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Vertical Ge photodetector base on InP taper waveguide

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ABSTRACT

In this work, simulation is conducted to investigate Ge photodetectors monolithically integrated on Si chip. The performance of vertical Germanium photodetector with FDTD Solutions (optical simulation) and electrical simulation has been studied. Selective heteroepitaxy of Ge is functioned in the monolithic integration of Ge photodetectors. The potential of CMOS-compatible monolithic integration of Ge as photodetector is investigated and the performance optimization is presented. Additionally, the investigation is extended to electrical part, particularly in the conversion efficiency as well as operation under low supplied voltage condition.

Introduction

In the advancement of fifth generation (5G) communication and Internet-of-things (IoT) that required high speed connectivity, existing telecommunication infrastructures are reaching bottleneck. Cost effective always important criteria in the tradeoff of telecommunication system. As a result, single fiber that able to support multiple channel transmission is highly demand to achieve scalability of the aggregate data rates. Owing to the mass productivity of silicon CMOS platform, silicon photonics are able to provide high performance with low cost photonics interface solutions. In such, monolithically integrated Si photonics [1] is one of the highlighted research area. However, integration between the CMOS and monolithically integrating Si photonics components in a same chip, always facing some difficulty, particularly in integration technique and thermal budget. There are some work have zoom into this issue [2], yet still lack of technical and scientific details.

On the other hand, photodetector is one of the most influential component in optical communication. With the drawback of large bandgap, Si is not able to be suitable candidate for photodetection in optical network system, especially in O-band, S-band, C-band and L-band. Therefore, other materials that exhibited smaller bandgap, such as germanium (Ge), has been used to overcome this issue. As reported, SiGe [3,4] and Ge [5] are able to incorporated in Si chip to function as photodetectors in O-, S-, C-, L-bands. Ge photodetectors in waveguided base have presented an excellent photodetection performance in C-band region with the advantages of long absorption region and absorption rate of Ge at C-band, that allow full absorption. On the other hand, others solution have been proposed to address the thermal budget, such as polycrystalline Ge [6,7]. Unfortunately, the carrier diffusion length is highly relied upon the crystalline quality. As a result, this method not able to achieve similar or better performance as compared to epitaxial monocrystalline Ge photodetection technique. Additionally, thermal budget can be improved through wafer bonding technique as well as ion-cut process to integrate Ge photodetector [8]. However, these techniques are relatively high cost and high complexity.

Materials such as solid states as indium arsenide (InAs), indium phosphide (InP), and gallium indium arsenide phosphide (GaInAsP) have shown good potentials for the applications of waveguide structures and layers, where they are very efficient to confine and guide the light within the structures[9–11]. In reference [12], the Blondeau et al. have proven that the semiconductor materials waveguides with a thickness less than one hundredth of the operating waveguide have great tendency to construct the quantic. InP has less insertion loss and also the confinement of the light is much better than silicon material. The fabrication of the silicon waveguide may be cheaper and easier because of the available CMOS

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foundries but the good light confinement and also the optimized material for this simulation would be InP. In the simulation of the taper waveguide, this method has been used to enhance the light coupling at a photodetector input port and it may be considered according to an embodiment with a tapered waveguide structure characterized by an input and an output of the respective dimensions.

In this work, selective heteroepitaxy of Ge is functioned in the monolithic integration of Ge photodetectors. The potential of CMOS-compatible monolithic integration of Ge as photodetector is investigated and the performance optimization is presented. Moreover, the investigation is extended to electrical part, particularly in the conversion efficiency as well as operation under low supplied voltage condition.

