-1 V Bias 67 GHz Bandwidth Si-Contacted Germanium Waveguide p-i-n Photodetector for 56 Gbps Optical Links

H. Chen1,2,*, P. Verheyen1, P. De Heyn1, G. Lepage1, J. De Coster1, S. Balakrishnan1, P. Absil1, W. Yao3, L. Shen3, G. Roelkens1 and J. Van Campenhout1

1Imec, Kapeldreef 75, Leuven B-3001, Belgium
2Photonics Research Group, Department of Information Technology, Ghent University—IMEC, B-9000 Ghent, Belgium
3Photonic Integration Group, Eindhoven University of Technology, 5600 MB Eindhoven, Netherlands

Abstract: We demonstrate a 67 GHz bandwidth silicon-contacted germanium waveguide p-i-n photodetector operating at -1 V with 6.8 fF capacitance. The dark current is below 4 nA. The responsivity is 0.74 A/W at 1550 nm and 0.93 A/W at 1310 nm wavelength. 56 Gbps on-off-keying data reception is demonstrated with clear open eye diagrams in both the C-band and O-band.

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References and links

1. Introduction

A germanium waveguide p-i-n photodetector (WPD) is a critical building block in silicon photonics optical interconnects and has been studied extensively [1-13]. Optical receivers based on high opto-electrical bandwidth, high responsivity and low dark current germanium photodetectors substantially enhance the performance of Si-based optical interconnects. Conventional germanium WPDs require doping in germanium as well as a metal contact on germanium to form the p-i-n junction. Light absorption from the metal contacts on germanium is responsible for a substantial responsivity loss in these devices. In addition, the process to form a metal contact to germanium is less well developed in standard CMOS foundries. In [10], a germanium WPD that does not require doping or contacting of germanium (named Si-LPIN GePD hereafter) was demonstrated showing a very high responsivity of 1.14 A/W at 1550 nm wavelength at -4 V bias. The 3-dB opto-electrical bandwidth was 20 GHz. The high bias voltage of -4 V is however not CMOS compatible. We demonstrated such a Si-LPIN GePD operating at -1 V showing high responsivity over 1 A/W across the whole C-band and a very low dark current of 3 nA [11]. However, the opto-electrical 3-dB bandwidth of the device was transit-time limited to 20 GHz at 1550 nm wavelength.

In this paper, by adopting a 160 nm thin germanium layer to reduce the transit time, the opto-electrical 3-dB bandwidth at -1 V is enhanced to 67 GHz and 44 GHz at 1550 nm and 1310 nm, respectively. The junction capacitance is 6.8 fF at -1 V. Light coupling from the silicon-on-insulator (SOI) waveguide to the germanium waveguide is optimized by adding a poly-Si taper on top of the fully etched Si taper. The measured responsivity at -1 V is 0.74 A/W and 0.93 A/W at 1550 nm and 1310 nm respectively. The dark current is as low as 4 nA at -1 V. These device properties make it an attractive candidate for Si photonics optical interconnects. 56 Gbps on-off keying data reception is demonstrated with clear open eye diagrams at both 1550 nm and 1310 nm wavelength. The opto-electrical 3-dB bandwidth beyond 67 GHz at higher reverse bias enables even 100 Gbps on-off keying optical receivers.

2. Device Design and Fabrication

The Si-LPIN GePDs were fabricated in imec’s fully integrated Si Photonics Platform along with Si modulators [14] and various passive devices [15]. They go through a process flow described in [16]. Light is coupled from a 220 nm thick single-mode Si waveguide to the germanium layer using a fully etched waveguide taper together with a 120 nm thick poly-Si taper on top, as shown in Fig. 1(a). The germanium layer dimensions and doping configuration in the Si-LPIN GePD are shown in Fig. 1(b). The electric field distribution at -1 V obtained by numerically solving Poisson’s equation is shown in Fig. 2(a). In the germanium region, the electric field is stronger than 10^4 V/cm at -1 V, strong enough for photo-generated carriers to drift at their saturation velocity. In [11], a 400 nm thick germanium layer was used in the Si-LPIN GePD, whose opto-electrical bandwidth was limited by the long transit time of the photo-carriers generated in the top part of the germanium, suffering from low drift
velocity as well as long drift distance. The electric field distribution at -1 V of this device is shown in Fig. 2(b) for reference. It can be seen that in the current device, this bandwidth limitation is eliminated by using a 160 nm thin germanium layer. Therefore, a much higher opto-electrical bandwidth can be expected.

Fig. 1. (a) 3-D schematic of the Si-LPIN GePD. (b) Cross-section schematic of the Si-LPIN GePD with a 0.16 μm thick and 0.5 μm wide germanium layer.

