Highly Sensitive 56 Gbps NRZ O-band BiCMOS-Silicon Photonics Receiver using a Ge/Si Avalanche Photodiode

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Abstract: A hybrid BiCMOS-Silicon Photonics receiver with a waveguide-coupled Ge/Si avalanche photodiode is demonstrated with OMA sensitivities of -14.4dBm for error-free operation at 50 Gbps and -18.6 dBm under the KP4-FEC limit at 56 Gbps NRZ-OOK.

OCIS codes: (040.1345) Avalanche photodiodes, (130.3120) Integrated optics devices, (060.4510) Optical Communication

1. Introduction

With 400Gb/s optical transceivers starting to emerge in today's cloud datacenters, the development of next-generation transceivers operating at 800Gb/s and 1.6Tb/s is becoming imminent [1]. For such high-data-rate optical links, improving link margins is of key importance, either to increase the reach of the link or to reduce the number of required lasers and their associated cost and power consumption. To achieve this, avalanche photodiodes (APDs) have shown potential to enable higher receiver sensitivities and improved optical link margins operating at 50 Gbps and beyond data rates [2]. In this paper, a receiver comprising a silicon photonics waveguide-coupled Ge/Si APD, wirebonded to a SiGe BiCMOS transimpedance amplifier (TIA) is presented. The receiver has an optical modulation amplitude (OMA) sensitivity of -18.6 dBm under the KP4-FEC limit at 56Gb/s NRZ-OOK, and -14.4 dBm running error-free at 50 Gb/s NRZ-OOK. To the best of our knowledge, this is among the highest reported sensitivities for Ge/Si APD-based receivers, while consuming just 140 mW.

2. Device fabrication and performance

The waveguide coupled Ge/Si APDs presented in this work were fabricated using imec's 200 mm Silicon Photonics Platform along with other passive and active waveguide components [2-3]. The devices use a lateral separate-absorption-charge-multiplication (SACM) implementation [2], with an epitaxial Ge waveguide acting as the absorption layer, and the charge and multiplication regions implemented in the 220nm Si device layer. A cross-sectional schematic of the device can be found in the inset of Fig 1. The doping profiles for the charge region in the device were optimized to have high electric fields in the multiplication region, while maintaining sufficient electric field in the absorption region to extract the photo-generated carriers. The device is coupled to a 220 nm thick Si waveguide using low-loss poly-Si tapers, and a grating coupler for TE polarization with peak coupling at 1310 nm was used for fiber-to-chip optical coupling. Fig. 1 shows the wafer-scale statistics of the APD's responsivity and dark current when illuminated at 1310 nm with an input optical power of -20 dBm. The operating bias voltage range is limited to -13V, beyond which the device fails catastrophically [4]. The small-signal characteristics of the device were also measured, and the extracted 3 dB opto-electrical bandwidth (f_{3dB}) are shown in Fig. 2. From the increase in measured RF power at increasing operating bias, we extract a multiplication gain (M) of 10. The resulting gain-bandwidth-product (GBP) of the device is 300 GHz at -13 V.

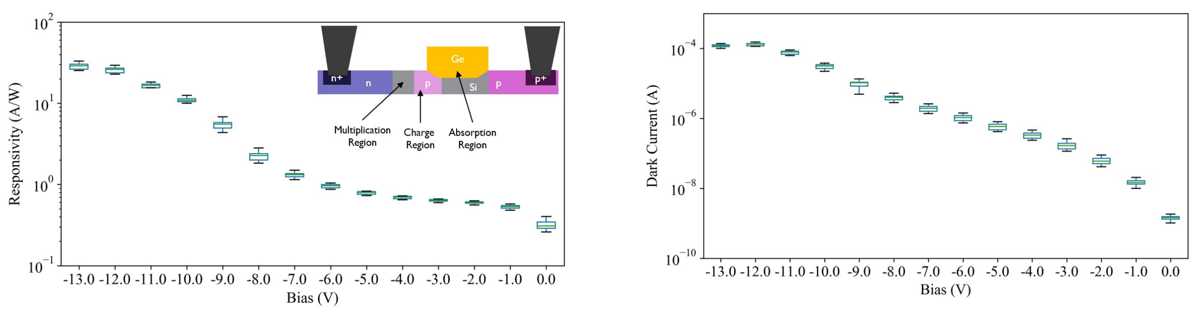

Fig.1 Wafer-scale responsivity and dark current measured from Ge/Si APD across 30 dies in a 200 mm wafer, with a cross-sectional schematic of the device in the inset [2]. The measurement was performed at 1310 nm and at an optical power of -20 dBm.