Research theory

As light is incident on the Germanium layer and being absorbed. Divergence of pointing vector can be used to solve the absorption per unit volume,

$$p_{abs} = -0.5 real(\vec{\Delta}\cdot\vec{P}) \quad (1)$$

Although the absorption per unit volume able to solve using Eq. (1), this equation is easily affected by numerical problems. As a result, the improved equation can be used to overcome the shortcoming of Eq. (1),

$$P_{abs} = 0.5 real(i\omega\vec{E}\cdot\vec{D}) \quad (2)$$

And able to derive as,

$$P_{abs} = -0.5\omega|E|^2 image(\varepsilon) \quad (3)$$

To obtain the absorption as a function of space and frequency, electric field intensity and the imaginary part of the permittivity are needed. Both quantities are able to measure in an Lumerical FDTD simulation. Absorbed photons per unit volume able to obtain through dividing *Pabs* by the energy per photon:

$$g = \frac{P_{abs}}{\hbar\omega} = \frac{-0.5|E|^2 imag(\varepsilon)}{\hbar} \quad (4)$$

where $\hbar\omega$ is photon energy, $\hbar$ is the reduced Planck constant, E is the local electromagnetic fields, D is electric displacement field, ω is the radian frequency and ε is the complex permittivity. The absorbed photons will generate electron hole pairs which will be separated out of the depletion region by the electric field and produce current flow. Active region of the VPD has a width of 9 μm which is coupled to the 0.3 μm wide waveguide with an InP material as taper waveguide. The taper can be included inside the optical simulation of the VPD or it can be simulated separately for optimization purpose. Given the fact that the eigenmode expansion (EME) solver is highly efficient in simulating and optimizing tapers. In the FDTD simulation, a mode source has been used with the telecommunications wavelength of 1.55 μm as optical input. The input signal flow into the designed photodetector. Then, the absorbed light by Ge is measured. The generation rate is obtained based on the input intensity of 1 W. Besides, length of the VPD is set to 12 μm and the silicon layer is used as the anode contact of the photodetector.

Results and discussions

In the taper waveguide which has been used in this simulation the parameters can be defined in Table 1. The InP material has a refractive index of 3.16 at the operating wavelength as 1550 nm.

The illustration of the taper base on InP material on SiO_2 substrate has been illustrated in Fig. 1.

Table 1
The material for grating that has been used is InP, and the details of the taper design with InP material have been listed.

L_{narrow}	0.3 μm
L_{wide}	9 μm
Thickness	0.22 μm
Total Length	12 μm
Refractive index at 1550 nm	3.16

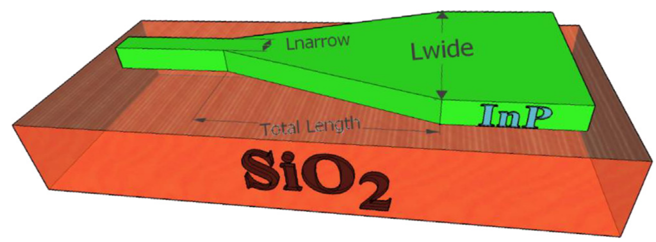

Fig. 1. The taper illustration.

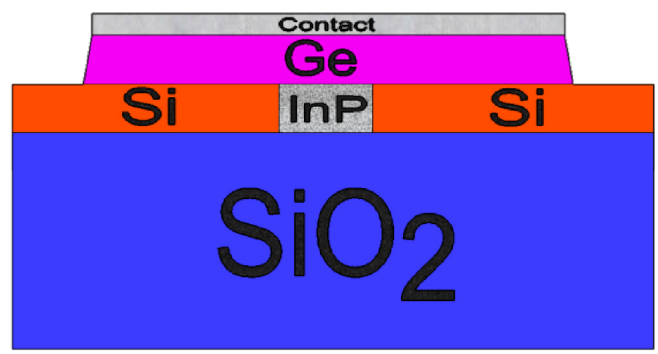

Fig. 2. The cross section of PD.

Table 2
The details of the simulated photodetector.

