On Optimum Designs of a RCE Si/SiGe/Si MQW Photodetector for long wavelength applications

Mukul K. Das[1], and N. R. Das[2]
[1]Dept. of Electronics & Instrumentation, ISM University, Dhanbad, India,E-mails:mukulkdas@ieee.org,
[2]Institute of Radio Physics and Electronics, University of Calcutta, India
92 Acharya P. C. Road, Kolkata – 700009, India. Tel. +91 33 2350 9115, Fax: +91 33 2351 5828. nrd@ieee.org

Abstract: In the present paper, performance analysis of a resonant-cavity-enhanced Si/Si$_{1-y}$Ge$_y$/Si multiple quantum well photodetector has been carried out. The effects of material parameters of active Si$_{1-y}$Ge$_y$ layers and carrier trapping by the potential barriers at the heterointerfaces of Si/Si$_{1-y}$Ge$_y$/Si quantum wells on the bandwidth (BW) and responsivity of the detector have been investigated using numerical simulation. Results on possible optimum designs of the photodetector have been suggested to maximize responsivity-BW product..

I. INTRODUCTION

Optical communication systems are widely used for high speed and high volume data transfer as well as for interconnection between different modules in a multimodule chip. Photodetector is one of the most important devices for optical communication system. Recently, Si-based photodetectors have attracted a lot of interest among researchers around the world mainly due to its low cost and mature manufacturing technology [1-3]. Performance of the Si-photodetectors, however, is not satisfactory for long-haul optical communication due to the weak absorption characteristics of Si at long wavelengths such as 1.3μm and 1.55μm. Incorporation of a small amount of Ge into Si helps in the shifting of the absorption peak towards longer wavelengths. Thickness of SiGe layer is limited by its critical value [4]. This thin absorption layer is suitable for high-speed operation of a transit-time limited photodetector but, it reduces the quantum efficiency and, hence, responsivity of the detector. Responsivity can be enhanced by using resonant cavity and multiple number of active layers. The presence of heterojunction in such structures affects the responsivity (QE) and bandwidth of the device. So, appropriate modeling is required considering this effect to predict the best possible design of the photodetector.

II. MODEL

We have considered a Resonant Cavity Enhanced Si/Si$_{1-y}$Ge$_y$/Si Multiple Quantum Well photodetector structure in our model where SiGe layers are assumed to be responsible for absorption. When light of suitable wavelength is incident on the active layer (SiGe), electron-hole pairs (EHPs) are generated. Because of the heterostructure, the carriers are trapped at the interfaces due to potential barrier. The carriers from this trap are emitted by a slow thermionic emission process over the potential barrier and the rate of emission depends on the effective potential barrier [5]. To calculate current density, we need to consider continuity equation and rate equation. The continuity equation is obtained assuming full width depletion of SiGe layers at applied bias and velocity of carriers is constant. Now, assuming low-level illumination, the rate equation (for hole say) can be obtained as,

$$dp_\tau / dt = j_{hm} / q - (e_{ho} + e_{rh}) p_\tau \qquad (1)$$

where e_{ho}, e_{rh} are respectively emission and recombination rate at heterointerfaces for holes, p_τ represents the holes trapped per unit area at the interface and j_{hmr} is the current density due to moving holes. Similar equations can be written for electrons also. Continuity equation and rate equation for holes and electrons can be solved considering the position dependent generation rate of carriers in the cavity and we can get the hole and electron densities $P(\omega,x)$ and $N(\omega,x)$ respectively in the frequency domain. So the current density in frequency domain, $J(\omega)$, is obtained as

$$J(\omega) = \frac{q}{Md} \sum_{r=1}^{M} \int_{(r-1)d}^{rd} \{N(\omega,x)v_e + P(\omega,x)v_h\} dx \qquad (2)$$

where M is the total number of SiGe layers, v_e and v_h are respectively the constant velocities of electrons and holes. Transit time limited 3-dB bandwidth can be obtained from the frequency response (2). In the limit $\omega \rightarrow 0$, d.c. current density (J_{dc}) can be calculated from (2) and then responsivity is calculated using the relationship, $\Re = J_{dc} A / P$, where P_i is the incident optical power.

