Study of Smart City Compatible Monolithic Quantum Well Photodetector

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Abstract. This work is focused on the exploration of the potential of Group IV alloy based nanostructured photodetector which can perform well in smart city environment. The theoretical model for multiple quantum well detector based on Germanium Tin (GeSn) alloy working in short wave infrared range (SWIR) is proposed after considering various design aspects. In this work, detectivity is estimated for SiGeSn/GeSn based interband multiple quantum well infrared photodetector. Detectivity is calculated by using responsivity and dark current, assuming appropriate conditions. After calculation, it is studied under variation of some important parameters. The result reveals the enhancement of detectivity with number of wells. It also indicates that the low biasing range is quite sufficient to make the proposed device work efficiently. Moreover, peak detectivity in the tune of 10^9 cm $Hz^{1/2}$ W^{-1} is attained.

Keywords: Smart City · GeSn · Detectivity · Group IV · MQWIP · Interband

1 Introduction

The concept of smart city aimed to advance the standard of human lives directly or indirectly. Smart cities provide all required infrastructure facilities and services more effectively than the conventional cities. Recently, with the advent of internet of things (IoT), the doors are opened for the city administrators to make the real implementation of smart city smoothly. Smart city really helps to incorporate advance and state of art technologies in various dimensions of city life like education, healthcare, sanitation, water supply, commutation services, among other. IoT proved to be a boon for providing smart city environment with the feasibility of automation in crucial aspects of citizen life [1]. However, it also manifests a large amount of data required in the tune of Zetta Bytes (ZB) or more. Unfortunately, it is just the beginning, because the demand of data is

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going to increase at an alarming rate. As a result of this, surge in energy requirement will emerge. Hence, data centers are expected to consume a big chunk of the world electric power.

Considering the above two points, requirement of high-speed processing as well as low energy consumption technology is first in the bucket list of any smart city technical administrator. Microelectronics engineers are working superbly to design ultra-low energy consumption and high data processing integrated chips which can consume up to pico-Joule of energy. Having said that, it is not sufficient energy saving which is expected in the smart city environment because of the large number of sensors and actuators required for signal processing. Concurrently, photonics also showed a tremendous surge specially after the invention of Laser. There is no doubt regarding the speed of this technology due to mass less photons which carry the data. Another important benefit of photonics in smart city is the low energy consumption of the photonic integrated circuit which is in the range of femto-Joule.

Due to the aforementioned advantages, photonic integrated circuit research field witnessed a large amount work done by the researchers in recent times [2]. In this integrated circuit, a single platform or substrate accommodate all components like detector, source and many more. As a result, we can design a low cost CMOS compatible monolithic integrated device [3]. Moreover, data is also transmitted as well as received at higher rate due to all optical processing in this monolithic integrated device which seems to be perfect in the smart city eco system. One of the indispensable parts of this device is a competent integrated detector, which is responsible for receiving and sensing the optical signal and convert it into its electrical counterpart.

Within this frame of reference, research on some important aspects of integrated photodetector and its fabrication is very much relevant. But before its fabrication, a detailed theoretical study for its suitable design should be done to validate its feasibility. The conventional material from III-V group family is not suitable due to difficulties in their growth on Silicon platform [4]. Moreover, the material processing and fabrication cost also increase for III-V materials like GaAs, InGaAs, among other. As a result, workers have to look for another option for an appropriate material which can fulfill the above criteria to serve as the material for integrated detector.

Considering the above points, the focus of the researchers shifted towards Silicon based materials like Si, Ge, etc. The biggest bottleneck for the realization of monolithic photodetector is the indirect bandgap nature of Si, Ge. But one property of Ge had given hope to researchers for the realization of all group IV photodetector. In Germanium (Ge), there is very little gap between the indirect bandgap and direct band gap. In other words, Γ and L band edges in Germanium are separated by only few mV [5]. This characteristic had provided the opportunity to make the direct bandgap edge lower than the indirect bandgap edge so that Ge act like a direct bandgap material. There are different types of techniques of doing that like ‘n’ doping in Ge, introducing strain in Ge and incorporation of Sn into Ge [6]. Among these methods, the third one is standout and received very well by the researchers. The findings of the wide-ranging work related to Sn incorporation in Ge are very interesting and have paved the path of the possible role of GeSn/SiGeSn alloy in integrated photodetector [7, 8].