Materials	Width(μm)	Hight(μm)
SiO_2	75	10
Si	33(2 side)	0.22
Ge	Top: 51 Bottom: 52	0.5
Contact (Al)	50	0.1

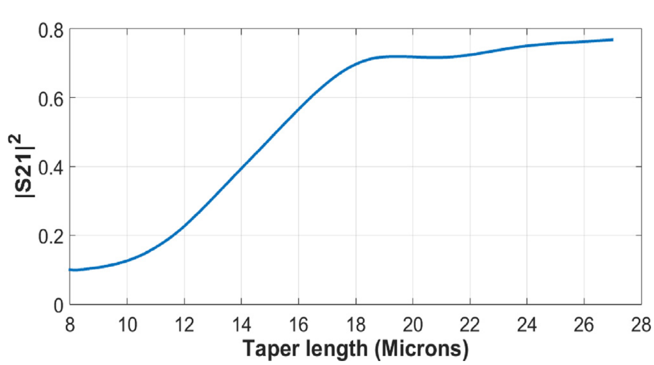

Fig. 3. Effect of taper length on transmission.

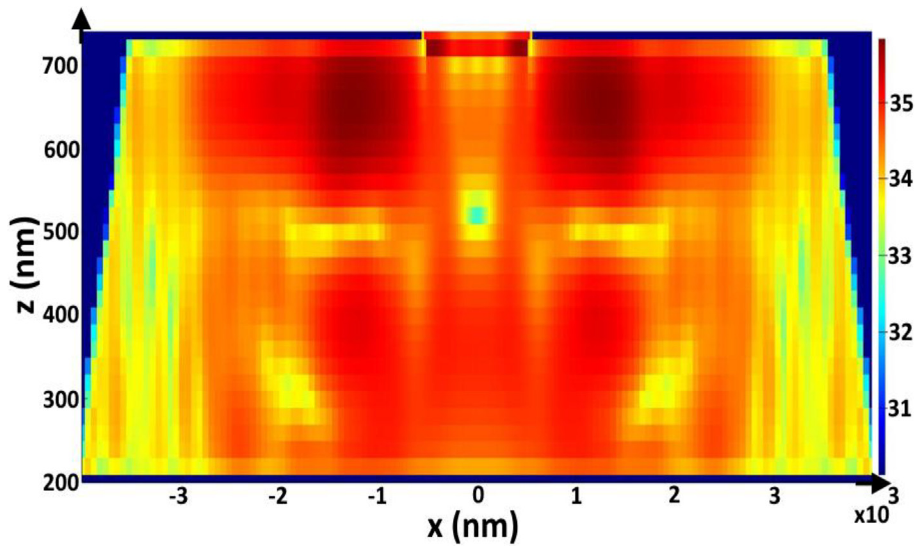

Fig. 4. Generation rate in y = 5889 nm.

As the taper waveguide has it is own benefit in case of decreasing the lost for the waveguide designs it also can be useful for the photodetector design as it can be more efficient to act as a waveguide in this design. By performing the optimizations in the simulation, the total length of the taper waveguide has been selected as 12 μm.

In Fig. 2 as it is illustrated the InP was the taper waveguide as we discuss about it and it is sandwiched between two silicon and from the upper cladding also germanium covered on the top of the design the contact has been designed. The important parameters that has been used in the photodetector design has been mentioned in Table 2. The germanium has the trapezoidal design as it can be useful in case of absorbing the light within this design. Trapezoidal structure with side walls can offer better and optimized absorption therefore, the incident light will be absorbed efficiently which is required for the photodetector devices.

The transmission through the taper as a function of length can be plotted in Fig. 3, by choosing $|S21|^2$. To design for an insertion loss less than 1 dB, the taper length is set to have a value of $|S21|^2$ greater than 0.7 dB. This provides an optimized length of approximately 19 μm for the taper.

FDTD Solutions

Fig. 4 was generated for a detector that showing the generation rate in y = 5889 nm by performing a 3D simulation.

The photodetector has been fully modeled in the electrical stimulation. The surface recombination velocities is used to show the p + Si with anneal device in Ref. [4]. The cathode and anode contacts have also been defined in the boundary conditions window and are set to simulate for a single bias of −1 V. For the initial simulation, the temperature dependence performance is studied as shown in Fig. 5. In Ref. [4], silicon is used as waveguide material, whereas InP as waveguide materials is simulated in this work.

