3rd URSI AT-AP-RASC, Gran Canaria, 29 May – 3 June 2022

Si-based High Responsivity Germanium-Tin MQW *p-i-n* Photodetectors for Broadband Applications

Harshvardhan Kumar[1] and Ankit Kumar Pandey[2]

[1]Electronics and Communication Engineering, The LNM Insititute of Information Technology, Jaipur, Rajasthan, INDIA, harshvardhan.kumar@lnmiit.ac.in

[2]Electronics and Communication Engineering, Bennett University, Greater Noida, Uttar Pradesh, INDIA

Abstract

We report a novel vertical p-i-n photodiode with a $Ge_{0.87}Sn_{0.13}/Ge_{0.92}Sn_{0.08}$ multiple-quantum-well (MQW) with an additional $i-$ GeSn(Sn = 9%) layer on a strain-free Ge virtual substrate on Si-substrate. $i-$ GeSn is considered to elongate the photon-absorption path (PAP). Thereby, a high spectral responsivity (SR) of 0.27A/W at -3V was achieved at 3050 nm. With the incorporation of $Ge_{0.87}Sn_{0.13}$ as the well and $Ge_{0.92}Sn_{0.08}$ as barrier leads the cut-off wavelength up to $3370\ n$m.

Keywords: GeSn, MQW, p-i-n, photodiodes, Si photonics, high responsivity.

1. Introduction

Group-IV alloys have enormous potentials for designing the future electronic and photonic devices owing to their extraordinary electronic and optical properties. In addition, they are also compatible with the current complementary metal-oxide-semiconductors (CMOS) technology. In particular, narrow bandgap semiconductors can enable photodetection from ultraviolet to mid-infrared (MIR) region[1]. Light detection in the MIR region of particular scientific interest and technological importance. MIR detection has a wide range of applications in chemical sensing, air quality and health monitoring, heat scavenging, security surveillance, industrial process monitoring, and thermal imaging [2], [3]. Till now, II-VI (e.g.HgCdTe) and III-V (e.g. extended InGaAs)-based photodiodes have been reported for these applications [4]–[6]. Despite their excellent performance and matured fabrication technology, the large lattice mismatch and advanced fabrication process requirements pose limits on the development of their applications. Therefore, investigating novel material with a high absorption coefficient in 2-5 μm bands, high carrier mobility, and CMOS compatibility is desired for MIR photonics.

Very recently, a novel group-IV alloy: GeSn shows a great potential candidate for MIR photonics. During the last five years, a few research works on GeSn-based photodetectors (PDs) have been studied for MIR applications [7]–[12]. However, they have inherently low responsivity due to the poor quantum efficiency and low-absorption path.

In this work, we report a novel high-responsivity MIR GeSn-based multi-quantum-wells (MQWs) PDs on Si substrate. We have considered an additional i-GeSn layer to extend the photo-absorption path (PAP). The proposed device exhibited a wide spectral range from short-wave infrared (SWIR) to MIR wavelengths. Under a milliwatt illumination, a peak responsivity of 1.29 A/W, 1.35 A/W, and 0.27 A/W are achieved at 1810 nm, 2230 nm, and 3050 nm, respectively for N = 2 (number of quantum well periods). The remarkable photoresponse at MIR wavelength enables novel photonic devices for detection applications such as atmospheric gas sensing.

