70 GHz, 2 A/W, Waveguide-Coupled Germanium-in-Silicon Avalanche Photodiode

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Abstract *In this work, we report a waveguide Ge/Si avalanche photodetector achieving high 3dB-bandwidths of 70 GHz and 50 GHz at an O-band responsivity of 2 A/W and 3.6 A/W, respectively, combined with sub-µA dark current performance in a simple, Si-contacted lateral diode design.*

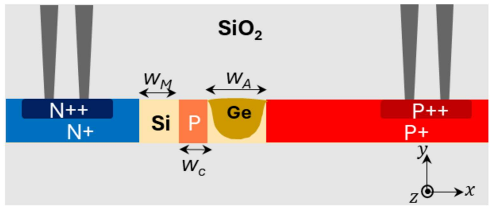
Introduction

With the recent exponential growth of global data traffic driven by applications such as datacenters, internet of things (IoT), and artificial intelligence (AI) requiring high-speed optical transceivers, Silicon Photonics (SiPho) has emerged as a critical technology, offering a promising solution to enable the necessary performance and scalability [1]. For SiPho transceivers, avalanche photodiodes (APDs) have gained a lot of interest as they offer the capability of achieving high speeds combined with high sensitivity for detecting low power optical signals conserving the link budget. APDs based on Germanium on Silicon (Ge/Si) are at the forefront of this interest due to the compatibility of Ge with the well-established complementary metal-oxide-semiconductor (CMOS) technology enabling the possibility of large-scale and high-yield production [2]. One of the most intensively studied APD structures is the separate absorption, charge, and multiplication (SACM) layer structure where the charge layer separates the multiplication and the absorption regions. The absorption occurs in Ge, while multiplication occurs in Si utilizing its low impact ionization coefficient [3]. Waveguide coupled SACM (WG-SACM) APDs have been realized using vertical and lateral configurations. In the vertical configuration, at least an extra epitaxy step of silicon is required, to act as the multiplication layer. Along with the need for Ge contacts, this adds an extra level of cost and fabrication complexity for those devices. Nevertheless, they can achieve high bandwidth (BW)/high gain operation combined with low dark current [4]. The lateral configuration, on the other hand, is easier to fabricate as it only requires a single Ge epitaxy step and does not need contacts on Ge.

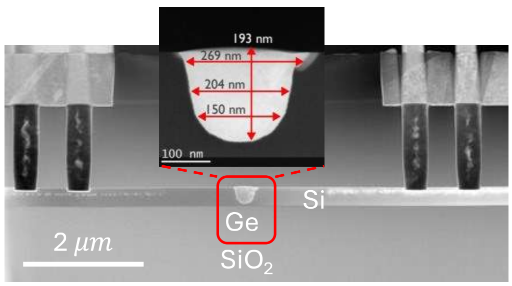
Previously we reported the results of our lateral WG-SACM APD fabricated on imec's 300-mm silicon on insulator (SOI) platform, which achieved a responsivity of 2 A/W at a BW of 35 GHz [5]. In this paper, the results of our new optimized lateral APD are presented, achieving high BWs values of 70 GHz and 50 GHz at an O-band responsivity of 2 A/W and 3.6 A/W, respectively. These results are achieved thanks to the new device structure in which a 200 nm wide Ge absorption region is deeply recessed inside the silicon waveguide, thereby enhancing its transit-time limited BW.

Device Structure

The cross section of the reported APD, shown in Fig. 1 (a), illustrates the WG-SACM structure having a lateral p^+-i-p-i-n^+ junction where the lightly doped p-region, having a width w_c of 75 nm, acts as the charge layer separating the i-Ge and i-Si. The i-Si region acts as the multiplication layer. Its nominal width w_M is 100 nm. As shown in the Transmission Electron Microscopy (TEM) image, Fig. 1(b), the device consists of a compact Ge absorption region deeply recessed in the silicon waveguide, with an average width W_A of 204 nm and a thickness of 193 nm, most of which is recessed in Si. The narrow Ge width combined with the deep recess results in a higher electric field in the Ge for a given voltage, consequently increasing the transit-time limited BW. The electric field profile is simulated at a voltage of -7 V using a Technology Computer Aided Design (TCAD) tool, Fig .2. The simulation shows an average electric field value of more than $10^5\ V/cm$ across the Ge, which is enough to accelerate all the carriers out of Ge at their saturation velocities. The device length is 10 µm, which is sufficient to reach the maximum primary responsivity at 1310 nm. The APDs are fabricated on imec's 300-mm SiPho platform using wafers with 220 nm SOI thickness on top of a 2 µm buried oxide layer [6].



