Beyond 100 GHz, High Responsivity, Waveguide-Coupled Deeply Recessed Germanium on Silicon Photodiode

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Abstract: *In this work, we report a waveguide deeply recessed Ge/Si photodiode achieving a 3-dB bandwidth of 106 GHz at -2 V along with a high O-band responsivity value of 0.93 A/W.*

Keywords: *Photodetectors, Si/Ge, Photonic integrated circuits*

I. INTRODUCTION

Silicon photonics technology has made great strides in the past decade, finding critical applications in optical communication, high-performance computing, and quantum signal processing [1]. Germanium (Ge), due to its favorable optical absorption properties in the near-infrared spectrum and its compatibility with silicon-based manufacturing, has become a material of choice for high-performance photodetectors in various silicon photonics systems. As the demand for higher data rates grows, opto-electrical (OE) bandwidths exceeding 100 GHz have become sought after to support symbol rates of 200 Gbaud and even 400 Gbaud. The bandwidth of Ge photodetectors (PDs) is generally constrained by two key factors: the transit time through the Ge intrinsic layer and RC parasitic effects. Techniques such as inductive peaking and varied electrode designs have been employed to enhance bandwidth and reduce RC parasitic impacts [2]. On the other hand, shrinking the Ge absorption region width to as low as 100 nm has been achieved yielding a record-breaking bandwidth of 265 GHz [3]. However, this came at the expense of reducing the responsivity of the device and adding extra fabrication process complexity to ensure the realization of such narrow feature and to protect the Ge from unwanted doping that would affect the OE bandwidth (BW).

In this work, we report on a high responsivity Ge/Si photodiode with bandwidth beyond 100GHz, fabricated using a simple integration process, by directly growing the narrow Ge absorption region in a deeply recessed trench inside the Si slab.

II. DEVICE DESCRIPTION

As shown in the Transmission Electron Microscopy (TEM) images illustrated in Fig. 1, the device has a compact Ge absorption region deeply recessed in the silicon slab. The device shown has an average Ge width of around 200 nm which goes down to 150 nm at the bottom and increases to a value of 269 nm on the Si surface. The thickness of the Ge is 193 nm, most of which is recessed inside the silicon slab. The narrow Ge width combined with the deep recess results in reducing the transit time BW and enabling a higher electric field in the Ge for a given voltage, promoting all the absorbed carriers in the Ge to move at their saturation velocities.

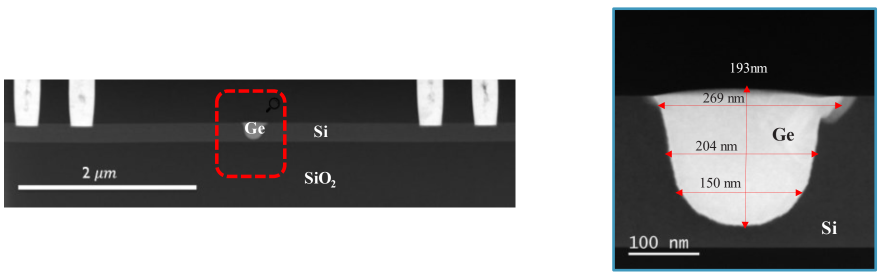
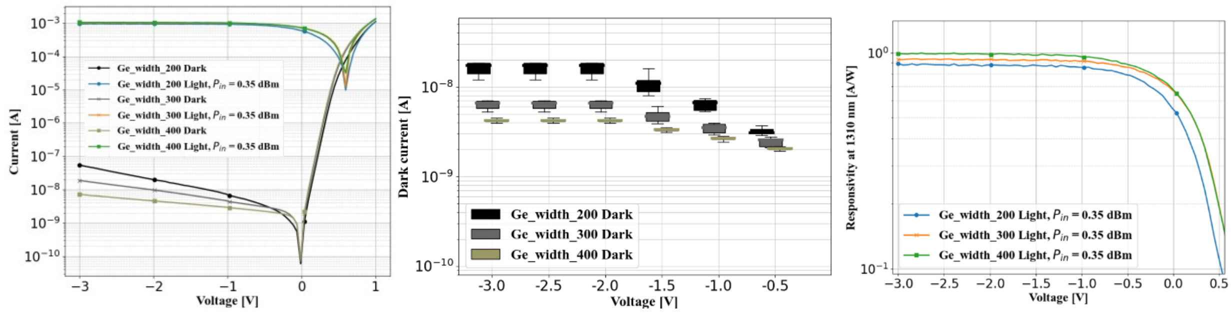