2. Device Design and Modeling

The 2-D schematic structure of $Ge_{0.87}Sn_{0.13}/Ge_{0.91}Sn_{0.09}$ MQW p-i-n PDs is shown in Fig. 1a. The structural details such as layer thickness, material, type of doping, and doping concentrations are given in Table I. The intrinsic (active) layer consists of 2 periods of 10 nm thick $Ge_{0.87}Sn_{0.13}$ as the well and 15 nm thick $Ge_{0.91}Sn_{0.09}$ as the barrier and an additional $i-Ge_{0.91}Sn_{0.09}$ layer of thickness 350 mm to elongate the optical path. The thickness of the $Ge_{0.87}Sn_{0.13}/Ge_{0.92}Sn_{0.08}$ MQW and $i-Ge_{0.91}Sn_{0.09}$ were kept below the effective critical thickness of the epitaxial pseudomorphic GeSn to ensure that the entire active layer is fully strained to the strain-relaxed Ge buffer layer [13]. Fig. 1b shows the simulated optical absorption coefficient (α) at different operating wavelengths (λ) for N=2. The simulated results show that α is high for the active layer $(\sim 7\times 10^{4}\ cm^{-1})$. At $\lambda = 2030\ nm$, $Ge_{0.87}Sn_{0.13}/Ge_{0.92}Sn_{0.08}$ QWs exhibit a higher value of α as compared to the other layers. However, with an increased λ (3050 nm), α is $\sim 6.5\times 10^{4}\ cm^{-1}$ for QWs and zero for other layers.

Table I: Structural details of the proposed photodetectors at 300 K

Layer	Material	Thickness t (nm)	Doping concentrations (cm^{-3})
p^+ −contact	Ge	100	10^{20}
p −layer	Ge	100	10^{18}
Barrier	$Ge_{0.92}Sn_{0.08}$	15	*Intrinsic*
Well	$Ge_{0.87}Sn_{0.13}$	10	*Intrinsic*
Additional absorber layer	$Ge_{0.91}Sn_{0.09}$	350	*Intrinsic*
n −buffer layer	Ge	400	10^{18}
p^+ −substrate	Si	2500	10^{20}

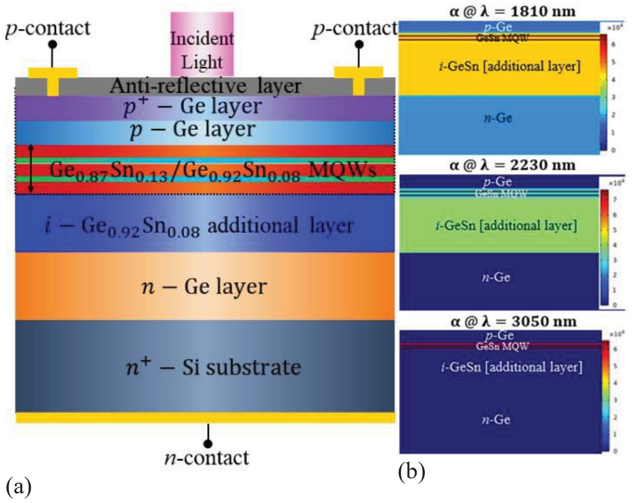

Fig. 1: (a) 2-D schematic structure of $Ge_{0.87}Sn_{0.13}/Ge_{0.92}Sn_{0.08}$ MQW *p-i-n* photodetectors on Si substrate. (b) Simulated absorption coefficient distribution at different wavelength in the p-i-n layers of our designed GeSn photodetectors for two periods of quantum wells.

