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Enhanced Signal-to-Noise Ratio of Ge/$Ge_{1-x}Sn_x$/Ge based Multiple Quantum Well Heterojunction Phototransistor for SWIR Photodetection

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Abstract

We have studied noise characteristics and signal-to-noise ratio (SNR) of n-Ge/p-$Ge_{1-x}Sn_x$/n-Ge Heterojunction Transistor (HPT) with multiple quantum well (MQW) inserted in the base and different base-width for efficient detection at 1.55 μm. The MQW inserted in the base significantly improves SNR in the high-frequency region, leading to efficient detection in the fiber-optic telecommunication windows. The results show that SNR is not only dependent on the frequency, but also on the base-width and number of quantum wells (QWs). The estimated result shows that SNR of > 61 dB up to 100 GHz can be achieved, which ensures the operation of the device in the high-frequency range and low-noise detector.

***Keywords**—GeSn-alloy; heterojunction phototransistors; Multiple Quantum Well; signal-to-noise ratio.*

1. Introduction

Heterojunction Phototransistors (HPTs) are considered to be useful alternatives for conventional p-i-n and avalanche photodetectors (APDs) [1]. HPTs have an internal gain like APDs but have the additional advantage of having no excess noise that is present in APDs. This leads to a better detector sensitivity and signal-to-noise ratio (SNR) in comparison to conventional photodetectors [2].

Till date, the existing HPTs used for C- and L-bands are made of group III-V semiconductors, making the system cost higher. Recently, successful growth of $Ge_{1-x}Sn_x$ alloy on the Ge-based virtual substrate grown on Si substrate and $Ge_{1-x}Sn_x$ alloy shows a direct band gap for Sn concentration exceeding 6-7% [3, 4]. The direct gap GeSn alloy has the potential for use in various optoelectronic devices, including HPTs.

Work on GeSn-based HPTs has been started by Basu et al [5], followed by a number of theoretical and experimental studies [1], [6]–[8]. Unfortunately, however, an important aspect: the noise modeling, has so far received no attention from workers. It is also surprising that there is only one detailed treatment of noise and SNR of InGaAs-based HPT [2]. In the present work, we study the noise characteristics and estimate the SNR of GeSn-based HPTs, in the base of which MQW is inserted. In addition, we then study the effect of different base-width on the performance of HPT to optimize the structure toward achieving a good SNR. It is found that MQW inserted in the base significantly enhance the SNR and shows excellent performance as a detector in the fiber-optic telecommunication windows.

This paper is organized as follows: section II describes the proposed device structure and theory, section III describes the noise characteristics of the device through results and discussions. Finally, section IV concludes the proposed work

2. Device Structure and Theory

The layered structure of the proposed three terminals $Ge_{1-x}Sn_x$-based HPT (x=8% for collector and emitter) is shown in Fig. 1 and band diagram is shown in Fig. 2. Base region has three periods of undoped MQW (x=17%) and barrier layers (x=13%). The thicknesses of the QW and barrier layers are 10 nm and 5 nm respectively. The optical illumination of wavelength 1.55 μm and 1 μW power, is incident on the top of the base. Table I shows the structural details of the GeSn-based MQW HPT.

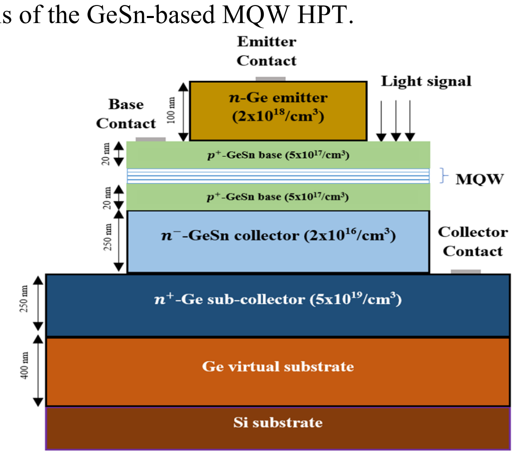

Fig. 1 Layered structure of proposed $Ge_{1-x}Sn_x$ as an HPTs

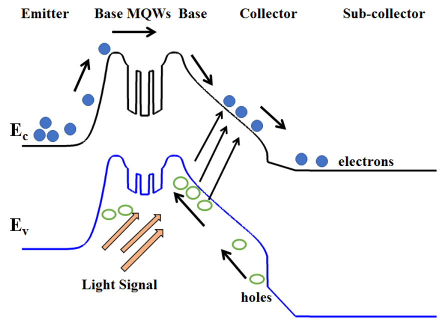

Fig. 2 Energy band diagram of $Ge_{1-x}S_x$ as HPT [7]

