Low Dark Current and High Responsivity Si-contacted Ge-on-Si Avalanche Photodetectors in a 300-mm Si Photonics Platform

Mathias Berciano(1),*, Chiara Marchese(1), Hakim Kobbi(1), Rafal Magdziak(1), Javad Rahimi Vaskasi(1), Peter Verheyen(1), Roger Loo(1), Filippo Ferraro(1), Yoojin Ban(1), Maumita Chakrabarti(1), Dimitrios Velenis(1), Joris Van Campenhout(1)

(1) imec, Kapeldreef 75, 3001, Heverlee, Belgium, *mathias.berciano@imec.be

Abstract *We report the 300-mm wafer-scale performance of Silicon-contacted Ge-on-Si lateral separate absorption charge multiplication avalanche photodetectors, demonstrating sub-μA dark currents consistently across the wafer, with responsivities of 6 A/W at 22 GHz bandwidth or 2 A/W at 35 GHz.*

Introduction

Silicon Photonics (SiPho) is emerging as a key technology covering an extensive range of applications such as datacom, telecom, and sensing[1]. By exploiting the mature Complementary Metal Oxide Semiconductor (CMOS) processing techniques, high-volume, low-cost and high-yield Photonic Integrated Circuit (PIC) products are introduced in various markets. Optical transceivers for high-bandwidth networking for telecom, cloud datacenters and in high-performance compute clusters are prime applications currently driving the development of SiPho.

Highly sensitive receivers based on Avalanche Photodetectors (APDs) offer an attractive option to improve the link budget in optical links, leveraging the high internal gain realized in the APDs[2]. In Separate Absorption Charge Multiplication (SACM) APD architectures, Ge is used for the absorption layer and Si for the multiplication layer, leveraging the lower k-ratio offered by Si to realize a low excess noise factor[3],[4]. Both lateral[5]–[8] and vertical[9]–[11] SACM Ge-on-Si APDs have been reported in literature the past 15 years, aiming at high-bandwidth, high responsivity, low dark current and low noise devices with high reliability.

In this paper, we report on the wafer-scale performance of Silicon-contacted Ge-on-Si lateral SACM (LSACM) avalanche photodetectors, seamlessly co-integrated in a 300-mm SiPho platform along with best-in-class Si ring modulators[12],[13], low-loss Si Wavelength Division Multiplexing (WDM) filters[14], and various other components required for implementing Tbps/mm WDM optical transceivers targeting next-generation optical I/O in AI/ML systems[15]. The LSACM APDs have wafer-scale responsivities of 6 ± 2 A/W at 22 GHz bandwidth or 2 ± 0.2 A/W at 35 GHz bandwidth, enabling future high-sensitive receivers at 32 Gbps or 50 Gbps NRZ lane rates respectively, ideally suited for realizing widely parallel, low-power WDM interconnects in AI/ML systems. Low dark current, below 100 nA and 600 nA respectively, are consistently measured across the wafer, signifying a robust integration process and providing a positive outlook for ongoing reliability studies.

Device design and process flow

The Ge-on-Si avalanche photodetectors are 15 μm long lateral p-i-p-i-n diodes fabricated in imec‘s 300-mm Silicon Photonics platform[16],[17], using Silicon-On-Insulator (SOI) wafers with 220 nm Si on top of 2 μm-thick Buried Oxide (BOX). A cross-section view of the final device is shown in Fig. 1. First, various Si patterning steps were performed to precisely shape the waveguides using 193-nm immersion lithography, followed by p-type and n-type Si implantations to form the various p-n junctions in Si. Ge was then selectively grown on top of Si using Selective Epitaxial Growth (SEG) followed by Chemical Mechanical Polishing (CMP) to form the waveguide-based avalanche photodetector. Standard Tungsten contact plugs landing on doped Si were then processed, followed by a deposition of 1 μm-thick Cu metal lines as first metal layer in the Back-End-Of-Line (BEOL). A second metal layer connected to the first by Vertical Interconnect Accesses (VIAs) was then processed before deposition of Al to create metal bond pads for device characterizations.