But before the actual realization of SiGeS/GeSn based sensors, one need to assess their validity theoretically. As a result, models need to be proposed which obey basic device physics and also practical fabrication aspects. The theoretical study is having its own limitations due to dearth of reported works in SiGeSn/GeSn photodetector regime [8]. In addition, properties of Sn and Ge make this task more challenging. For instance, lattice constant difference between Ge and Sn is very large. Excessive mismatching cause strain gross imperfection during fabrication if ignored. This makes design of theoretical model for SiGeSn/GeSn detector more challenging.

In order to resolve this issue, a theoretical model for GeSn/SiGeSn Quantum well infrared photodetector (QWIP) was introduced by one of the authors [9, 10]. In this model, the strain factor was compensated by introducing some modifications which are explained later. Different aspects of QWIP performance were investigated in single well and multiple well configuration [9, 10]. Having said that, minimum detectable signal still needs to be studied under different variables for GeSn/SiGeSn QWIP. Detectivity is a most important parameter from a device designer perspective and proper effort should be devoted towards its exploration. Because in case of all group IV based QW based detector, detectivity is hardly reported.

Thus, in this work, photosensitive device compatible to smart city applications is studied along with its crucial parameters. This device is analyzed by introducing a theoretical model of group IV based MQWIP. The remaining sections of this paper will give a brief summary about the studied model, methodology and a detailed discussion on the results obtained.

2 Design of MQWIP

The theoretical model for considered MQWIP is provided in Fig. 1. It possesses multiple quantum well structure. Each quantum well is formed by periodic repetition of single quantum well (SQW) which consists of GeSn active well which is surrounded by SiGeSn barriers on either side. The bandgap of SiGeSn is higher than GeSn active well, which is a type I quantum well configuration [11]. Moreover, the thickness of the well is carefully chosen to allow single state in each of conduction band and valence band. The mole fraction of Sn in GeSn well is selected so that GeSn become direct bandgap in nature [9]. The device operational wavelength as per design is 3.4 μm.

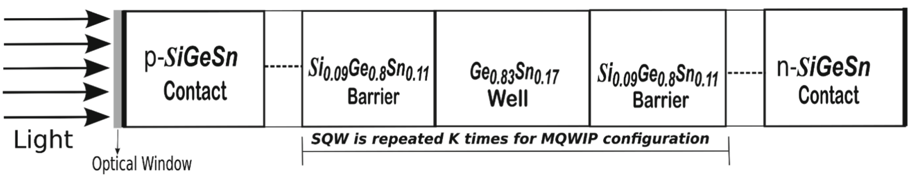

Fig. 1. Considered multiple quantum well infrared photodetector model

In the design of the considered QWIP structure, each quantum well structure consist of one GeSn narrow bandgap well and two SiGeSn wide bandgap barriers. This structure is repeated 'K' times in a periodical manner. Now regarding the content of well, 17% of Sn is considered which is sufficient to induce direct band gap nature in the GeSn layer [10]. The SiGeSn layer acts as a barrier with 9%, 80% and 11% of Si, Ge and Sn content respectively. The width of the barriers is also one of the important aspects in design of this QWIP. This is because of the involvement of alloys like GeSn and SiGeSn which are difficult to grow in normal conditions. The large lattice mismatching between Sn and Ge/Si tempts the researchers to look for other ways to successfully fabricate the GeSn and SiGeSn layers. Dislocation can occur if this problem cannot be handled properly. Hence in order to avoid this issue, the strain compensating technique is used, which is already successfully applied in case of GeSn based quantum well lasers [12, 13]. The dimension of barriers is chosen according to following strain balance environment equation as below [13],

$$\sum_{i=1}^{p} \frac{X_i j_i e_i}{l_i}; X_i = E_{11}^{(i)} + E_{12}^{(i)} - 2\frac{E_{12}^{(i)2}}{E_{11}^{(i)}} \tag{1}$$

where p is the number of layers, the coefficients of elasticity are E_{11}, E_{12}, the width of the layer is represented by j, and e denotes the dielectric constant. In this strain balancing environment, well and barrier experience opposite strain. In our design, well is chosen to be under compressive strain whereas barriers are under tensile strain. By using the above expression (Eq. 1), the width of the barrier is attained as 36 Å. A buffer layer is also considered to make fabrication feasibility and strain compensating conditions favorable. In Fig. 1, P and N contact layers are also shown. The compositions of these layers are chosen to make them lattice matched to buffer. The input electromagnetic signal (light) is considered to be propagate in transverse electric mode owing to the compressive strain in well [11].