Table I
Structural Details of $Ge_{1-x}Sn_x$ based MQW HPT

Layer	**Material**	**Thickness (nm)**	**Doping Concentration (cm^{-3})**
Emitter	n −doped Ge	100	2×10^{18}
Base	p −doped $Ge_{1-x}Sn_x$	20 (both sides of QWs)	5×10^{17}
Quantum well	$Ge_{0.83}Sn_{0.17}$ (Well)	10	Undoped
	$Ge_{0.87}Sn_{0.13}$ (Barrier)	5	Undoped
Collector	n^- −doped $Ge_{1-x}Sn_x$	250	2×10^{16}
Sub-collector	$n^+ - Ge$	250	5×10^{19}
Virtual Substrate	Ge	400	-
Substrate	Si	-	-

We considered thermal noise (N_3), shot noise (N_2) source at the base-emitter (B-E) and shot noise (N_1) at the base-collector (B-C) junctions. Flicker noise (1/f noise) is neglected since it occurs only below 1 MHz. Our analysis essentially follows the model of Chakrabarti et al [2]. The gain and other characteristics relevant to HPTs having MQW in the base are taken from Pandey and Basu [7]. The output signal power of HPTs can be defined by

$$S_{out} = I_{ph}^2 |H(f)|^2 R_{eq} \quad (1)$$

Where, I_{ph} is the photogenerated current under illumination and R_{eq} is the equivalent output resistance. The total noise power can be calculated by

$$N_{out} = \overline{i_n^2}(t) R_{eq} \quad (2)$$

Where, $\overline{i_n^2}(t)$ is the mean square value of the total noise current. By using equation (1) and (2), SNR of the HPT can be defined as

$$SNR = \frac{I_{ph}^2 |H(f)|^2 R_{eq}}{\overline{i_n^2}(t) R_{eq}} = \frac{I_{ph}^2 |H(f)|^2}{\overline{i_n^2}(t)} \quad (3)$$

3. Results and Discussions

A. Effect of Operating Frequency on Noise Behavior

Numerical calculations have been carried out for the proposed HPT at 300 K. Fig. 3 shows the variation of various noise components with frequency for MQW structure. It is apparent that shot noise power at the B-C junction is almost constant up to 4 GHz and beyond 4 GHz, it increases steeply with an increase in frequency. This increase in shot-noise at BC junction is attributed to the small-signal current signal decreases for $f > 4\ GHz$ due to RC effect. It is also observed that thermal noise power is independent of frequency and shot noise power at the B-E junction is almost constant. Fig. 4 shows the variation of SNR with operating frequency for a structure having MQW in the base. It is evident that SNR decreases with increase in operating frequency. This is expected as we take into account the values of noise power.

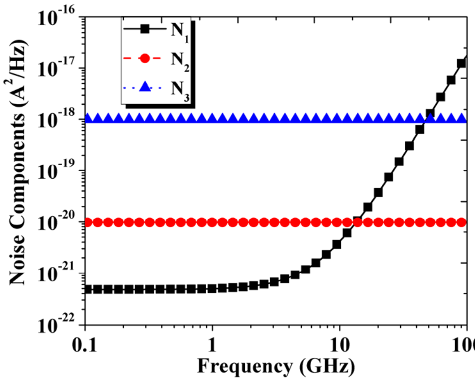

Fig. 3 Variation of various noise components with operating frequency for the structure having MQW in the base.

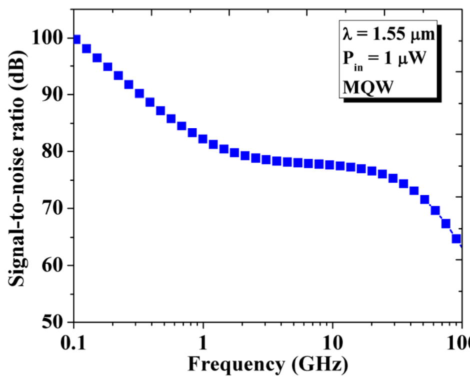

Fig. 4 Variation of signal-to-noise ratio with operating frequency for the structure having MQW in the base.