Wafer-scale DC characterization

The APDs were characterized at room temperature using a wafer prober station for wafer-scale DC and RF opto-electrical measurements. The test setup included a tunable wavelength laser

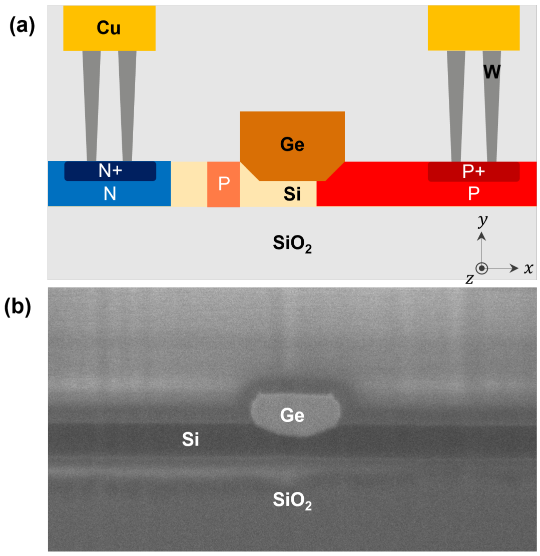

Fig. 1: Cross-section view schematics (a) and SEM image on Ge (b) of the lateral SACM APDs.

source, a polarization controller to optimize light coupling into the integrated waveguides through Fiber Grating Couplers (FGCs), and a power sensor. A source meter was also used to apply DC bias to the devices by means of Ground-Signal (GS) probes landing on Al-based metal bond pads.

Two successive I-V sweeps were performed with laser off and then on, in order to collect dark and light current respectively. A 0.5 mA current compliance was applied during the measurement campaign. Throughout the measurements, the input optical power at the APD under test was kept at an estimated -15 dBm (about 30 µW) at 1310 nm wavelength. Typical dark and light I-V curves are shown on Fig. 2, illustrating a sharp avalanche breakdown for applied voltages lower than -13 V.

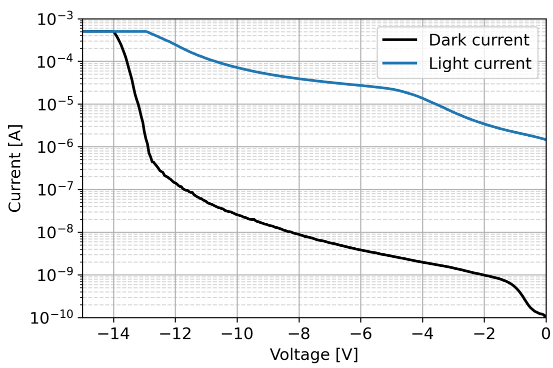

Fig. 2: Example of experimental dark and light I-V sweeps of the lateral APDs.

The wafer-scale dark current and responsivity (at 1310 nm wavelength) data across 14 dies are shown on Fig. 3 and Fig. 4 respectively. Median responsivity values up to 13 A/W could be achieved at -13 V applied voltage, while 6 A/W median responsivity could be obtained at -12 V together with sub-µA dark current level.

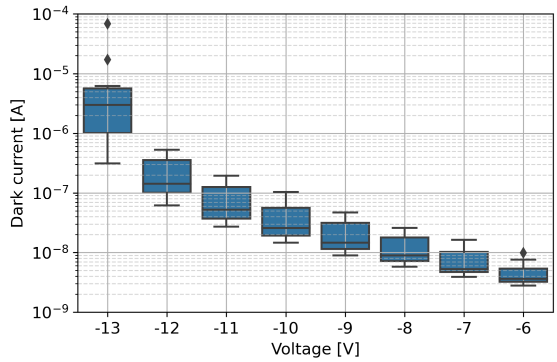

Fig. 3: Wafer-scale dark current measurement results across 14 dies.

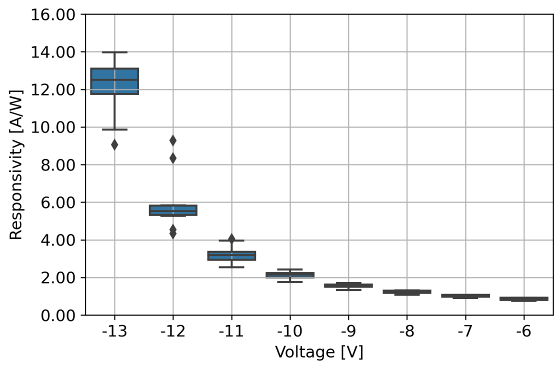

Fig. 4: Wafer-scale responsivity measurement results at 1310 nm wavelength across 14 dies.