3 Performance Evaluation

Sensitivity of the sensor is a very important decisive parameter in its performance. In terminology of photonic detection, it is termed as detectivity. It is almost mandatory to specify detectivity for device engineers as well as manufacturers. Actually, detectivity indicates the minimum signal which can be detect by the sensor without any noise. The detectivity, DMQWIP can be calculated with the help of Eq. (2) [4]:

$$D_{MQWIP} = \frac{1}{2}(R_{espK})\left[q\left(Id_{darkK\_electrons} + Id_{darkK\_holes}\right)\right]^{-1/2} \tag{2}$$

where R_{epsK} indicates responsivity for 'K' quantum well periodic structure (as shown in Fig. 1), the current density in absence of light denoted by $Id_{darkK\_electrons}$ and Id_{darkK_holes} respectively. As it is clear from the above equation, evaluation of D_{MQWIP} requires the values of current in presence of light (in the form of responsivity) and absence of light (dark current).

Current is generated by the movement of charge carriers triggered by the incident light. this current can be calculated in terms of responsivity. In order to obtain this parameter, the charge mechanism of MQWIP should be studied in detail. Further, the use of the continuity equation becomes crucial here. In MQWIP, the charge carriers are moving across multiple interfaces and also there is an interaction between carriers of adjacent well in multiple quantum well structure. The light absorption parameter is also playing a vital role in this analysis.

After responsivity, the sensitivity calculation requires the current which is generated in the absence of light. The calculation of this current is not straightforward, and it requires certain assumptions and considering special conditions which are as follows. Firstly, in the absence of light, no charge carriers are generated, that is why the corresponding parameter should be neglected in the rate equation. Now if light is not present to trigger the charge carrier movement, temperature role become very important. So, instead of optical rate, thermal rate of generation is considered in the calculation of the current in absence of light. As we are considering interband transition in this case, charge carriers relaxation time in interband state also plays a key role in this calculation. The generation rate of carriers, g_d, in dark conditions can be calculated as [11]

$$g_d = \frac{n_{int,2D}(T)}{t_{interband\_ relaxation}} \tag{3}$$

In the above expression $n_{int,2D}$ is the temperature dependent carrier density in intrinsic state and $t_{interband\_relaxation}$ is the relaxation time of carriers in interband state.

Now, current in absence of light both for holes and electrons can be obtained by using the rate equation under DC conditions. Some changes are required to make in the conventional rate equation and it is given as [14],

$$\frac{\delta n_{QW,dark}}{\delta t} = \frac{cap_p}{q} id_{max,e} + g_d - n_{QW,dark} R_{total} \tag{4}$$

In the above expression, the generated carriers in dark conditions are denoted by $n_{QW,dark}$, the peak value of current density in absence of light indicated by $id_{max,e}$ for a solo well. The combination of carrier rates by different mechanism like optical generation, thermionic and tunneling are shown by R_{total}. Moreover, in this calculation, the model for MQWIP coined by Ryzhii is adopted, hence the probability of capture of carriers is used here, which is denoted by cap_p. This calculation is implemented for multiple quantum well structure and considering the process reported by Ryzhii [15]. Then after getting the values of responsivity and dark current density, sensitivity can be calculated for proposed MQWIP as shown in Eq. 2.

Another important parameter for study is the distribution of the electric field, which is most crucial when the device is to be designed for smart city environment. The calculation of the electric field and its spatial distribution in a quantum well is evaluated with the help of the Ryzhii model [16]. The emitter layer and tunneling layer are considered in this model. The current density of emitter layer, j_e, is related to the electric field of the tunneling layer, E_t, as shown in Eq. 5.

$$\frac{j_m}{j_e} = \exp\left(\frac{E_t}{E + ME_D\left(1 - \frac{n_{QW}}{n_{i,2D}}\right)}\right) \tag{5}$$

where j_m is the maximum emitter current density, E is the electric field over the active sensing region, n_{QW} is the electron concentration in quantum well, and E_D is the field due to intrinsic sheet concentration $n_{i,2D}$.

