Comprehensive Study and Noise Analysis of GeSn-based p-n-p Heterojunction Phototransistors for Efficient Detection

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***Abstract*— This work presents analytical study of gain, noise behaviour, absorption coefficient and optical responsivity of $Ge_{1-x}Sn_x$-based p-n-p Heterojunction Photo-Transistor. Estimated results ensure that HPTs can be used as an alternative of existing III-V based photodetectors.**

***Keywords*—GeSn-alloy; HPTs; voltage gain; SNR, absorption coefficient, responsivity.**

I. INTRODUCTION

Germanium (Ge) and Silicon (Si) are the dominant semiconductor materials for photonic devices. However, the indirect bandgap nature of these materials make them non-suitable from being utilized as an efficient light-emitting component and detector. Therefore, the interest in the GeSn material has significantly increased over the last few decades. Theoretically, the direct bandgap transition in the heterojunction phototransistors (HPTs) grown on Si can be achieved [1], [2] by tensile strained GeSn alloys or growing lattice matched. $Ge_{1-x}Sn_x$ alloy shows almost 10 times absorption in C-band and 20 times absorption in the L-band than pure Ge [3]. HPTs possess high internal gain, high signal-to-noise ratio (SNR) [4] and low voltage operation over p-i-n photodetectors and avalanche photodiodes (APDs). Various p-i-n photodetectors and avalanche photodiodes (APDs) based on GeSn have been reported [5], [6]. Various heterojunction phototransistors (HPTs) based on GeSn for fibre-optic telecommunication and mid-infrared region has been theoretically reported recently [7], [8]. To address the problem of limited donor solubility in n-p-n GeSn HPTs, p-n-p GeSn HPTs can be more promising candidate to achieve high current gain, high SNR and high quantum efficiency because of the occurrence of the heavily p-type doping $>10^{20}/cm^{-3}$ in the Ge. AlGaAsSb–InGaAsSb based p-n-p HPTs was reported by Shao et al. [9], are likely to provide higher emitter injection ratio than n-p-n HPTs, which leads to higher quantum efficiency. Therefore, it may be very interesting to study p-n-p HPTs for fibre-optic telecommunication networks and mid-infrared region applications.

In this research work, we studied theoretically the performance of 3-terminals p-n-p HPTs with common-emitter configuration. We calculate the voltage gain, SNR, absorption coefficient and spectral response. We then examine the effect of Sn composition in the base layer and structural parameters on the performance to optimize the proposed HPTs to achieve high SNR and optical responsivity.

This paper is organized as follows: Section II describes the device structure and theory, Section III describes the results and discussion and finally section IV describes the conclusion of the proposed research work.

II. DEVICE STRUCTURE AND THEORY

Fig. 1 shows a five-layered structure of the proposed p-n-p HPTs grown on Si (001) substrate, in which light is incident normally on the top of the base of power 1 μW. The base material chosen for the proposed HPTs is $Ge_{1-x}Sn_x$, due to its smaller band gap yielding, a wider absorption in the telecommunication bands and mid-infrared region than pure Ge. SiO_2 antireflective layer is also incorporated in the structure to minimize the reflection. Fig. 2 shows the band diagram of our proposed HPT.

HPTs possess mainly four major noise components, flicker noise, thermal noise, shot noise at base-emitter (B-E), and shot noise at base-collector (B-C). For the noise analysis of proposed p-n-p HPTs, we will consider only thermal noise, and shot noise at B-E and B-C junction. For HPTs noise analysis, flicker noise (1/f noise) is neglected since it occurs only below 1 MHz.