The voltage has been selected to operate as steady state voltage, and the anode voltage to range from 0 to −2 V with 21 steps. Within this condition for every temperature, all 21 values of bias will be swept, the results have been illustrated in Fig. 6.

The simulation has been studied with the contact bias from 0.25 to −2 V in 26 steps. For consistency purposes, an input power of 0.009 mW which corresponds to 1 mA of short circuit current is used. The Figs. 7 and 8 are normalized photocurrent versus bias

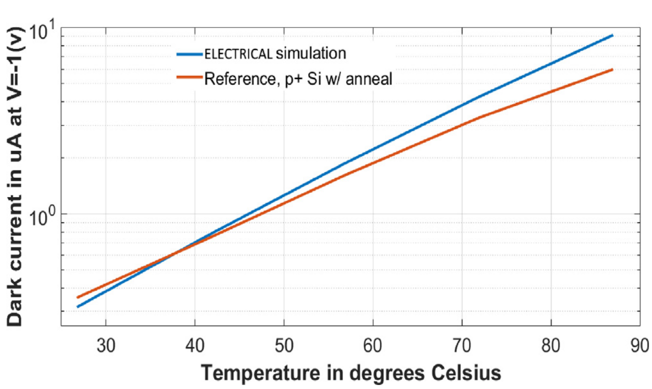

Fig. 5. Dark current versus temperature.

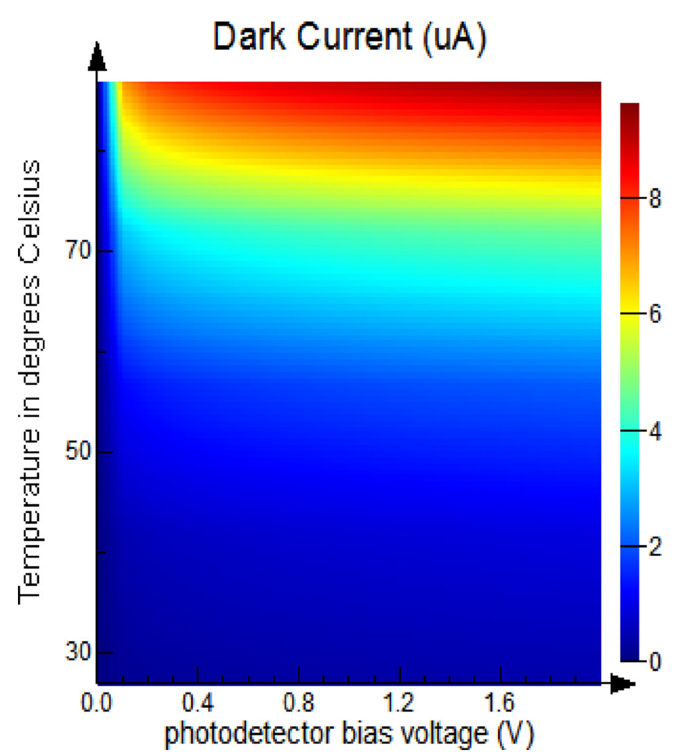

Fig. 6. Dark current versus bias voltage and temperature.

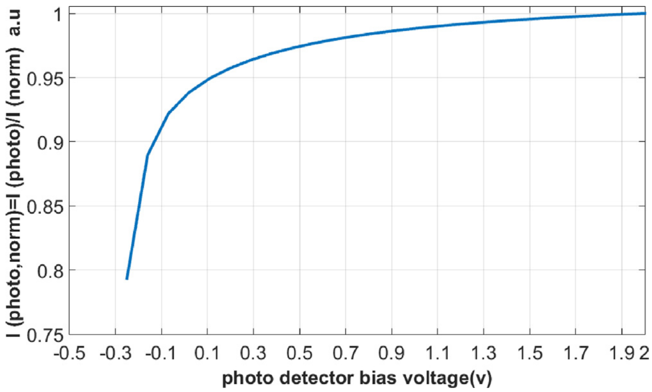

Fig. 7. Normalized photocurrent.