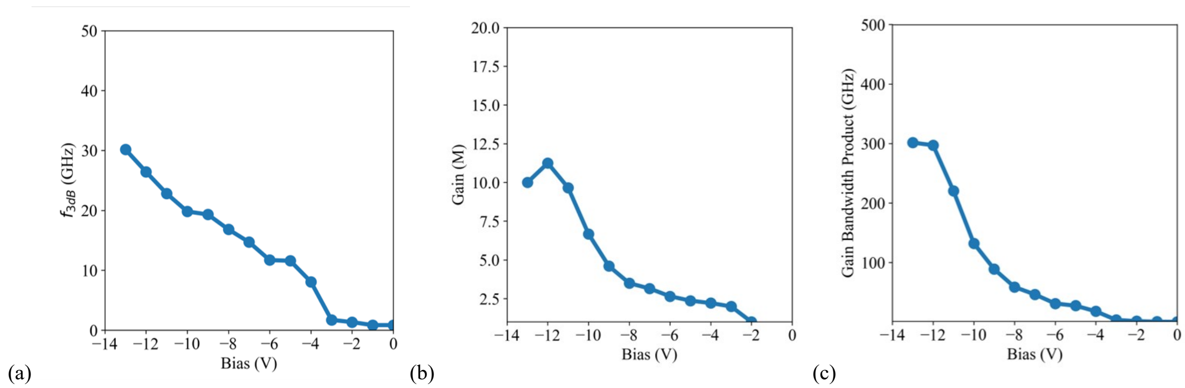

Fig.2. (a) Measured 3dB opto-electrical bandwidth (f_{3dB}), (b) avalanche multiplication gain (M) and the estimated (c) gain-bandwidth product from small-signal measurements.

3. Experiment setup and results

The TIA chip in the receiver presented in this work was fabricated in a 55 nm SiGe BiCMOS technology. Nominally, it consumes 140 mW for 50-56 Gb/s operation. However, at the cost of maximum 2dB sensitivity penalty, its power consumption can be reduced further down to 1.8-2 pJ/bit (100 mW) [4]. The TIA chip and the APD were wirebonded to a test PCB as seen in Fig. 3 (a). The APD supply voltage was set to -10.5 V, which resulted in -10 V effective reverse bias over the device. Fig. 3 (b) shows the experimental setup used for the bit-error-rate measurements. A 92 GSa/s arbitrary waveform generator (AWG) was used to generated 50 Gb/s and 56 Gb/s 2^{15}-1 pseudorandom binary (PRBS) input signals in NRZ-OOK modulation format. A 1310 nm laser was modulated by a 35GHz Mach-Zehnder Modulator driven by a 50 GHz RF amplifier. The optical eye sent to the silicon photonics receiver was measured using a 70 GHz DC-coupled reference photodetector. The measured extinction ratio was 7.5 dB for all data rates. The BER was measured by a SHF 11100B error analyzer (EA).

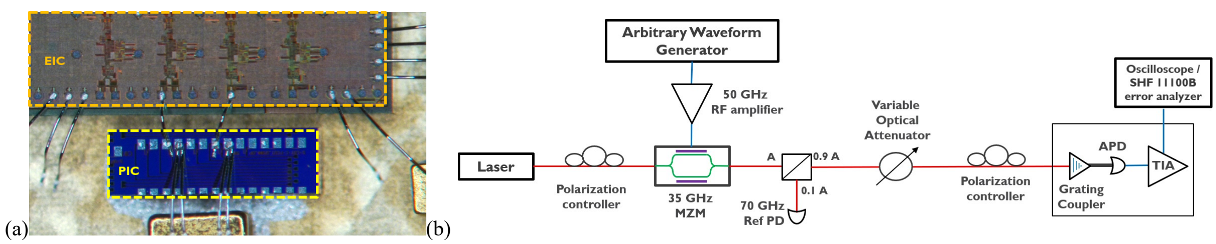

Fig. 3. (a) An optical micrograph of TIA and APD wirebonded to a test PCB. (b) Experimental setup used to estimate the sensitivity of the receiver.

Fig. 4 shows the measured transmitted optical eye from the MZM and the eye from the receiver with APD through the TIA. The BERs plotted vs the received OMA are shown in Fig. 5. The OMA is referred to the input waveguide of the APD using the measured average photocurrent at -3 V where the responsivity is accurately measured. Fig. 5 shows that the receiver has the potential to operate error-free (BER<10^{-12}) with an OMA sensitivity of -14.4 dBm and -11.6 dBm for 50 Gbps and 56 Gbps NRZ-OOK modulation respectively. Compared to a standard Ge/Si p-i-n photodiode, wirebonded to the same TIA as reported in [4], the APD receiver shows a sensitivity improvement of ~1.8 dB for BER=10^{-12} at 50 Gbps data rates, while matching the same OMA sensitivity at 56 Gbps. Under the KP4-FEC limit, the APD receiver has a sensitivity improvement of 4.4 dB and 3 dB for 50 Gbps and 56 Gbps respectively compared to the p-i-n photodiode.

