Numerical Examination of Detectivity in Group-IV alloy based Infrared Photodetector

Prakash Pareek¹ and Ravi Ranjan²

¹Department of Electronics and Communication Engineering, Vishnu Institute of Technology (A), Bhimavaram, W.G., A.P., India-534202
²Department of Electrical and Electronics Engineering, Dharbhanga College of Engineering, Bihar, India-846005

prakash.p@vishnu.edu.in

Abstract In this work, a numerical exploration is carried out for detectivity in Tin incorporated group IV alloys based multiple quantum well infrared photodetector. An optimized theoretical model of the device is developed and explained along with appropriate justifications. Responsivity and dark current are used to attain detectivity after applying proper considerations. The calculated detectivity is then examined under deviation of some important parameters. The results depict an increment of detectivity with number of wells. Furthermore, the results also estimate a considerable detectivity in the range of $10^9$ cm Hz$^{1/2}$ W$^{-1}$.

1. Introduction

In the last few years, a lot of work has been devoted for the realization of photonic integrated chip (PIC) [1]-[3]. In PIC, all optoelectronic components like light source, detector, coupler are on a single substrate (preferably Si). This design gives various advantages like low cost, fast processing of data as electronic and optical domain are available on a single platform [4]. In this context, design and fabrication of monolithic photodetector is a key objective. However, the biggest concern is the selection of proper material of photodetector. III-V semiconductors already proved their worth over the last decade as the main constituent of quantum well infrared photodetector [5]. But, these materials are not compatible with silicon as required for monolithic detector.

Therefore, the attention of the researchers diverted towards Group IV material family because of their low cost and CMOS compatibility [6]. Nevertheless, the indirect BG of these materials proved to be a major hurdle in realizing monolithic optoelectronic devices. Fortunately, a unique property of Germanium (Ge) has opened the door for introducing direct band gap nature in it. Actually, there is very less distance between direct ($\Gamma$) and indirect band edge (L) in Ge, which can be overcome to renovate Ge into a “direct band gap” semiconductor [5,6]. Researchers have adopted various approaches like n doping in Ge, inducing tensile strain in Ge to overcome this difference [7]. Incorporation of Tin (Sn) into Ge has emerged as one of the fruitful techniques to transform Ge into direct BG material [8]. In recent times Tin doped Group IV alloys have emerged as the potential material for desired PIC components specially photodetector [9].

Now, modelling of tin doped photodetectors become crucial due to lack of extensive literature as compared to that of their III-V counterpart [10]. Moreover, strain also comes into picture due to substantial difference between lattices of Ge and Sn [8]. This strain can produce many dislocations
during fabrication. In this framework, GeSn based QWIP model and its absorption coefficient are already described in literature by the corresponding author [11, 12]. Same research group also studied single and multiple quantum well GeSn photodetectors and reported other important parameters. Although most influential parameter i.e. detectivity is still unexplored for multiple quantum well infrared photodetector, as per authors knowledge. Therefore, in this paper detectivity is calculated for proposed SiGeSn/GeSn MQWIP. After calculation of detectivity, it is studied under different values of M (number of quantum wells) which is very crucial aspect. Dark current is also studied under variation of number of wells. Organization of the rest of this paper is as follows. Section 2 briefly elaborate proposed MQWIP along with its design aspects. Section 3 summarized the stepwise methodology of calculation for obtaining detectivity. Section 4 and Section 5 depict important result explanation and salient conclusion respectively.

2. MQWIP model and design Considerations

The schematic of MQWIP proposed in this work is provided in Fig.1. It consists of ‘M’ numbers of quantum well. One period of quantum well is shown in the figure. In the quantum well structure, Ge$_{0.83}$Sn$_{0.17}$ quantum well layer of narrow bandgap (BG) is provided in the middle of two Si$_{0.02}$Ge$_{0.8}$Sn$_{0.11}$ barriers of larger BG. The Ge, Sn compositions of well and barriers are carefully selected to provide following conditions. Firstly, type I quantum well structure is made available by sandwiching a narrow BG well between wideband gap barriers [13]. Furthermore, the direct band gap nature of GeSn quantum well layer is obtained for high performance in detection. For the purpose of induction of direct band gap nature, Sn concentration (17%) is selected [11]. It may also relevant to mention here that the detection wavelength of QWIP as per considered composition of well is approximately 3.5 µm.