On further simplifying Eq. 5,

$$\left(1 - \frac{n_{QW}}{n_{i,2D}}\right) = \left(\frac{E_t}{\ln(j_k)} - E\right)\frac{1}{ME_D} \tag{6}$$

where $j_k = (j_m/j_e)$, and j_e can also be expressed in terms of tunneling electric field in another way as [16],

$$j_e = j_m \exp\left(\frac{-E_t}{E_e}\right); E_e = \frac{E_t}{\ln(j_k)} \tag{7}$$

Now, position dependent potential can be written by using the Poisson equation for quantum well and it is written as [16],

$$p_d(x) = V\frac{x}{W} + \frac{2\pi q n_{i,2D}}{\varepsilon w_p}.x(W - x)\left(1 - \frac{n_{QW}}{n_{i,2D}}\right) \tag{8}$$

where V is the applied bias, p_d is the position dependent potential, w_p is the quantum well period ($w_d + w_B$), ε is the dielectric constant, x is the position coordinate, and W is the total width of well. Then, the electric field for the first quantum well period is written as considering Fig. 1 and Ryzhii model [16],

$$E_1 = \left.\frac{d(p_d)}{dx}\right|_{x=w_p} = \frac{V}{W} + \frac{2\pi q n_{i,2D}}{\varepsilon w_p}.(W - 2w_p)\left(1 - \frac{n_{QW}}{n_{i,2D}}\right) \tag{9}$$

MQWIP is the main focused device structure. So, for the M^{th} quantum well, expression of the electric field is given by:

$$E_M = \left.\frac{d(p_d)}{dx}\right|_{x=Mw_p} = E + \frac{2\pi q n_{i,2D}}{\varepsilon w_p}(W - 2Mw_p)\left(1 - \frac{n_{QW}}{n_{i,2D}}\right) \tag{10}$$

From Eqs. 6, 7 and 10, the final expression for the electric field over MQWIP is written as:

$$E_M = \frac{E_t}{\ln(j_k)} + \frac{2\pi q n_{i,2D}}{\varepsilon w_p}\left(\frac{E_t}{\ln(j_k)} - E\right)(W - 2Mw_p)\frac{1}{ME_D} \tag{11}$$

The above expression will be used to determine the distribution of the electric field across different wells of MQWIP.

4 Results and Discussions

As explained in the previous section, detectivity is evaluated by calculating the photo current and the current in absence of light. The value of the photo current, taking into consideration of carrier mechanism, had already been published by the first author for single quantum well detector [15]. In this work, a similar procedure was adopted to calculate the photo current for multiple quantum well photodetector. The current in absence of light is also obtained by adopting the process as explained in the previous section. Consider the number of well in the proposed model of MQWIP as 'M', then total current in absence of light can be shown under variation of 'M'. Therefore, in Fig. 2, Id_{dark} (summation of holes and electron current without light) is shown for different numbers of quantum well. It is clear from this figure that the current in absence of light reduces with enhancement in 'M'.

The carrier movement in absence of light is due to thermal effect. Thus, thermionic emission is the primary source of carrier generation, when there is no light. The trend in Fig. 2 is due to the following reason. When the number of well enhances, the effective field reduces. As the electric field drive the thermionic emission, this emission rate decreases on increasing the number of well. Reduction of the thermionic emission rate also cause decreasing of the current in absence of light. It can be also observed from the figure that after a particular value of QW number 'M', the dark current saturates, which was also reported by Ryzhii [16].

Equation 2 is used to calculate sensitivity or detectivity. It actually indicates the minimum amount of signal which can be detect by the device without any ambiguity. DMQWIP is calculated as explained in the previous section and the corresponding peak values are shown w.r.t. bias (V), for various 'M' in Fig. 3. It is revealed from the figure that as V increase, detectivity decreases, because the impact of V is more on the dark current rather than on responsivity. At minimum values of V, a maximum value of DMQWIP is obtained, i.e. 2.3 x 10^9cmHz$^{1/2}$W^{-1} for M = 14. Moreover, Fig. 3 also discloses that detectivity enhances with M. Another important point depicted from this figure is that low biasing is sufficient for good sensitivity for the proposed detector. In smart city environment, low range of biasing will be ideal as energy consumption would be low, which is desirable.