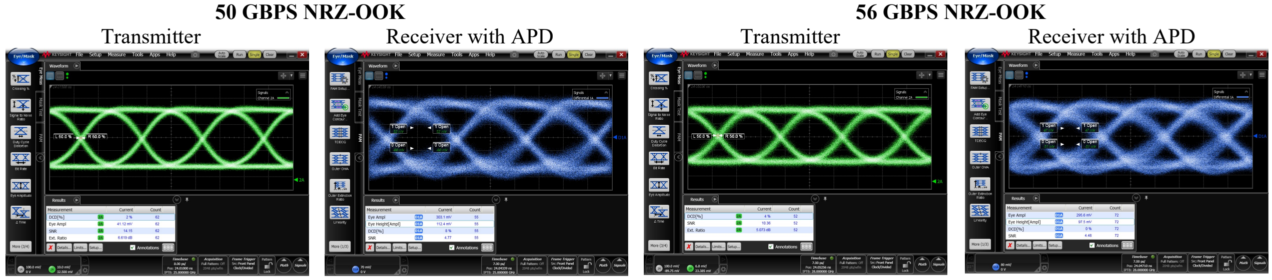

Fig 4. Optical and electrical eyes of the transmitter and receiver with the Ge/Si APD at 50 Gbps and 56 Gbps NRZ-OOK data rates.

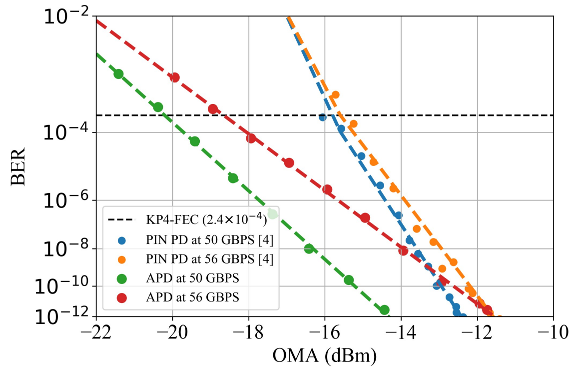

Fig. 5. BER measured with an error detector. The APD was biased at -10 V and measured at 1310 nm, whereas the p-i-n PD in [4], was measured at 1550 nm.

It should be noted that receivers with standard Ge/Si p-i-n photodiode and reported in [4] were measured in the C-band, whereas the APDs in this work were measured at O-band. In Table I, we compare our BER results with current state-of-the-art Ge/Si based APDs. On comparing with other published results, our receiver achieves some of the best sensitivities for KP4-FEC BER limits.

Table I: Benchmarking with selected prior published Ge/Si APD-based receivers at 1310 nm.

Ref	Device type	Data rate	Voltage (V)	Dark Current (A)	Gain (M)	BW (GHz)	OMA sensitivity
[5]	Fiber coupled	53.125 Gb/s	-11.38	3×10^{-6}	7	20	-16 dBm, KP4-FEC
[6]	Waveguide coupled	56 Gb/s	-3.95	NA	NA	>20	-12 dBm, BER=2×10^{-5}
This work	Waveguide coupled	56 Gb/s 50 Gb/s	-10 -10	3×10^{-5} 3×10^{-5}	10 10	20 20	-18.6 dBm, KP4-FEC -14.4dBm, BER = $1\text{x}10^{-12}$

4. Conclusion

A silicon photonics receiver consisting of a waveguide integrated Ge/Si avalanche photodiode wirebonded to TIA fabricated in 55 nm SiGe BiCMOS technology is presented. The receiver operates at O-band and has an OMA sensitivity of -18.6 dBm under the KP4-FEC limit at 56 Gb/s and -14.4 dBm running error-free at 50 Gb/s NRZ-OOK. The APD enables a sensitivity improvement of 1.8 to 4.4 dB when compared to a standard Ge/Si p-i-n photodiode. A receiver with such a device has the potential in improving optical link margins for 400 GbE and beyond applications.

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References

[1] 2018 Ethernet Alliance Roadmap – www.ethernetalliance.com
[2] S.A. Srinivasan, et al. "Silicon-contacted waveguide integrated Ge/Si avalanche photodiode with 32 GHz bandwidth and multiplication gain >8." *European Conference on Optical Communication (ECOC)*, 2019.
[3] M. Pantouvaki, et al. "Active components for 50 Gb/s NRZ-OOK optical interconnects in a silicon photonics platform." *Journal of Lightwave Technology* 35.4: 631-638, 2017.
[4] J. Lambrecht, et al. "90-Gb/s NRZ Optical Receiver in Silicon Using a Fully Differential Transimpedance Amplifier." *Journal of Lightwave Technology* 37.9: 1964-1973. 2019.
[5] S. Park, et al. "50-Gbps Receiver Subsystem using Ge/Si Avalanche Photodiode and Integrated Bypass Capacitor." *2019 Optical Fiber Communications Conference and Exhibition (OFC)*. IEEE, 2019.
[6] A. Samani, et al. "Highly Sensitive, 112 Gb/s O-band Waveguide Coupled Silicon-Germanium Avalanche Photodetectors." *Optical Fiber Communication Conference*. Optical Society of America, 2019.