Fig. 1. TEM images of the Ge/Si PD showing the deeply recessed Ge inside the silicon

The device was fabricated in imec's 300-mm silicon photonics platform [4] using 220 nm silicon on insulator (SOI) wafers on top of a 2 μm buried oxide layer. After implantation and anneal of the N and P dopants in the SOI layer, a narrow deeply recessed cavity is formed inside the Si slab in which the Ge is selectively grown.

III. Device Performance

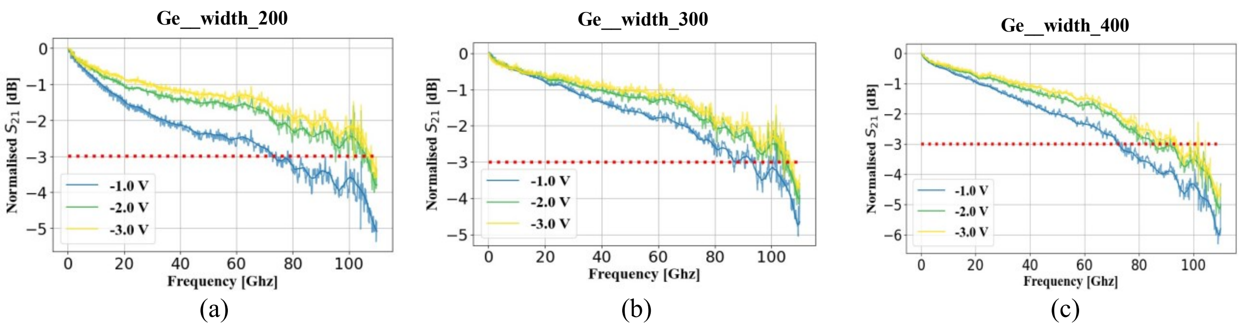
To investigate the effect of the Ge absorption width on the device performance, three devices having Ge widths of 200 nm, 300 nm, and 400 nm were measured. First, the static performance of these devices is characterized by measuring the dark current under no illumination and then measuring the photocurrent as shown in Fig. 2(a). The three devices are named Ge_width_200, Ge_width_300 and Ge_width_400. The measurements were performed at a wavelength of 1310 nm. The light was coupled to the PD through a TE-optimized grating coupler from a single mode fiber. To assess the optical power reaching the device, the grating coupler losses were characterized with a reference waveguide connected to similar grating couplers. Low dark current levels are observed for all three devices. At a reverse bias of -2 V, the dark current level is around 20 nA for the narrowest device and goes down to 6 nA and 4 nA for the 300 nm and the 400 nm devices, respectively. Dark current measurements were also conducted on 10 dies for the three devices distributed across the wafer, and the resulting box plots, shown in Fig. 2(b). The box plots show low variations across the wafer indicating the consistency of the fabrication process across the wafer. To calculate the responsivity, the optical power reaching the device is calculated to be 0.35 dBm. The responsivity, reported in Fig. 2(c), is calculated by dividing the generated photocurrent by the calculated optical power reaching the device. At a reverse bias of -2 V, a high responsivity of 0.88 A/W is achieved for the narrowest device and it goes up to 0.93 A/W and 0.98 A/W for the wider devices of 300 nm and 400 nm, respectively. The build-up of responsivity from 0.55 A/W at 0 V up to 0.88 A/W at -2 V indicates that below -0.5 V, insufficient electric field exists inside the Ge to sweep all the carriers before they recombine.