(a)



(b)

Fig. 1: (a) Cross-section view of the lateral WG-SACM APD. (b) TEM image of the APD showing the deep recessed Ge in Si.

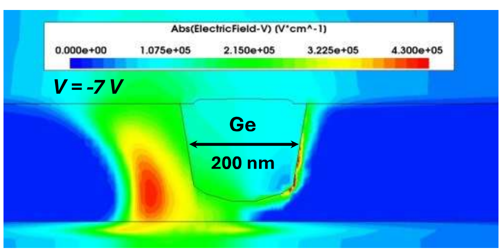
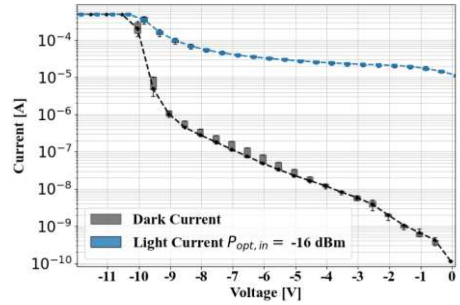


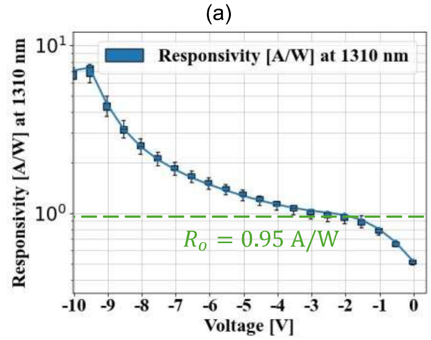
Fig. 2: Simulated electric field profile at a voltage bias of -7 V.

DC Performance

Fig. 3. (a) shows the wafer scale I-V characteristics of the APDs measured on 10 dies across the wafer with the median line going across the box plots. The dark current was first measured with no input optical power and then the photocurrent was measured at an input power level of -16 dBm reaching the APD as the optical losses from the grating coupler are calculated using a reference waveguide. The measurements were carried out at a wavelength of 1310 nm. The breakdown voltage (V_{br}) of the APD, defined as the voltage at which the dark current reaches 10 μA, is about -9.5 V. The dark current value remains below $1\mu A$ up until -9 V with small within-wafer variations ($\pm\, 0.1\, \mu A$). The responsivity, shown in Fig. 3(b), is subsequently determined by subtracting the dark current from the light current and dividing the result by the input optical power. The average primary responsivity (R_o) is 0.95 ± 0.05 A/W at a bias voltage of - 2V. For an input power of -16 dBm, the responsivity reaches an average peak value of 7 ± 0.5 A/W at a voltage of -9.5 V and a responsivity of 4.5 ± 0.25 A/W is achieved at 0.95* V_{br} (-9 V).



(a)



(b)

Fig. 3: (a) IV curves of the Ge-on-Si SACM APDs measured on 10 dies across the wafer for dark current and generated photo current at an input optical power level of -16 dBm at a wavelength of 1310 nm. (b) Extracted responsivity of the APDs at a power level of -16 dBm and a wavelength of 1310 nm.

High Speed Performance

The small signal RF performance of the APD has been characterized using a 110 GHz Precision Network Analyzer (PNA) from Keysight accompanied by a 110 GHz modulator from Thorlabs. Fig. 4(a) shows the normalized S_{21} (opto-electric frequency response) curves measured for the APD at various voltage levels. The raw S_{21} data are fitted to calculate the 3-dB BW. The RF measurements were also carried out at an optical input power level of -16 dBm. Fig. 4(b) and (c) show the 3-dB BWs vs voltages and gain values respectively as extracted from the S_{21} curves. At -7 V bias, a BW of 70 GHz is achieved with a gain of around 2.2, which corresponds to a responsivity of around 2.1 A/W. At -7.5 V bias and beyond, the BW starts decreasing as the avalanche build up time [7] starts dictating the BW response, resulting in a BW of around 50 GHz at -8.5 V, with a gain of 3.8 corresponding to a responsivity of 3.6 A/W. The large signal response of the APD is then measured using a pseudorandom binary sequence (PRBS) signal with pattern length of 2^{31}-1 (PRBS31) at a data rate of 70 Gbps using a Non-Return-to-Zero On-Off Keying (NRZ-OOK) modulation format (Fig. 5). The generated signal was fed to a lithium niobate ($LiNbO_3$) modulator with an optical input at a wavelength of 1310 nm. The input optical signal is first measured using a reference PD having a BW of 70 GHz, input optical eye in Fig. 5.

