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Numerical analysis of SiGeSn/GeSn interband quantum well infrared photodetector

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ABSTRACT

In this paper, detailed theoretical investigation on the frequency response and responsivity of a strain balanced SiGeSn/GeSn quantum well infrared photodetector (QWIP) is made. Rate equation and continuity equation in the well are solved simultaneously to obtain photo generated current. Quantum mechanical carrier transport like carrier capture in QW, escape of carrier from the well due to thermionic emission and tunneling are considered in this calculation. Impact of Sn composition in the GeSn well on the frequency response, bandwidth and responsivity are studied. Results show that Sn concentration in the GeSn active layer and applied bias have important role on the performance of the device. Significant bandwidth is obtained at low reverse bias voltage, e.g., 200 GHz is obtained at 0.28 V bias for a single $Ge_{0.83}Sn_{0.17}$ layer. Whereas, the maximum responsivity is of 8.6 mA/W at 0.5 V bias for the same structure. However, this can be enhanced by using MQW structure.

1. Introduction

Over the last decade, III–V based quantum well infrared photodetectors (QWIPs) transform themselves into backbone of high speed communication and sophisticated sensor systems. Also, they find their presence 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 [1–3]. However, their high cost and incompatibility to silicon restrict them to be used in electronic photonic integrated circuits (EPICs). EPICs offer cheap and commercially viable technology which is crucial to meet the demand of high speed communication and refined sensor systems [4,5]. Recently, a lot of research is conducted towards realizing group IV (Gr-IV) based active photosensitive devices which are cheap, as well as offer heterogeneous integration with CMOS technology to realize EPICs [6,7]. The advent of a direct band gap GeSn alloy is said to be a milestone in this quest of low cost monolithic optoelectronic devices specially photodetectors [8–10]. Add to this fact, recent progress in growth of high quality GeSn photodetectors by chemical vapour deposition (CVD), molecular beam epitaxy (MBE), and magnetron sputtering epitaxy is also motivating researchers to work towards realizing more improved versions of these detectors [11–13]. However, most of the reported works are either concentrated on telecommunication wavelength or employed bulk scale structure. So, it does not give a clear idea to understand the physics of QWIP utilizing longer wavelength range (say 3–5 μm), which is very crucial for certain applications. Therefore, modelling of GeSn QWIP is very crucial before its fabrication to study and re-engineering its properties. Particularly issues related to strain which come into play due to a large lattice mismatch between Ge and Sn. However, strain balanced structure is used to shield the active GeSn well layer from excessive strain during fabrication [14]. In a strain balanced system, strain in well region can be minimized by adjustment of a lattice constant of barrier and buffer layers. Moreover, due to its simple structure, a single quantum well structure is most appropriate for a better comprehension of various physical aspects.

In this context, authors had already proposed a model for an absorption coefficient considering interband transition in a strain balanced GeSn based single QWIP and a significant absorption in an active GeSn layer at a peak wavelength of 3.34 μm is obtained [15]. However, absorption coefficient is not the sole performance parameter for a QWIP, but a large bandwidth and high responsivity are necessary ingredients of a competent detector. Therefore, a detailed analysis for frequency response and responsivity in GeSn based QWIP is necessary. This analysis requires understanding the physical phenomena like capture of carriers into quantum well,

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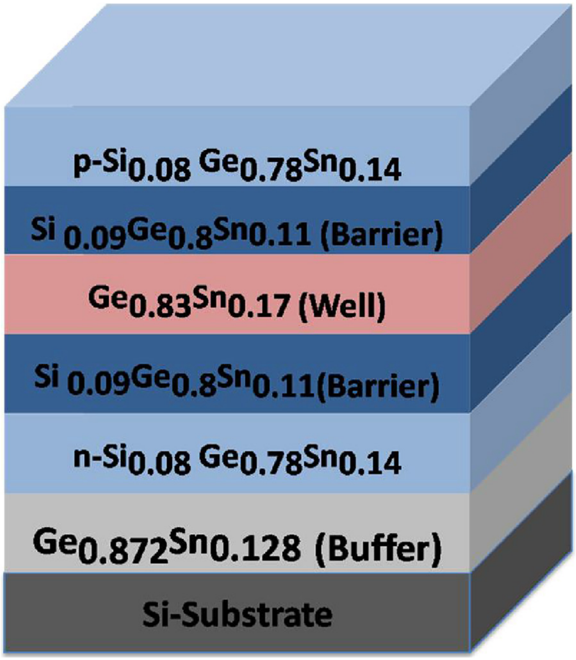

Fig. 1. Schematic structure of strain balanced GeSn QWIP (not to scale).

escape of carriers from quantum well, and effect of barrier height on these phenomenon. Although these aspects have been studied in depth by numerous theoretical and experimental investigations in case of conventional III–V based QWIPs [16–19]. But, physics considering all the above mentioned aspects is not clearly understood completely in case of Gr-IV based interband QWIPs. Even though few studies to demonstrate GeSn based p-i-n detectors using quantum well structure have been reported in Refs. [20,21], theoretical modelling for the device, considering the quantum mechanical transport, has not been reported yet. Also, the effect of Sn content on the performance of the device has not been explored in detail to the best of author's knowledge.