Other than composition of well, its thickness also plays a key role in the performance. The intended mode of transition in quantum well photodetector is interband transition between state in $\Gamma$ conduction band and valence band. Therefore, the thickness of well is selected as 80 Å to allow interband transition between sole quantized state in each band of well [13]. The other most decisive parameter which is very crucial from design point of view is strain. This structure is most likely to be affected by strain due to large lattice disparity between Germanium and Tin.

Accordingly, some design arrangements are required to avoid strain dislocations at the time of fabrication. The considered thickness of well is selected (80 Å) already above the critical thickness which is most key requirement to avoid strain dislocations by Sn content in well. Moreover, interlayer strain is also expected in this case because of large lattice mismatch between GeSn well and SiGeSn barrier. Therefore strain balanced configuration is suggested by the researchers as an ideal mechanism to rectify the problem of interlayer strain [14]. In strain balanced configuration, quantum well structure with double barrier structure is grown on a relaxed buffer. The composition (both Ge,Sn) is selected such that buffer induced strain observed by well and barrier is contrasting in nature. In the proposed device Ge$_{0.872}$Sn$_{0.128}$ relaxed is selected as buffer, on which quantum well structure is grown. As aforementioned, content of buffer is selected to maintain one of the important conditions for strain balanced structure i.e. opposite strain for well and barrier. The quantum well is compressively strained whereas barrier layer is tensile strained in the considered device structure.

Another condition for maintaining strain balance environment is the required thickness of barrier as per mathematical condition for strain balance. This condition can be represented in the form of equation which is shown as [15]

$$\sum_{i=1}^{n} \frac{S_i t_i e_i}{a_i} S_i = C_{11}^{(i)} + C_{12}^{(i)} - 2 \frac{C_{12}^{(i)2}}{C_{11}^{(i)}}$$

(1)
where \( C_{11}, C_{12} \) are elastic constants, \( t \) is layer thickness, \( \varepsilon \) is dielectric constant, suffix ‘i’ stands for ith layer and it varies from 1 to \( n \), the integers. On using this equation and material parameters of Si, Ge and Sn, the tensile strained barrier thickness is obtained as 35Å. P type \( Si_{0.08}Ge_{0.78}Sn_{0.14} \) and n-\( Si_{0.08}Ge_{0.78}Sn_{0.14} \) layers, act as contact layers as shown in figure. TE mode polarization is considered for the incident light as compressive strained well strongly support this mode [12].

![Period of MQWIP, 'M' periods are considered in this work](image)

Figure 1. Schematic of considered MQWIP (buffer is not shown)

3. Methodology for detectivity calculation

Detectivity is very important performance parameter for MQWIP, from its application point of view as an IR detector. It basically signifies the minimum detectable signal for an input optical signal. General expression of detectivity is given as [5]

\[
D = \frac{1}{2} (R_M) \left[ q \left( j_{\text{darkM.electrons}} + j_{\text{darkM.holes}} \right) \right]^{-1/2}
\]

(2)

where, \( R_M \) is responsivity for ‘M’ number of wells, \( j_{\text{darkM.electrons}} \) and \( j_{\text{darkM.holes}} \) are dark current density for holes and electrons respectively. Therefore, detectivity basically requires calculation of two parameters. These parameters are responsivity and dark current.

Continuity and rate equation are solved to attain responsivity, at DC condition considering carrier transport mechanism from one well to another in MQWIP configuration as already reported [16]. In multiple quantum well structure, mechanism of carrier transport is different from that in single well structure. In MQWIP, generated carriers from a particular quantum well interact with the wells in its path while moving towards contact [16]. Responsivity is calculated considering this aspect of carrier transport in multiple well configurations. In the calculation of responsivity, absorption coefficient is required which is already reported in the literature [11].