3. Device Characteristics

3.1 Static measurements

A typical static current-voltage characteristic of a 14.2 μm long and 0.5 μm wide Si-LPIN GePD is shown in Fig. 3(a). The device exhibits a dark current as low as 2.5 nA and 3.5 nA at -1 V and -2 V. The light current was measured in the C-band at 1550 nm wavelength and in the O-band at 1310 nm wavelength under a received optical power of -5.8 dBm and -2.5 dBm, respectively. The light current is almost constant from 0 V to -2 V owing to the strong built-in electric field that is capable of sweeping out the majority of the photo-generated carriers within their lifetime. The measured responsivity at -1 V is 0.72 A/W and 0.98 A/W at 1550 nm and 1310 nm, respectively.

Fig. 2. (a) Simulated electric field distribution in the Si-LPIN GePD reported in this paper at -1 V. (b) Simulated electric field distribution at -1 V for a Si-LPIN GePD with a 400 nm thick germanium layer. The only difference between the 2 Si-LPIN GePD devices is the germanium layer thickness. The electric field direction is annotated in the graph.

Wafer-scale dark current data of the Si-LPIN GePD are shown in Fig. 3(b). The mean dark current value is 2.4 nA and 3.6 nA, with a standard deviation of 0.4 nA and 0.8 nA, at -1 V and -2 V, respectively. In Fig. 3(c) and Fig. 3(d), contour plots of the wafer-scale
Responsivity data of the Si-LPIN GePD at -1 V at 1550 nm and 1310 nm are shown. The mean responsivity value is 0.74 A/W and 0.93 A/W respectively, with a standard deviation of 0.05 A/W.

Fig. 3. (a) A typical I-V characteristic of a 14.2 μm long and 0.5 μm wide Si-LPIN GePD. (b) Variability plot of the wafer-scale dark current data of the Si-LPIN GePD at -1 V and -2 V. Contour plot of the wafer-scale responsivity data of the Si-LPIN GePD at (c) 1550 nm and (d) 1310 nm at -1 V.

The wavelength dependence of the responsivity in the C-band and O-band at -1.2 V are shown in Fig. 4(a) and Fig. 4(b), respectively. Only responsivity data in 40 nm optical bandwidth are shown, limited by the optical bandwidth of the fiber-to-chip grating coupler used to interface to the photodetector. The device has a higher responsivity in the O-band than in the C-band, due to the relatively short device length (14.2 μm) and the higher modal absorption coefficient in the O-band. The higher modal absorption coefficient in the O-band further results from both the higher modal confinement factor in the germanium layer and the stronger material absorption coefficient in the germanium layer in the O-band. The drop in responsivity in the C-band is mainly due to the decrease of the germanium absorption coefficient at longer wavelength, and can be improved by increasing the length of the device (i.e. the germanium layer).
3.2 Small-signal measurements

Small-signal radio-frequency (RF) measurements were carried out at wafer scale using a 50 GHz Agilent vector network analyzer (VNA) to characterize the high-speed performance of the Si-LPIN GePD. Typical $S_{21}$ transmission parameters as a function of frequency, at 1550 nm and 1310 nm wavelength, using an average input optical power of -6 dBm and -5 dBm are shown in Fig. 5(a) and Fig. 5(b), respectively. At -1 V, the device shows a 3-dB opto-electrical bandwidth of >50 GHz and 45 GHz at 1550 nm and 1310 nm, respectively. The opto-electrical bandwidth is further enhanced to over 50 GHz for both wavelengths as the bias voltage is increased to -2 V. The opto-electrical 3-dB bandwidth data extracted from the wafer-scale measurement $S_{21}$ curves for both wavelengths are shown in Fig. 5(c). At 1550 nm wavelength, the wafer-scale 3-dB bandwidth is over 50 GHz at both -1 V and -2 V bias voltage. At 1310 nm, the wafer-scale 3-dB bandwidth is over 50 GHz at -2 V. At -1 V, the mean 3-dB bandwidth value is 44 GHz with a standard deviation of 2.2 GHz.