3. Results and Discussion

Fig. 2a shows the distribution of the squared normalized optical field of our designed normal-incidence GeSn MQW *p-i-n* PDs on the Si substrate for different operating wavelengths. The confirms that the maximum incident light is mainly confined in the active region. A strong standing-wave pattern is developed at $\lambda = 3050\ nm$ due to the resonance effect. As a result, light intensity is enhanced in the GeSn active layer, and thus the responsivity of the device increases. Fig. 2b shows the spectral responsivities of the GeSn MQW p-i-n PDs realized in this work. The spectral responsivity can be calculated by using $R = I_{ph}/P_{in}$, where, I_{ph} and P_{in} are the photogenerated current and incident optical power, respectively. The result shows that for bulk structure (N =0), the photodetection range was limited to $2.5\ \mu m$. However, with the insertion of $Ge_{0.87}Sn_{0.13}/Ge_{0.92}Sn_{0.08}$ QWs in the active layer, the photodetection range extends to the $3.37\ \mu m$ due to the Sn alloying. Furthermore, the carrier confinement in the active layer increases with the number of QWs periods, and thus the responsivity. The peak spectral responsivities of 1.29 A/W, 1.35 A/W, and 0.27 A/W were achieved at $\lambda = 1810\ nm, 2230\ nm,$ and $3050\ nm$, respectively for N = 2. The absorption coefficient for GeSn active layer increases first from $\lambda = 1810$ to $2230\ nm$ and then it decreases from $\lambda = 2230$ to 3050 nm is the major reason for the increase and decrease of spectral responsivity. Compared with the recently published work, the enhancement in the spectral responsivity is as high as 7 times at $\lambda = 1877\ nm$ and 10 times at $\lambda = 2004\ nm$ [7] because of the elongated optical path in the vertical direction, showing the remarkable benefit of using an additional $i - Ge_{0.91}Sn_{0.09}$ layer. To our best knowledge, the first time, the spectral responsivity at $\lambda = 3050\ nm$ has been reported in this work.

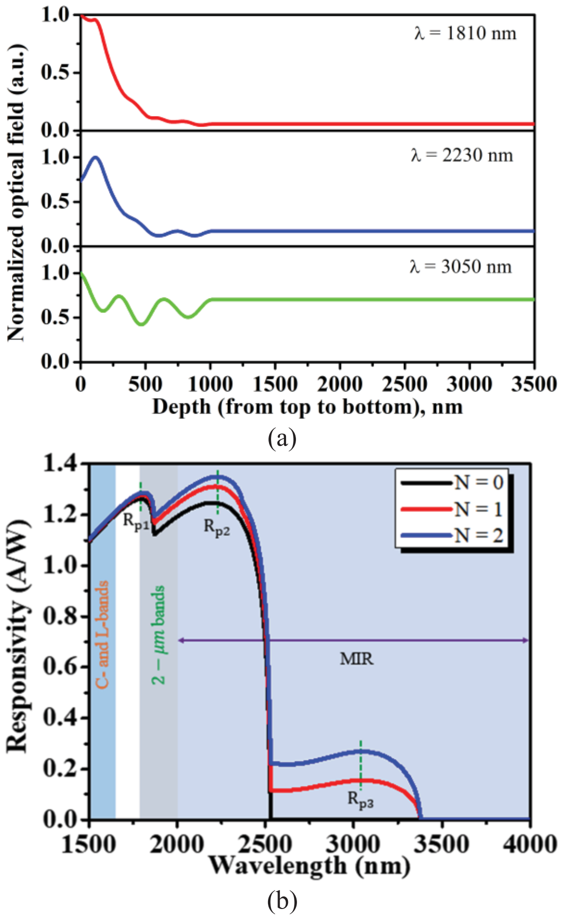

Fig. 2 (a) Simulated squared normalized optical field distribution at different wavelength of our proposed vertical GeSn MQW p-i-n photodetector. (b) Spectral responsivities as a function of operating wavelength for the designed GeSn MQW photodetector.

4. Conclusion

In conclusion, a $Ge_{0.87}Sn_{0.13}/Ge_{0.92}Sn_{0.08}$ MQW photodetector operating at the MIR wavelength was demonstrated. Benefiting from the quantum confinement and elongated optical path in the vertical direction, the peak spectral responsivities of 1.29 A/W, 1.35 A/W, and 0.27 A/W were achieved at 1810 nm, 2230 nm, 3050 nm, respectively. The spectral responsivity was improved ~7 times at 1877 nm and ~10 times at 2004 nm. This result paves the path in realizing a new type of GeSn *p-i-n* photodiode for MIR applications.

References

[1] V. Ryzhii, M. Ryzhii, V. Mitin, M. S. Shur, and T. Otsuji, "Far-infrared photodetectors based on graphene / black-AsP heterostructures," *Opt. Express*, vol. 28, no. 2, pp. 2480–2498, 2020, doi: https://doi.org/10.1364/OE.376299.