To characterize the APD, 2 power levels were used, -10 dBm and -15 dBm. A variable optical attenuator (VOA) was used to attenuate the input optical power to the desired value that would reach the APD considering the losses from the grating coupler. The eye diagrams were measured at two bias voltages of -7 V and -8.5 V corresponding to responsivity values of 2.1 A/W and 3.6 A/W respectively. Open eyes are visible in all the measurements conditions.

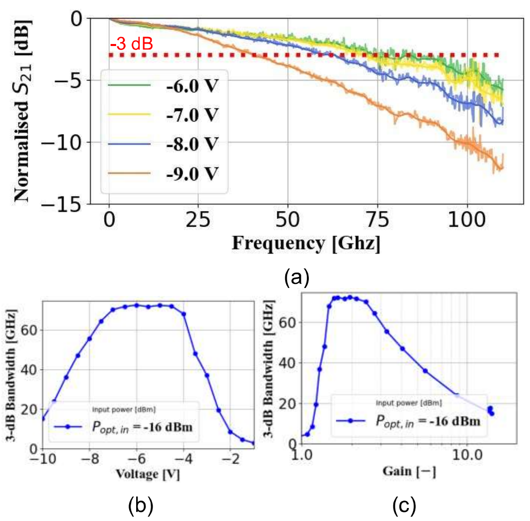


Fig. 4: (a) Small signal RF measured S_{21} curves of the APD at different bias voltages. (b) Extracted 3-dB opto-electrical BW from S_{21} curves. (c) Gain vs BW curve for the APD.

Benchmarking and Conclusion

We have demonstrated a WG-LSACM APD able to reach BWs of 70 GHz and 50 GHz at O-band responsivity values of 2.1 A/W and 3.6 A/W respectively, implemented in a 300-mm SiPho platform using only silicon contacts. Tab. 1 shows a comparison of the reported APD to other recently published Ge/Si APDs, illustrating that the reported APD achieves a state of the art performance combining low dark current, relatively low operating voltage, with high primary responsivity and a record high BW of 70 GHz. This high BW value is achieved without using the negative differential resistance effect to boost the BW [8] which is typically accompanied by high dark current levels ($> 100\,\mu A$) [9] that degrade the APD sensitivity, increase its power consumption and shot noise.

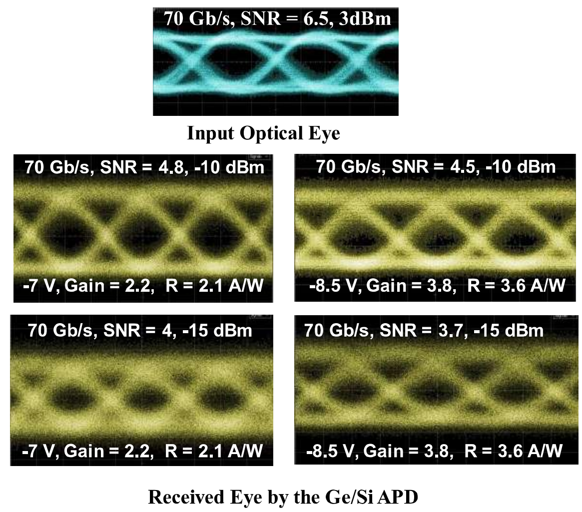


Fig. 5: On wafer eye diagram measurements for the Ge-on-Si APD at a data rate of 70 Gb/s at input power levels of -10 dBm and -15 dBm.

Acknowledgement

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Tab. 1: Benchmarking of recent Ge/Si APDs

Ref.	Architecture	$\lambda\ [nm]$	V [V]	$I_{dark}\ [\mu A]$	P_{opt} $[dBm]$	Primary Responsivity [A/W]	Responsivity [A/W]	3-dB BW [GHz]
[4]	WG-VSACM*	1310	-17 -18	0.1 0.2	-13	0.6	3.6 6	42 36
[9]	WG-LSACM**	1550	-9.5 -10.5	200 700	-15	0.77	5 4	49 67
[10]	WG-LSACM	1310	-10 -14	0.3 100	-15	0.93	4 11.9	27 48
[11]	WG-VSACM	1310	-12.6	1.4	-17	0.57	3.5	45.8
This Work	**WG-LSACM**	**1310**	**-7** **-8.5**	**0.1** **0.4**	**-16**	**0.95**	**2** **3.6**	**70** **50**

*WG-VSACM: Waveguide Coupled Vertical Separate Absorption Charge Multiplication

**WG-LSACM: Waveguide Coupled Lateral Separate Absorption Charge Multiplication

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