The photodiode capacitance of the Si-LPIN GePD was extracted by fitting the real/imaginary part of the $S_{22}$ reflection parameters (measured at wafer scale) based on an equivalent circuit model shown in the inset of Fig. 5(d). In the circuit model, $C_j$ is the capacitance of reverse biased p-i-n junction, and $R_s$ is the series resistance related to the p-i-n junction. $C_{OX}$ and $R_{Si}$ are related to the current path through the silicon substrate and the buried oxide (BOX). $C_m$ represents the metal pad capacitance. The extracted junction capacitance ($C_j$) data and series resistance ($R_s$) data of the Si-LPIN GePD are shown in Fig. 5(e) and Fig. 5(f). The mean junction capacitance value is 6.8 fF and 6.2 fF at -1 V and -2 V, respectively. The mean series resistance value is 103 $\Omega$ and 91 $\Omega$ at -1 V and -2 V, respectively. One example of the experimental and fitted real/imaginary part of the $S_{22}$ parameters is shown in Fig. 5 (d).
The opto-electrical bandwidth of the Si-LPIN GePD was further characterized using a 67 GHz Agilent vector network analyzer (VNA) at 1550 nm wavelength. The measured $S_{21}$ curves using an average input optical power of -5.5 dBm are shown in Fig. 6(a). At -1 V, the device shows a 3-dB opto-electrical bandwidth of ~67 GHz, and the bandwidth is enhanced to beyond 67 GHz as the bias voltage is increased to -2 V and -3 V. The dip around 15 GHz and the fast roll off between 64–67 GHz appearing on the $S_{21}$ curves are attributed to the calibration of the VNA together with RF cables and RF probe used in the experiment. The
impact of the optical input power on the opto-electrical bandwidth of the Si-LPIN GePD was also characterized using an Erbium-doped Fiber Amplifier (EDFA) together with a Variable Optical Attenuator (VOA) to control the input optical power. The measured opto-electrical 3-dB bandwidth as a function of the input optical power is shown in Fig. 6(b).

3.3 Large-signal measurements

On-off keying data transmission experiments were implemented. A (2³¹-1) long optical non-return to zero (NRZ) pseudo random bit sequence (PRBS) data pattern at 50 Gbps and 56 Gbps, generated by a commercial LiNbO₃ modulator at 1550 nm was launched into the Si-LPIN GePD (56 Gbps is the upper limit of the pulse pattern generator operation range). A -1 V bias voltage was applied to the photodetector using a 50 GHz RF probe connected to a 40 GHz bias-tee. The output electrical data was measured with an Agilent infiniium sampling oscilloscope with a 60 GHz remote sampling head plug-in. The 50 Gbps and 56 Gbps reference transmitter eyes at 1550 nm wavelength are shown in Fig. 4(a-b). The electrical eye diagrams from the Si-LPIN photodetector at -1 V are shown in Fig. 4(c-d). The same experiment was also implemented at 1310 nm wavelength as shown in Fig. 5(a-d). The clear open electrical eye diagrams from the Si-LPIN GePD at -1 V indicate the high quality data reception performance of the Si-LPIN GePD at 56 Gbps, in both the C-band and O-band.

4. Discussion and Outlook

The frequency response of the equivalent circuit in Fig. 5(d) exhibits a 3-dB bandwidth of 120 GHz and 140 GHz at -1 V and -2 V assuming a 50 Ω load. Comparing these values to the experimental data reveals that the opto-electrical bandwidth of the Si-LPIN GePD is limited by the carrier transit time instead of the RC-constant. It can be seen from Fig. 2(a) that the photo-carriers will drift along the electric field in a non-linear trajectory before being collected. Moreover, certain photo-carriers will hit the top surface and/or the sidewall of the germanium layer in the drifting. These will increase the transit time compared to a simple case where photo-carriers drift in a straight line.
It can be seen from Fig. 2 that the thicker the germanium layer, the longer the equivalent carrier transit distance of a Si-LPIN GePD device, and thus the lower the opto-electrical bandwidth, as indicated in Fig. 9(a), comparing the experimental $S_{21}$ curves for a germanium layer thickness of 160 nm and 400 nm (with the same the same germanium width of 500 nm). On the other hand, the modal absorption coefficient is larger for a device with a thicker germanium layer due to the larger modal confinement factor in the germanium layer.
Therefore, the Si-LPIN GePD with a 400 nm thick germanium layer has a higher responsivity than that of the device with a 160 nm thick germanium layer (14.2 μm long), as shown in Fig. 9(b). These indicate that the germanium layer thickness can be designed to optimize the opto-electrical bandwidth or responsivity performance of a Si-LPIN GePD device. Furthermore, since the opto-electrical bandwidth is limited by the carrier transit time, the responsivity of the 160 nm thick Si-LPIN GePD can be improved by increasing the length of the device (i.e. the germanium layer) without compromising on the opto-electrical bandwidth.

Fig. 9. (a) Small-signal Si3 transmission parameters as a function of frequency at 1550 nm of the Si-LPIN GePD with a 400 nm thick Ge layer and a 160 nm thick Ge layer. (b) Responsivity as a function of wavelength in the C-band of the Si-LPIN GePD with a 400 nm thick Ge layer and a 160 nm thick Ge layer. The only difference between the 2 Si-LPIN GePD devices is the germanium layer thickness.

5. Conclusion
A 67 GHz germanium waveguide p-i-n photodetector that has neither doping in nor metal contacts on germanium operating at -1 V is reported. The device was characterized in both the C-band and O-band, showing low dark current and high responsivity. 56 Gbps on-off keying data reception is demonstrated. The opto-electrical 3-dB bandwidth beyond 67 GHz at higher reverse bias should enable even 100 Gbps on-off keying optical receivers.

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