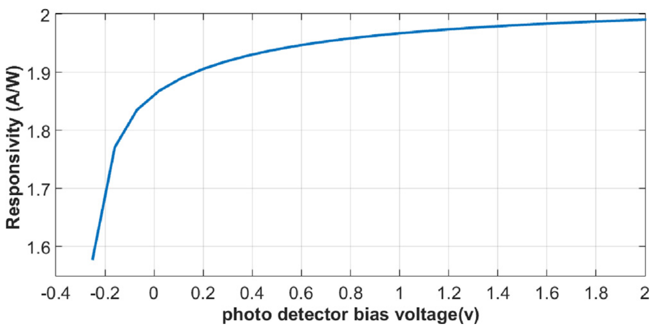

Fig. 8. Responsivity of the VPD.

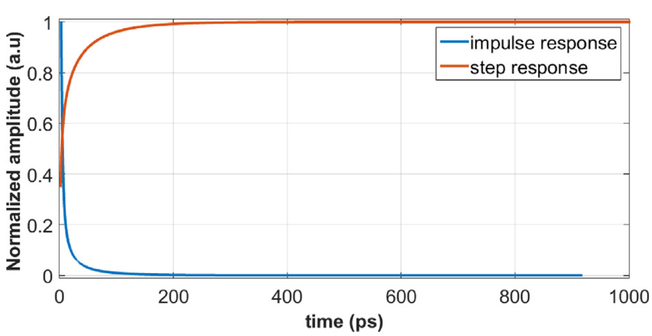

Fig. 9. Step and impulse response.

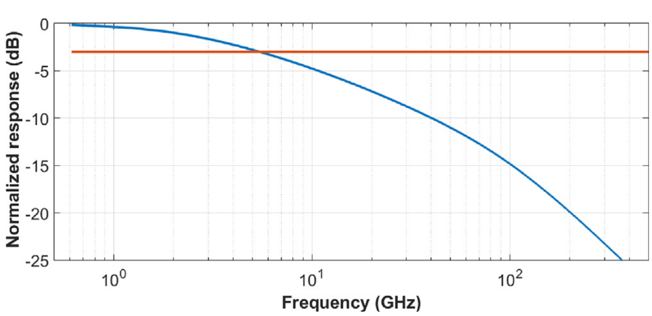

Fig. 10. Frequency response of the VPD.

and responsivity versus bias. The responsivity of the simulated structure at 0.2 V is approximately 1.9 A/W as part of the incident light goes through the device length without getting absorbed.

The transient behavior of the system can also be studied by modifying the contact voltage to be a function of time, v(t). The anode bias has been modified to be time dependent. The cathode voltage is kept fixed at 0 V. The time dependence will apply to all contacts. In the case of the fixed voltage contacts, the solver will apply the same constant voltage at every time step. In anode, the first-time point is 0 ps and the second one is 1 μs. The voltage value for both of these is set to −0.5 V. Within the minimum times of 1 ps, it can be plotted as the step function, as shown in Fig. 9. For consistency purposes, an input power of 0.09 mW which corresponds to 100 μA of short circuit current is used. The frequency response is then calculated by taking the fast fourier transform (FFT) of the impulse response as presented in Fig. 10.

Conclusion

Simulation upon Ge photodetectors that monolithically integrated on the Si platform. Within the InP as taper waveguide to shape the VPD. The transient behavior of the system studied by modifying the contact voltage to be a function of time, by modifying the anode bias so it was time dependent. The cathode voltage was fixed at 0 V. The frequency response is then calculated by taking the fast fourier transform (FFT) of the impulse response. The responsivity of the simulated structure at 0.2 V is approximately 1.9 A/W as part of the incident light goes through the device length without getting absorbed. The absorption of light is optically simulated using FDTD Solutions, while DC and transient responses of the system are electrically simulated. The electrical simulation reveals the role of material interface losses and allows one to extract key behavioral parameters such as dark current, responsivity and bandwidth.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.rinp.2018.03.014.

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