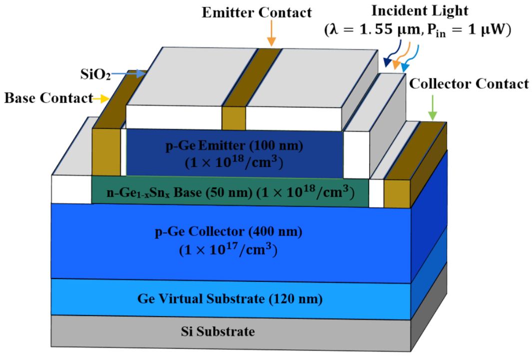

Fig. 1. Layered Structured of GeSn-based p-n-p HPTs

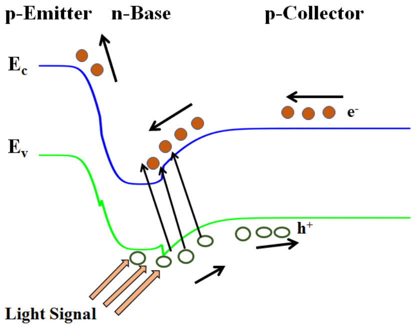

Fig. 2. Band diagram of our proposed HPT

III. RESULTS AND DISCUSSIONS

Numerical calculations for the proposed p-n-p HPTs are carried out at 300 K. Fig. 3 shows the voltage variation with operating frequency of HPTs and fig. 4 shows the variation of SNR with operating frequency for pure Ge and Sn composition of 3%. It is evident that both the voltage gain and

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SNR decrease with increase in the operating frequency. Voltage gain starts decreasing beyond 1 GHz because of the negative feedback and presence of the various parasitic capacitance. SNR decreases beyond 1 GHz steeply because of the shot noise increases precipitately at the B-C junction. It is also observed that SNR increases with increase in the Sn composition. This is because of the high voltage gain occurs for Sn composition of 3 %.

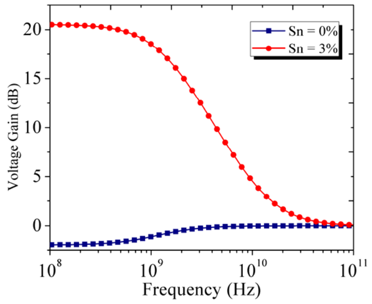

Fig. 3 Variation of voltage gain with operating frequency.

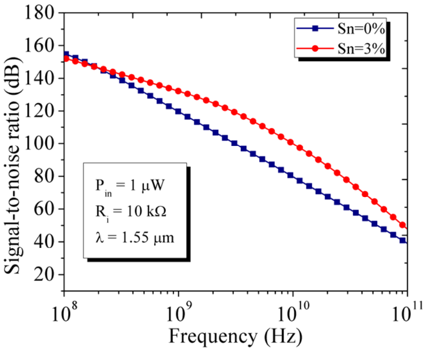

Fig. 4 Variation of SNR with operating frequency.

Fig. 5 shows the estimated absorption coefficient for GeSn-based p-n-p HPT for the pure Ge and Sn composition of 3%. As the Sn contents in the base layer increases, bandgap becomes narrower and absorption in the base layer increases. As the bandgap decreases with increase in the Sn composition in the active base layer, cut-off wavelength extends to higher values.

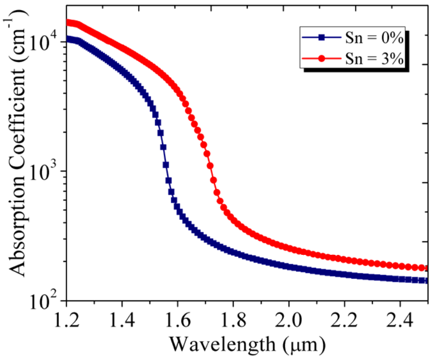

Fig. 5. Calculated absorption spectra variation with wavelength

Fig. 6 shows the calculated spectral responsivity for the proposed p-n-p HPTs for pure Ge and Sn composition of 3%. Higher absorption at 1.55 μm with Sn composition of 3% increases optical responsivity and sensitivity of detection process. It is evident that for Sn composition of 3%, responsivity is higher that pure Ge. This is because small signal current gain is higher for Sn composition of 35 than pure Ge.

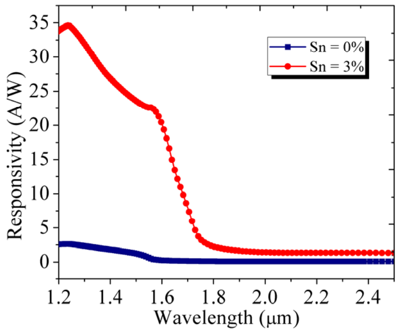

Fig. 6 Variation of optical responsivity with the wavelength

IV. CONCLUSION

We studied theoretically the performance of p-n-p HPTs with $Ge_{1-x}Sn_x$ as the base material with varying Sn concentration**.** Calculated results reveal that SNR >95 dB up to 10 GHz and 60 dB up to 100 GHz has been predicted at the output. Based on calculated results, the proposed p-n-p HPTs may be a promising candidate as an alternative of III-V based photodetectors in optical communication and mid-infrared region applications.

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