III. RESULTS AND DISCUSSIONS

Bandwidth: Our model is verified with the experimental data available in the literature [6], which shows the frequency response in a vertical MQW Si/SiGe PD structure. Experimental value of the 3-dB bandwidth is 7.2GHz whereas the bandwidth is 8.5 GHz from our model, which indicates a good agreement with the experimental results. Plot of 3-dB bandwidth as a function of Ge-content is shown in Fig.1. It is seen that for very low values of Ge-content (y) the 3-dB bandwidth increases linearly. This is due to the increase in velocity of carriers as mentioned before and be effect cause of insignificant trapping. However, after a particular value of y the 3-dB bandwidth starts to fall off depending on the applied bias. This optimum value of y depends on the applied bias as well as active layer thickness.

Responsivity: For verification of the model, the structure given in [7] has been considered and a reasonably good agreement of the model has been found with the experimental data. It is seen that responsivity initially increases with increasing Ge-content and then after a particular value of y, it starts to decrease. Plot of responsivity as a function of reverse bias is shown in Fig.2. It is clea that the responsivity initially increases with bias and finally becomes constant at a high bias. Effective potential barrier decreases with increasing bias and thereby carrier trapping effect decreases. Thus, the carrier loss by recombination at the heterointerface is reduced, and the responsivity increases with bias ultimately reaching a constant value. The constant responsivity is higher for larger number of wells (M) because of the increase in the total thickness of absorption region.

Responsivity-BW Product: In some application of photodetector, the bandwidth and responsivity both should be high. So, the study of their product is very important. Due to the presence of maxima in BW and responsivity variation with Ge-content, there are some values of Ge-content for which the responsivity-BW product exhibits maximum value. Some maximum responsivity-BW (R-BW) products are summarized in Table 1.

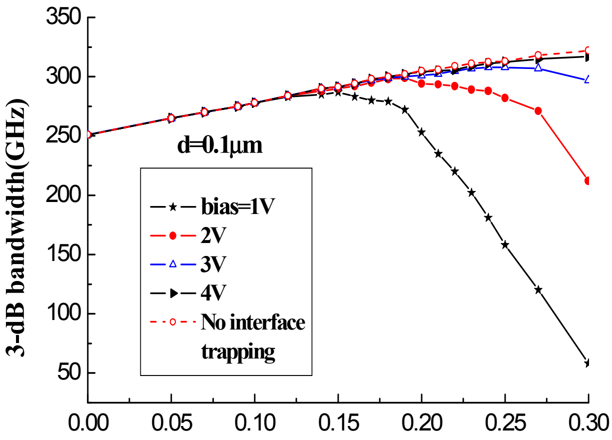

Fig. 1: 3-dB bandwidth vs. Ge-content (y) for different biases.

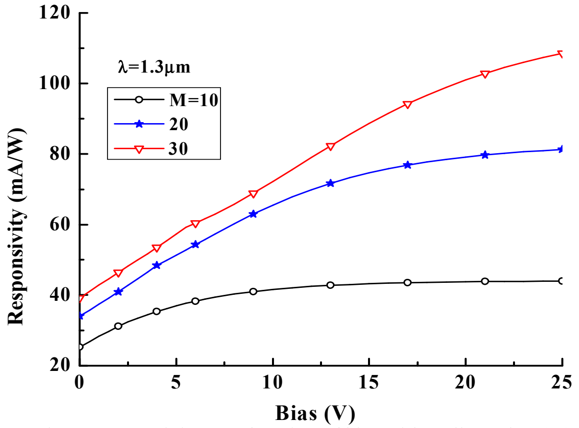

Fig.2: Responsivity as a function of bias with well number (M)

TABLE 1

Some optimum choice of y and bias for maximum R-BW Product at two different wavelengths.

λ (*μm*)	Bias (*V*)	*M*=1		*M*=3		*M*=5	
		y (%)	R-BW (A-GHz/W)	*y* (%)	R-BW (A-GHz/W)	*y* (%)	R-BW (A-GHz/W)
1.0	0	31	129.3	25	67.3	23	45.4
	1	45	227.0	33	84.0	27	51.5
	2	58	290.0	41	96.6	32	55.6
1.3	0	40	8.4	37	2.0	28	1.3
	1	48	57.0	41	15.0	39	5.2

IV. CONCLUSION

The effect of Ge-content on the transit time limited bandwidth, responsivity and responsivity-BW product of a SiGe/Si MQW photodetector has been investigated. Effects of the carrier trapping, well thickness and well numbers have been considered in this analysis. For long wavelength application, the Ge-content should be high and applied bias should also be made high to reduce carrier trapping effect and, hence to enhance the performance of the device.

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