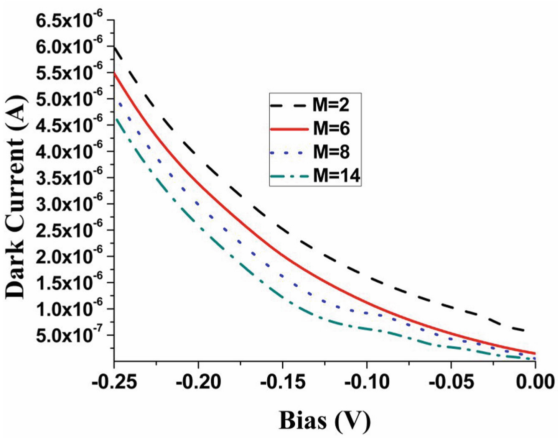

Fig. 2. Current without light input for various M

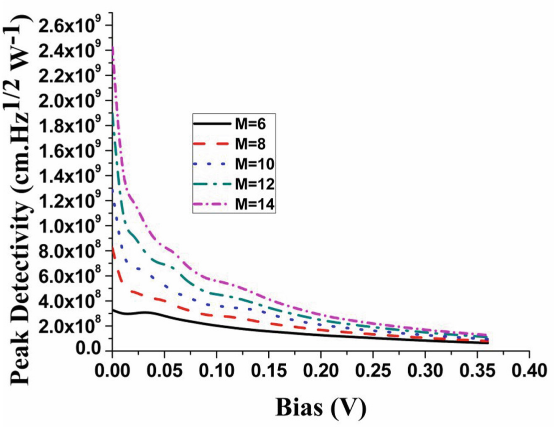

Fig. 3. D_{MQWIP} for various M

Now, the spatial distribution of the electric field for M = 8 is calculated and shown in Fig. 4 at applied bias 0.1 V. It can be observed from the figure that the minimum field in device, for M = 8, is in the saturation region. So, using the saturation velocity for our analysis seems to be appropriate. It can also be inferred from the figure that the first quantum well field is very high due to direct injection of emitter tunneling current into this well. Low biasing is good enough to operate this photosensitive device which can generate good amount of electric field.

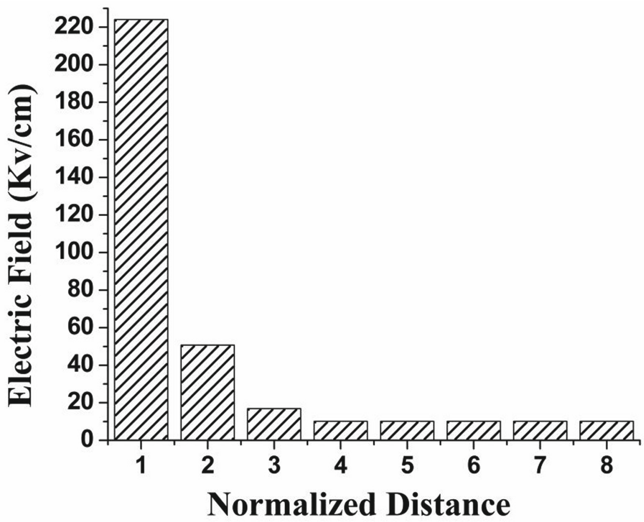

Fig. 4. Electric field distribution in MQWIP for M = 8

5 Conclusion

The present work focuses on the investigation of the potential of group IV based MQWIP for its compatibilities with smart city technologies by proposing a theoretical model. Sensitivity is calculated by considering various charge carrier mechanisms observed by multiple quantum well structure and its interfaces. The value of detectivity (~10^9 cm $Hz^{1/2}W^{-1}$) obtained in this work is in the range of that of III-V based photodetectors, which is a very encouraging sign. It further motivates the researchers to explore more this device to make it suitable for one of the components of photonic integrated circuit monolithic chip. The outcome of this work depicts that the photonics is at the pole position among other emerging technologies to become an integral part of smart cities network. The proposed detector has immense potential to provide a solution of low energy consumption in smart city environments.

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