RF characterization

The 3-dB bandwidth of lateral APDs was extracted at room temperature from small signal opto-electric S-parameters measurements, using a 50 GHz Lightwave Component Analyzer (LCA). Typical raw S_{21} data are shown on Fig. 5.

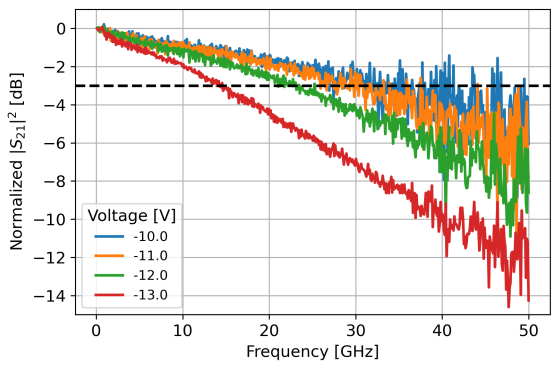

Fig. 5: Example of S_{21} measurement results for different applied DC voltages.

The 3-dB cut-off frequency (or 3-dB bandwidth) was directly extracted from the square magnitude $|S_{21}|^2$ for each and every applied DC voltage. The results across 3 dies are shown on

Tab. 1: Summary results of the reported Ge-on-Si lateral SACM APDs and comparison with recent literature.

Ref.	Voltage [V]	Dark current [µA]	Wavelength [nm]	Optical power [dBm]	Responsivity [A/W]	Bandwidth [GHz]
[5]	-12	100	1310	-14	8	27
[5]	-12	100	1310	-20	25	27
[7]	-5	5.5	1310	-15	3	31.4
[7]	-5	5.5	1310	-23	26	32.3
[8]	-10	0.3	1310	-15	4	27
This work	-10	0.03 ± 0.03	1310	-15	2 ± 0.2	35 ± 2
This work	-12	0.15 ± 0.2	1310	-15	6 ± 2	22 ± 1

Fig. 6. Bandwidth values of 35 GHz and 22 GHz were achieved, at -10 V and -12 V applied DC voltages respectively. When increasing the applied reverse voltage to -13 V, the bandwidth drops down to 13 GHz (at -13 V) owing to the increase in avalanche buildup time as the multiplication gain increases[18]. A summary of the DC and RF results can be found in Tab. 1, illustrating the competitive dark currents of our LSACM APDs when compared with recent state-of-the-art reports, at similar responsivity and bandwidth levels (for comparable input optical power).

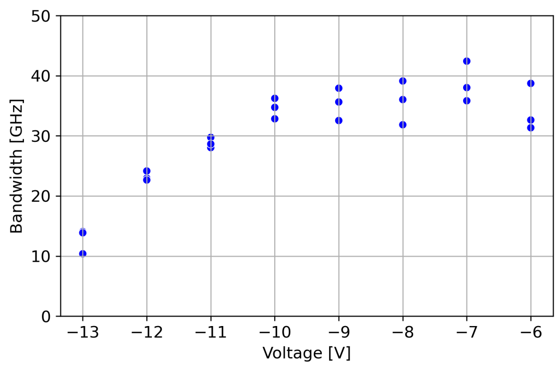

Fig. 6: Bandwidth measurement results at 1310 nm wavelength across 3 dies.

Conclusions

We reported the wafer-scale integration of low dark current and high-responsivity Si-contacted Ge-on-Si lateral SACM waveguide APDs in a 300-mm SiPho platform, along with high-performance Si (ring) modulators and high-end passive devices as required for optical interconnects for next-generation AI/ML compute systems. At -15 dBm input optical power, the LSACM APDs have responsivities of 13 A/W for 13 GHz bandwidth, 6 A/W for 22 GHz bandwidth or 2 A/W for 35 GHz bandwidth. Importantly, the APDs operate with much lower, sub-µA dark current levels as compared to previous reports, and with low variability across the wafer. Not requiring any metal contacts to Ge or dedicated Si epitaxial growth, the LSACM APDs are an attractive alternative over more conventional vertical SACM designs.

Acknowledgements

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