[2] R. Soref, "The past, present, and future of silicon photonics," *IEEE J. Sel. Top. Quantum Electron.*, vol. 12, no. 6, 2006, doi: 10.1109/JSTQE.2006.883151.

[3] R. Soref, "Mid-infrared photonics," in *Optical Fiber Communication Conference, OFC 2015*, 2015, no. 1, pp. 3–5, doi: 10.1364/ofc.2015.w4a.4.

[4] M. Mauk, Z. Shellenbarger, J. Cox, P. Sims, J. Lesko, and A. M. Barnett, "Development and characterization of GaInAsSb and InAsSbP mid-infrared photodetectors," in *Proceedings of the International Conference on Microelectronics, ICM*, 1999, vol. 2000-Janua, no. 1 00, pp. 31–34, doi: 10.1109/ICM.2000.884798.

[5] H. Inada *et al.*, "Mid-infrared photodetectors with InAs/GaSb type-II quantum wells grown on InP substrate," in *Conference Proceedings - International Conference on Indium Phosphide and Related Materials*, 2013, vol. 19, pp. 19–20, doi: 10.1109/ICIPRM.2013.6562598.

[6] P. Chakrabarti, R. K. Lal, M. Jain, and S. Gupta, "Theoretical analysis of room temperature InAs0.89Sb 0.11 mid-infrared (MIR) photodetector for CO detection," in *2002 23rd International Conference on Microelectronics, MIEL 2002 - Proceedings*, 2002, vol. 1, no. Miel, pp. 331–334, doi: 10.1109/MIEL.2002.1003204.

[7] H. Wang, J. Zhang, G. Zhang, Y. Chen, Y.-C. Huang, and X. Gong, "High-speed and high-responsivity p-i-n waveguide photodetector at a 2 μm wavelength with a Ge 092 Sn 008 /Ge multiple-quantum-well active layer," *Opt. Lett.*, vol. 46, no. 9, pp. 2099–2102, 2021, doi: 10.1364/ol.419302.

[8] C.-H. Tsai, K.-C. Lin, C.-Y. Cheng, K.-C. Lee, H. H. Cheng, and G.-E. Chang, "GeSn lateral p-i-n waveguide photodetectors for mid-infrared integrated photonics," *Opt. Lett.*, vol. 46, no. 4, pp. 864–867, 2021, doi: https://doi.org/10.1364/OL.414580.

[9] H. Kumar and R. Basu, "Study of the effect of temperature on the detectivity and sensitivity of GeSn-based heterojunction phototransistor for mid-wave infrared applications," *Appl. Phys. B Lasers Opt.*, vol. 127, no. 2, pp. 1–5, 2021, doi: 10.1007/s00340-020-07569-3.

[10] H. Kumar and R. Basu, "Effect of Defects on the Performance of Si-Based GeSn/Ge Mid-Infrared Phototransistors," *IEEE Sens. J.*, vol. 21, no. 5, pp. 5975–5982, 2021, doi: 10.1109/JSEN.2020.3036890.

[11] H. Kumar and R. Basu, "Design and Analysis of Ge/Ge1−xSnx/Ge Heterojunction Phototransistor for MIR Wavelength Biological Applications," *IEEE Sens. J.*, vol. 20, no. 7, pp. 3504–3511, 2019, doi: 10.1109/JSEN.2019.2960006.

[12] H. Kumar and R. Basu, "Effect of Active Layer Scaling on the Performance of Ge 1– x Sn x Phototransistors," *IEEE Trans. Electron Devices*, vol. 66, no. 9, pp. 3867–3873, 2019, doi: 10.1109/TED.2019.2925892.

[13] S. Assali, J. Nicolas, and O. Moutanabbir, "Enhanced Sn incorporation in GeSn epitaxial semiconductors via strain relaxation," *J. Appl. Phys.*, vol. 125, no. 2, pp. 025304(1–12), 2019, doi: 10.1063/1.5050273.