Characteristics of Heterojunction Phototransistors With $Ge_{1-x}Sn_x$ Multiple Quantum Wells in the Base

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***Abstract*– Germanium-tin alloy ($Ge_{1-x}Sn_x$), due to its direct gap nature for $x > 0.08$, has higher absorption coefficient than that of pure Ge. Using COMSOL Multiphysics, we have simulated the characteristics of Ge/GeSn/Ge heterojunction phototransistor, the base of which incorporates a multiple quantum well (MQW) structure made of $Ge_{0.87}Sn_{0.13}$ barrier and $Ge_{0.75}Sn_{0.155}$ well at a wavelength of 1.55 µm. The 3-QW structure shows high current gain over a wider range of base-emitter voltage than a single QW structure and a structre without any QW.**

***Index terms*– Heterojunction Phototransistor, GeSn alloy, Multiple quantum well, current gain**

I. INTRODUCTION

Silicon (Si) based photodetectors and sensors find a number of applications in various fields [1]. However, Si based photodetectors cannot be used in C and L bands of communication due to incompatibility of its bandgap properties. Though germanium (Ge) based photodetectors fit into the near infrared (NIR) and mid-IR (MIR) regions, the absorption coefficients are very low, which can affect the performance of the device.

$Ge_{1-x}Sn_x$ alloys possess direct bandgap nature for $x > 0.08$ and show large absorption coefficient [2-4]. Photodetectors with p-i-n configuration based on GeSn alloy have been fabricated and their performance has been demonstrated in NIR and MIR regions [5, 6]. Heterojunction phototransistors (HPTs) are attractive alternative for detection, since HPTs have current and optical gain but does not have excess noise as in Avalanche Photodetectors. The performance of GeSn based HPTs in communication windows, as well as in NIR and MIR regions has been studied in some recent works [7-9]. In these works, various parameters such as optical/current gain, responsivity, terminal currents etc. have been examined. It turns out that the performance of HPTs based on GeSn alloy are comparable and sometimes better than the InGaAs based HPTs [7]. In a previous work [9], we have demonstrated HPT simulation using COMSOL Multiphysics which is based on finite element method (FEM).

The present work provides a simulation study using COMSOL of HPTs with GeSn alloy as base material incorporating within the base a multiple quantum well (MQW) structure using two different GeSn alloys as the well and barrier layers. We have obtained the Gummel plots of base and collector currents versus base-emitter voltage as well as the values of current gain for MQW structures. We have also examined how the values of current gain alters when a single QW, or no QW is inserted in the base. Our results indicate that the current gain is substantial over a large range of base-emitter voltage when a 3-QW is included.

The paper is organized as follows: Section 2 deals with the structure of MQW GeSn based HPT. Results and discussion are given in Sec. 3. The conclusions are drawn in Sec. 4.

II. DEVICE STRUCTURE

Figure 1 shows schematic of the device, which contains six layers grown on Si substrate. The emitter is formed by n-type Ge, p^+ GeSn makes the base, the n^-GeSn collector is grown on n^+-Ge subcollector and the layers are grown on a thick Ge virtual substrate. In between the base and collector three periods of MQW having total thickness of 50 nm, having $Ge_{0.87}Sn_{0.13}$ as barrier and $Ge_{0.75}Sn_{0.155}$ as well, are inserted. The thickness of each layer is indicated in Fig. 1 and the doping concentrations in different layers are assumed to be the same as given by Kumar et al [9]. Light signal of 1.55 µm wavelength and optical power of ~1µW falls normally on the base, as shown in Fig. 1.

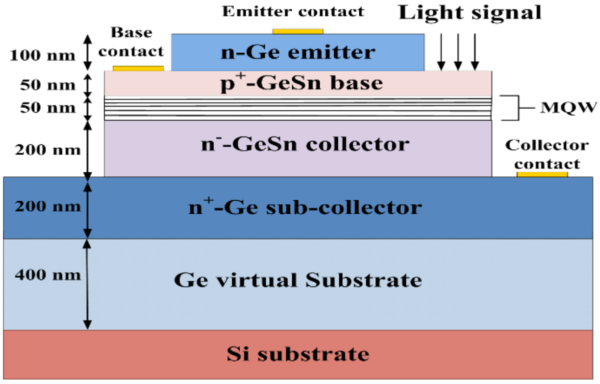

Figure 1. Schematic of the HPT structure having three periods of MQWs (4 nm barrier and 10 nm well)

Two "barrier" (each of 4 nm thickness) regions surround one "well" (10 nm thick) region. The bandgap of Ge is taken to be 0.664 eV. The Ge virtual substrate is assumed to have a thickness of 400 nm, which is sufficient to avoid the presence of any defect in the main device region, which is fabricated on Si substrate.

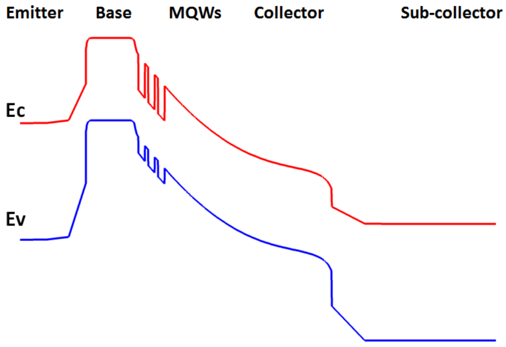

Figure 2. Simulated band diagram of device structure

The band diagram for the whole device structure obtained by simulation is shown in Fig. 2.