(a) (b) (c)

Fig. 2. (a) I-V curve of the Ge/Si PD measured for different Ge widths of 200 nm, 300 nm and 400 nm showing dark current and photocurrent at an input power of 0.35 dBm at a wavelength of 1310 nm. (b) Box plots of the dark current measured on 10 dies across the wafer for the 3 devices. (c) Responsivity of the Ge/Si PDs at different reverse bias voltages.

To estimate the 3-dB bandwidth of the different PDs, S_{21} (opto-electric frequency response) measurements were performed on the three devices. The measurements were carried out using a 110 GHz Precision Network Analyzer (PNA) from Keysight accompanied by a 110 GHz modulator from Thorlabs. Fig. 3 shows the normalized S_{21} curves for the different devices measured at different reverse bias voltages. The raw S_{21} data is fitted to calculate the 3-dB BW. For the two devices having widths of 200 nm and 300 nm, a similar BW of around 106 GHz is achieved at -2 V, while it drops down to 85 GHz for the wider device of 400 nm. The similar BWs achieved for the 300 nm and 200 nm wide devices may point to the fact that RC parasitics are limiting the BW in the 200 nm case. This indicates that further increase in BW could be achieved for the narrowest device. To characterize the variations across the wafer, 6 different dies were measured (Fig. 4). Wider devices of 300 nm and 400 nm show small variations at different bias points while the 200 nm device show some outliers at -1 V & -2 V.



(a) (b) (c)

Fig. 3. Normalized S_{21} small signal frequency response of the Ge/Si PD with a Ge width of (a) 200 nm, (b) 300 nm, and (c) 400 nm.

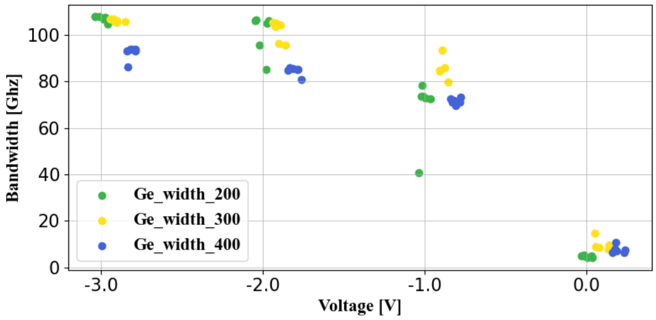


Fig. 4. 3-dB BW measured for the Ge/Si PD with different Ge widths of 200 nm, 300 nm and 400 nm on 6 different dies across the wafer.

IV. Benchmarking and Conclusion

A Ge/Si PD achieving a BW of 106 GHz at -2 V accompanied by a high responsivity value of 0.93 A/W and low dark current of less than 10 nA was demonstrated. The device was fabricated by deeply recessing a Ge absorption region inside the Si slab to a depth of 190 nm. Cross wafer measurements were made showing small variations promoting the uniformity of the used fabrication process. Table 1 shows how our device stands in comparison to recent state of the art Ge/Si PDs. Apart from [3], the device shows comparable performance in terms of 3-dB bandwidth without relying on inductive peaking like the case in [2]. The devices also demonstrate low dark current levels and high responsivity values, meaning no compromise is made to achieve >100 GHz BW. These specs enable the presented Ge/Si devices to be used in applications targeting 200 GBd and beyond.

Table I
Benchmarking of recent wave guide coupled Ge/Si PDs

Reference	Architecture	λ [nm]	V [V]	I_{dark} $[nA]$	Responsivity [A/W]	3-dB BW [GHz]
[3]	Lateral	1550	-2	100	0.45	240
[2]	Vertical	1550	-1	1.5	0.95	103*
[5]	Lateral	1550	-2	4000	0.8	120
[6]	Lateral	1550	-2	300	0.64	110
This Work	**Lateral**	**1310**	**-2**	**6**	**0.93**	**106**

* Inductive peaking used to push the BW from 83 GHz to 103 GHz

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