In the present paper, we have studied the frequency response and responsivity of a strain balanced $Si_{0.09}Ge_{0.8}$ $Sn_{0.11}/Ge_{0.83}Sn_{0.17}$ QWIP by varying different material parameters, Sn-composition in particular. Interband transition is considered in this analysis which yields a peak wavelength of operation in the range of 2.9-3.86 μm (effective bandgap ~0.3–0.42 eV). It may be relevant to mention here that the present analysis is done at room temperature, i.e., 300 K. However, the performance parameters of the proposed QWIP will be more superior at 77 K which is the operating temperature of conventional QWIPs. At the same time it is crucial and demanding to optimize the performance of a group IV QWIP at 300 K. As most of the significant applications of integrable Group IV based QWIPs require room temperature operation [22].

The paper is organized as follows. In Sect. 2 a brief model description is explained along with its design considerations. Sects. 3 & 4 give the detailed derivation of frequency dependent photogenerated current density and responsivity, respectively. Sect. 5 gives results and their discussions. Finally, summary of the work with conclusion is provided in Sect. 6.

2. Model description

A single quantum well with double barrier is considered here due to its simple structure and hence for better understanding of the aspects responsible for QWIP operation. The schematic structure of the device is shown in Fig. 1. Structure 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 barriers are optimized to facilitate a low direct bandgap well layer, as well as a wide bandgap barrier for quantum carrier confinement [15]. The thickness of well is chosen as 76 Å to enable single bound state. This thickness of well is also above the critical thickness to prevent dislocations.

Both quantum well and barrier are considered to be undoped in this case. This double barrier quantum well is considered to be grown on a relaxed $Ge_{0.872}$ $Sn_{0.128}$ buffer to form a strain balanced structure. The Ge and Sn content of the buffer layer is chosen such that the strain induced by buffer on well and barriers are exactly the same but opposite in nature. Thus, quantum well is compressively strained and barrier layers are tensile strained with respect to a buffer layer in order to ensure the strain balance condition. According to strain balance condition [23], the barrier thickness is computed as 35 Å. But this small dimension may lead to a very high electric field across depletion region which may cause breakdown of the device. Thus, this fact is considered while choosing the dimension of barrier thickness. As a result, barrier thickness is increased by 35% so that the structure still remains under partial strain balance conditions. Hence, the thickness of the barrier is taken as 50 Å. Now, this partial strain balanced structure is further sandwiched between two heavily doped contact layers (p-$Si_{0.08}$ $Ge_{0.78}$ $Sn_{0.14}$ and n-$Si_{0.08}$ $Ge_{0.78}$ $Sn_{0.14}$) to form a p-i-n structure. TE polarized light is assumed to be incident from top as shown in Fig. 1. Moreover, the fabrication of the proposed model is quite feasible owing to the recent progress in fabrication of GeSn based devices. For instance, Ghetmiri et. al. reported the fabrication of similar type of strain balanced, SiGeSn/GeSn/SiGeSn quantum well structure in 2017 [24]. The same group also reported the fabrication of a 8.2 nm thick GeSn quantum well layer in 2016 [25].

In this work, intersubband transition is not considered due to the following reasons. Firstly, the thickness of quantum well is chosen such that single bound energy state [in conduction band, heavy hole (HH) band and light hole (LH) band each] exists in the well. Secondly, the intersubband transition is difficult to take place due to consideration of normal incidence of light in this model. As intersubband absorption in quantum well occurs when polarization of the incident radiation has a component along the growth direction. Here, the quantum well is assumed to be grown vertically (z-direction). Hence, the incident light needs to have a polarization component along z-direction to satisfy the polarization selection rule. Thus, the incident radiation, normal to the quantum well plane, has zero absorption probability. Whereas, for interband transitions, it states that only transitions involving same quantum number states in the valence and conduction bands are allowed which is considered in this work, i.e., ($E_{HH1} \rightarrow E_{c1}$) transition. Now, there may be a little chance of E_{LH1}-E_{HH1} intersubband transition. But, this can easily be neglected due to a very low band offset of LH band as reported by the authors previously [15]. It causes confinement of light holes weaker which become worse on increasing electric field further. Hence, only interband transition is considered this work.

3. Frequency response

In this section, a detailed carrier transport mechanism is considered while obtaining expression of frequency dependent current density in QWIP. The calculation is carried out for a generalized distribution of carriers generated by a light impulse, in the active quantum well layer. Let the light of an appropriate wavelength be incident on p-side of the device as shown in Fig. 2, where w_d is the thickness of the active QW layer. As shown in figure, position coordinate, x is pointed from n to p. For the sake of simplifing the