Calculation of detectivity also requires computation of current in absence of light. In case of no optical input, optical generation rate is nil. In this work compressive strained well is considered which support HH- \( \Gamma \) conduction band interband transition more strongly. In dark condition, interband transition is more likely to occur by thermal energy. At 300K, thermal generation rate \( (G_{\text{dark}}) \) can be calculated by using intrinsic sheet carrier concentration and inter band relaxation time of carriers. It is given as [12]

\[
G_{\text{dark}} = \frac{n_{i,2D}(T)}{T_{\text{interband.relaxation}}}
\]

(3)
where \( n_{i,2D} \) is carrier concentration and \( T_{\text{interband}, \text{relaxation}} \) is interband relaxation time. The dark current density can be evaluated by appropriately modifying the steady state rate equation of quantum well dark condition as [16]

\[
\frac{\delta n_{\text{QW,dark}}}{\delta t} = \frac{P_c}{q} j_{\text{maxd,electrons}} + G_{\text{dark}} n_{\text{QW,dark}} R_e
\] (4)

where \( n_{\text{QW,dark}} \) is temperature dependent carrier excited into quantum well in absence of light, \( j_{\text{maxd,electrons}} \) is maximum dark current density for electrons considering a single well, \( G_{\text{dark}} \) is carrier generation rate in well under dark condition, \( R_e \) denotes summation of rate of thermionic emission, tunnelling and recombination[16], \( P_c \) is capture probability as we considered theoretical model adopted by Ryzhii [17]. Now considering multiple quantum well configuration, the dark current density for electrons in \( M \) no. of wells i.e., \( j_{\text{darkM,electrons}} \) can be determined by using Ryzhii model and interwell carrier transport mechanism. Similarly, dark current density for holes for \( M \) no. of wells is also calculated.

After obtaining responsivity for \( M \) no. of wells \( (R_M) \), dark current for electrons and holes for ‘\( M \)’ no. of wells \( (j_{\text{darkM,electrons}} \text{ and } j_{\text{darkM,holes}}) \), Detectivity \( D \) is calculated with the help of Eqn. 2.

4. Results and discussion

In calculation of detectivity for MQWIP, responsivity and dark current are evaluated and substituted in Eqn.2. Responsivity considering interwell carrier transport mechanism is calculated and reported by one of the authors [16]. Same methodology is also used here for \( R_M \) which is obtained by solving rate equation along with continuity equation. Dark current for hole and electron component is calculated by the process as described earlier. The summation of electron and hole dark current is plotted as a function of bias for different \( M \), in Fig. 2. The figure depicts dark current decreases with increasing number of wells, which can be justified as follows. As the number of well increases, saturated electric field becomes lower. The main source of dark current is thermionic emission which also depends on electric field across well. Therefore, due to this reduced electric field, the overall rate of thermionic escape of carriers decreases. It causes results in reduction of dark current and beyond \( M=14 \), dark current almost saturates, this is in agreement with the observation of Ryzhii published in 1997 [17].

Detectivity, which indicates the minimum detectable signal, is calculated with the help of Eqn. 2 after calculating the dark current and responsivity as described earlier. Plot of detectivity with bias for different \( M \) is shown in Fig. 3. It can clearly be observed that detectivity decreases with increasing bias mainly due to the more dominant effect of bias on the dark current compared to its effect on responsivity. A significant value of maximum detectivity of \( 2 \times 10^9 \text{cmHz}^{1/2}\text{W}^{-1} \) is obtained for 14 or more number of wells at very low bias. The result also reveals that detectivity increases on increasing number of wells.
Figure 2. Plot of dark current versus bias for different M.

Figure 3. Variation of peak detectivity as a function of bias.
5. Conclusion

Detectivity which is most important performance parameter, particularly for Tin doped Group IV alloy based monolithic midinfrared photodetector, has been studied in this work. Result depicts an enhancement in detectivity which is in the typical range of $10^9 \text{cm Hz}^{1/2} \text{W}^{-1}$, on increasing number of wells. This result further usher the idea of designing reliable low cost monolithic photosensor and also enhances the potential of GeSn based photodetectors to be used in PICs. However, number of wells should be chosen judiciously to maintain the appropriate bandwidth.

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6. References

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