B. Effect of Quantum Wells (QWs) on Noise Behavior

Figs. 5, 6, and 7 show that variation of noise power variation with a number of quantum wells. Noise power increases with a decrease in the quantum well. It is observed that maximum noise occurs in the case of bulk structure. Fig. 8 shows the variation of SNR with a number of quantum well. It is evident that maximum SNR (~ 80 dB sustainable up 30 GHz) is obtained for the structure having 3 QWs due to better gain confinement, and carrier confinement. Minimum SNR (~ 60 dB sustainable up 30 GHz) is obtained for bulk structure, that is, without any QW. Table II gives the SNR value for the structure having MQW, single QW, and without QW at different frequencies.

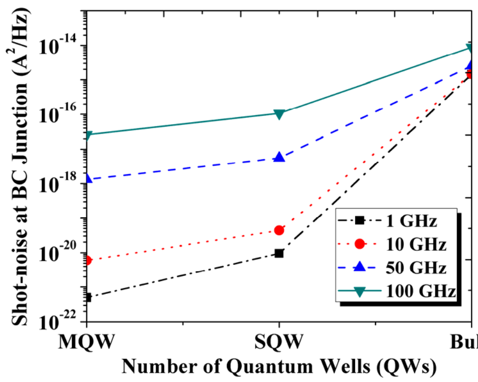

Fig. 5 Shot-noise at BC junction as a function of the number of quantum wells in the base at a different frequency.

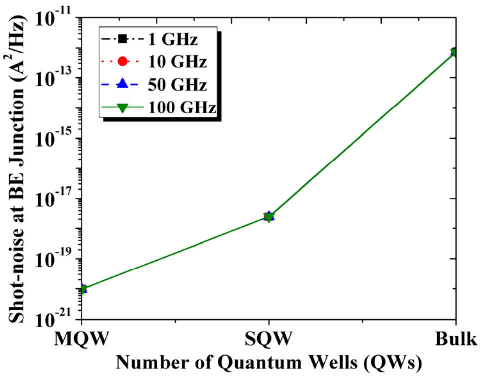

Fig. 6 Shot-noise at BE junction as a function of the number of quantum wells in the base at a different frequency.

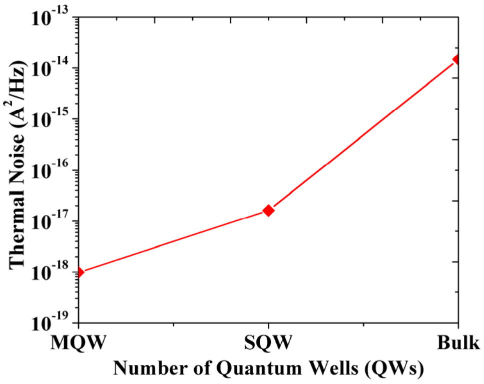

Fig. 7 Thermal noise as a function of a number of quantum wells.

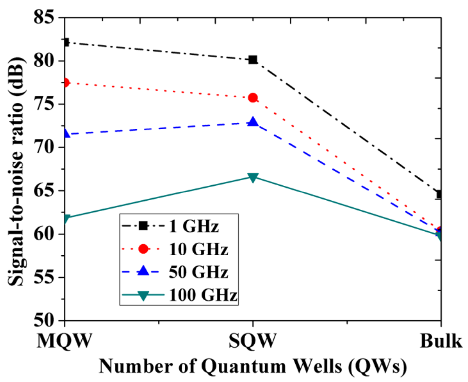

Fig. 8 Signal-to-ratio as a function of a number of quantum wells at a different frequency.

Table II SNR value for the structure having MQW, single QW, and without QW at different frequencies

Frequency (GHz)	SNR (dB)		
	Multiple QW	Single QW	Without QW
0.1	99.7	97.64	81.35
1	81.19	79.17	63.62
10	77.47	75.72	60.34
100	61.83	66.65	59.805

C. Effect of Base-width on Noise Behavior

Figs. 9, 10, and 10 shows the variation of noise power with base-width. It is observed that shot-noise power at BC and BE junction increase with increase in the base-width. This increase in shot-noise can be explained as recombination increases with increase in the base-width. From the figure 11, it is seen that thermal noise decreases with increase in the base-width. This behavior is attributed to the decrease in the transconduction under illumination (transconductance, $g_{mop} = i_{cop}/V_T$, where, i_{cop} is the collector current under illumination and V_T is the thermal voltage, i_{cop} decreases with increase in the base-width leads to decreases in the thermal noise). Figure 12 shows the variation of SNR with base-width at the different operating frequency. it is evident that maximum SNR (~ 80 dB sustainable up 30 GHz) is obtained for base width of 20-nm on both sides of the MQW, while minimum SNR (~ 72 dB sustainable up 30 GHz) is obtained for base width 50-nm on both sides due to recombination increases with increase in the base-width. Table III gives the SNR value with varying base width at different frequencies.