III. RESULTS AND DISCUSSION

The device simulation uses a combination of two modules, viz, electromagnetic wave and semiconductor, along with frequency domain analysis. In semiconductor module, trap assisted recombination with Shockley-Read-Hall model as a domain trapping model is used. Input port is taken at the top of the base and output port at the bottom of the structure. Continuity periodicity is applied. Forward Gummel plot (variation of the base and collector currents with base emitter voltage for constant collector voltage, $V_c = V_b$) is obtaine by using simulation for the structure. Fig. 3 gives the plots of the terminal currents (base and collector currents) as a function of base-emitter voltage (V_{be}) varying from 0 to 0.65 V for 1 V collector voltage (V_c).

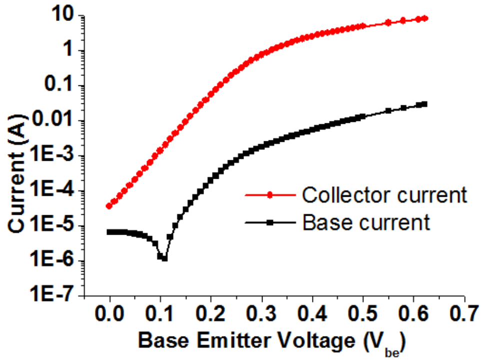

Figure 3. Gummel plots of terminal currents

Fig. 4 shows the gain variation with applied base emitter voltage with MQW in the base (blue curve). We examined how the gain varies if a single quantum well (SQW) is inserted, as well as when no QW is present in the base. The base doping is kept unchanged for the three cases. With no QW in the base, gain curve is almost flat with a low value of gain. The SQW-HPT structure shows maximum gain for voltage range of 0 - 0.2 V; but the gain shows a peaked nature and rapidly falls with increasing V_{be}. The gain curve for MQW-HPT shows a peak but attains a somewhat constant value for higher values of V_{be}. With increasing number of QWs in the base, there is more absorption of light at the base. A significantly higher and constant current gain is obtained in the MQW-HPT structure in comparison to the values obtained for HPT without ay QW.

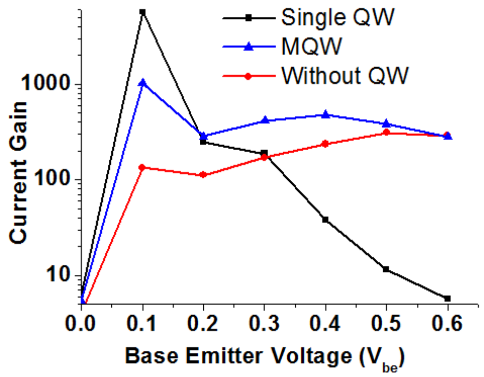

Figure 4. Variation of current gain with applied base emitter voltage for different device structures

It appears from Fig. 4 that, on increasing V_{be}, there is decrease in gain. Higher recombination in the base region as well as within QWs increases the base current, which contribute towards reduction of current gain.

Calculation of the responsivity and optical gain of the structures is under progress.

IV. CONCLUSION

We have obtained current gain and terminal currents in a Ge-GeSn-Ge HPT with its base illuminated by light of 1.55 µm wavelength by using COMSOL Multiphysics. GeSn alloy with its direct gap has a large absorption coefficient than Ge. In the present work, we have examined whether inclusion of MQWs in the absorption region leads to better results. The present work establishes that current gain increases by including a SQW, but the gain is peaked at some value of V_{be}. As the number of QWs becomes 3, large current gain over a broader range of V_{be} is obtained.

REFERENCES

[1] M. J. Deen and P. K. Basu, "Silicon Photonics: Fundamentals and Devices", John Wiley, UK 2012.

[2] V. R. D'Costa et al., "Sn alloying as a means of increasing optical absorption in Ge at the C- and L- telecommunication bands," S. Sc. Tech., vol. 24, pp. 115006 (1-8), 2009.

[3] P. K. Basu, Bratati Mukhopadhyay and R. Basu, Ch. 14 in Semiconductor Laser Theory, CRC Press (T & F), Boca Raton, 2015.

[4] S. Wirths, D. Buca, and S. Mantl, "Si–Ge–Sn alloys: From growth to applications", Progress in Crystal Growth and Characterization of Materials 62 (2016) 1–39.

[5] M. Oehme, et al, " GeSn p–i–n detectors integrated on Si with up to 4 % Sn". Appl. Phys. Lett., 101(1–4), 141110 (2012).

[6] H. H. Tseng et al., "GeSn-based p-i-n photodiodes with strained active layer on a Si wafer," Appl. Phys. Lett., vol. 103, no. 23, p. 231907, 2013.

[7] R. Basu et al., "Predicted performance of Ge/GeSn hetero-phototransistors on Si substrate at 1.55µm," Opt. Quantum Electron., vol. 47, no. 2, pp. 387–399, 2014.

[8] G. E. Chang et al., "Design and modeling of GeSn-based heterojunction phototransistors for communication applications," IEEE J. Sel. Top. Quantum Electron. 22(6), 8200409 (2016).

[9] Dur vesh Kumar et al., "Simulated Characteristics of a Heterojunction Phototransistor with Ge1-xSnx Alloy as Base", Optical Engineering - SPIE, vo. 55(12), pp. 127103, 2016.