higher bandwidth up to 200 GHz is obtained at a bias of 0.28V for considered Sn content (0.17). The bandwidth increases with Sn content in well due to strain balanced condition but Sn content should be constrained below 20% due to intolerable strain. The content of Sn in active well layer can play a decisive role in the performance of QWIP. Thus the proposed QWIP is a potential candidate to be used in cheap and commercial CMOS based EPICs.

5. References
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