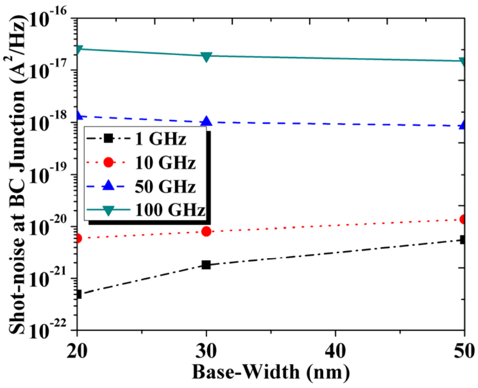

Fig. 9 Shot-noise at BC junction as a function of base-width at a different frequency.

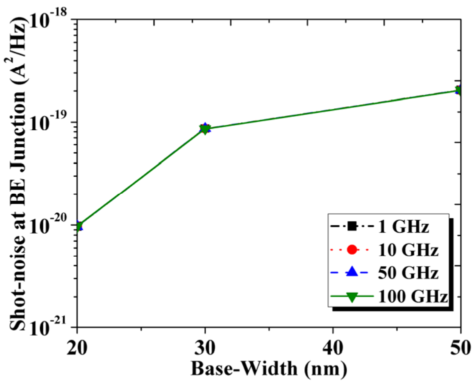

Fig. 10 Shot-noise at BE junction as a function of base-width at a different frequency.

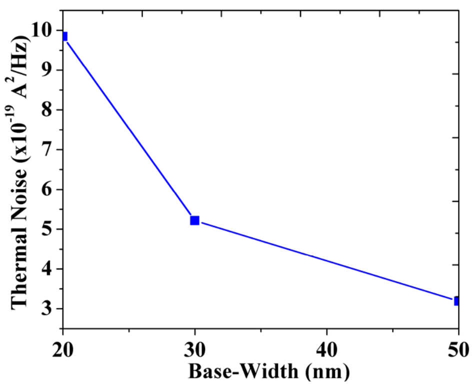

Fig. 11 Thermal noise as a function of base-width.

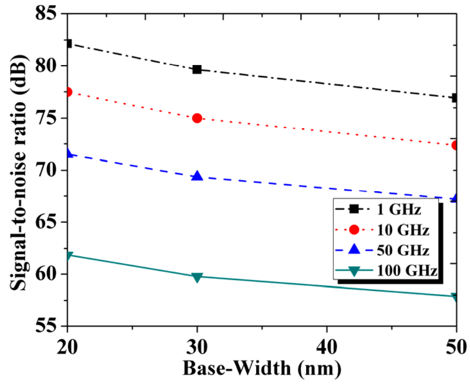

Fig. 12 Signal-to-noise ratio as a function of base-width at a different frequency.

Table III SNR value with varying base width at different frequencies

Frequency (GHz)	SNR (dB)		
	Base Width = 20-20 nm both sides	Base Width = 30-30 nm both sides	Base Width = 50-50 nm both sides
0.1	99.7	96.7	92.6
1	81	78.6	75.97
10	77.4	74.99	72.35
100	61.8	59.76	57.88

4. Conclusion

We have studied the performance of HPTs with $Ge_{1-x}Sn_x$ as the base material, having MQWs in the base (well; x=17%, barrier; x=13%) and for different base widths**.** Our results show a strong dependency of SNR on frequency and base-width. Inserting the MQWs in the base can considerably increase the SNR. A good signal-to-noise ratio of 99.7 dB at 0.1 GHz for structures having MQW and 57.88 dB at 100 GHz for the base width 50-nm on both sides of MQW are achievable. Based on our calculated results, we conclude that Ge/$Ge_{1-x}Sn_x$/Ge MQW HPT can be utilized for efficient photodetection with high SNR at 1.55 µm.

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7. References

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