A 112 Gb/s all-silicon micro-ring photodetector for datacom applications

Meer Sakib, Peicheng Liao, Ranjeet Kumar, Duanni Huang, Guan-lin Su, Chaoxuan Ma, and Haisheng Rong
Intel Corporation, 2200 Mission College Blvd, Santa Clara, CA 95054
meer.nazmus.sakib@intel.com

Abstract: We demonstrate an all-silicon micro-ring resonant photodetector with a responsivity of 0.23 A/W and dark current <100nA capable of detecting 112 Gb/s PAM4 signal with an eye closure penalty of <1.0 dB.

OCIS codes: (250.0250) Optoelectronics, (250.0040) Detectors

1. Introduction

Silicon photonics technology has proved to be the platform of choice of low-cost photonic integration for high speed optical interconnect and data communications [1]. Optical detection of high-speed signals in silicon photonic integrated circuits is usually achieved by using Germanium (Ge) or Indium Phosphide (InP) photodetectors, which requires Ge growth or heterogeneous integration of expensive compound semiconductors on silicon with added material costs and process complexity. Recently, silicon-based waveguide photodetectors (Si-PD) for power monitoring and high-speed detection have been demonstrated [2-9] in both straight waveguide and ring resonator configurations. Compared to a straight silicon waveguide PD [3-6], a ring resonator-based Si-PD has the advantages of lower dark current and capacitance due to its smaller size [7, 8]. The optical resonant enhancement effect in the ring cavity makes it possible to achieve responsivity comparable to a longer straight waveguide PD, resulting in better overall signal-to-noise ratio. In addition, such resonant-type photodetectors are wavelength sensitive and can serve simultaneously as a wavelength filter in a wavelength division multiplexing (WDM) system. Despite these advantages, all the reported time domain measurements of the ring silicon PD's have limited data rate of 35-40 Gb/s with < 0.05 A/W responsivity [7, 8]. Here we report the first demonstration of a 112 Gb/s (56 GBaud PAM4) all-silicon micro-ring photodetector (MRPD) with responsivity > 0.23 A/W and an eye closure penalty (ECP) of <1.0 dB.

2. Device description and characterization

The silicon micro-ring photodetector consists of a 10 µm radius ring resonator with a PN junction occupying 71% of the ring circumference. The rest of the ring is dedicated to a heater for its resonance tuning and control. These devices were fabricated using Intel's silicon photonics process. For sub-bandgap light detection, the photo current is generated by a combination of two photon absorption (TPA), surface state absorption (SSA), and photon assisted tunneling (PAT) effects in the Si PN junction under high reverse bias voltage [2-9].

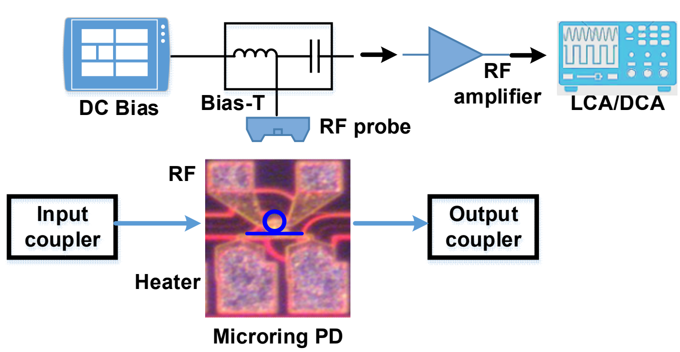


Fig. 1. Experimental setup for evaluating the DC and high-speed performance of the silicon MRPD.

We characterized the silicon MRPD at 1310 nm using the setup in Fig. 1. We measured the S11 parameter using a 67 GHz vector network analyzer (VNA) as shown in Fig. 2. The resistance (R = 26.3 Ω) and capacitance (C = 41 fF) of the silicon MRPD were extracted by fitting the measurement data to an equivalent circuit model, resulting in a RC limited bandwidth of 148 GHz. Fig. 3(a) shows the responsivity as a function of wavelength detuning from the ring resonance and the corresponding small signal opto-electric (OE) bandwidth at a fixed reverse bias of 5.8V. Fig. 3(b) shows the S21 response at a wavelength detuning of 40 pm from the ring resonance at -5.8 V and -5.9 V bias voltages. The measured dark currents were <100 nA and <400 nA at -5.8 V and -5.9 V bias, respectively. The ring resonator has a loaded quality factor of 3300, corresponding to a photon lifetime limited bandwidth of 70 GHz. The measured 3-dB OE bandwidth varies from 30 to 45 GHz depending on the wavelength detuning from the resonance. The OE bandwidth is determined by a combination of the transit time, RC bandwidth, and photon lifetime. The responsivity decreases, but the OE bandwidth increases with the wavelength detuning. At -5.8V reverse bias and 40 pm detuning, the measured OE bandwidth was 35 GHz with a responsivity of 0.23 A/W and dark current of <100 nA. The responsivity and bandwidth of the silicon MRPD is a strong function of the reverse bias as shown in Fig. 3(c). A responsivity of 0.7 A/W can be achieved at -5.9 V bias with an OE bandwidth of 11.2 GHz. We found that the S21 response at this higher bias rolls off rather smoothly so we can still achieve higher data rates by using a FFE equalizer.

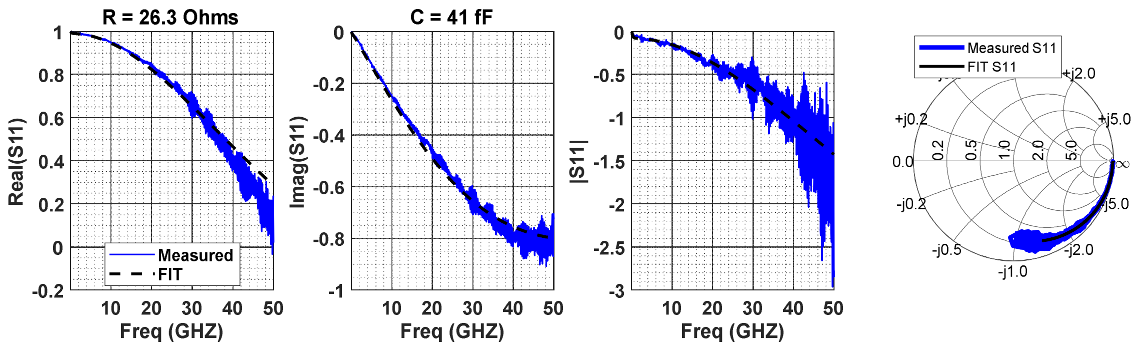


Fig. 2. Measured S11 and extracted RC parameters.

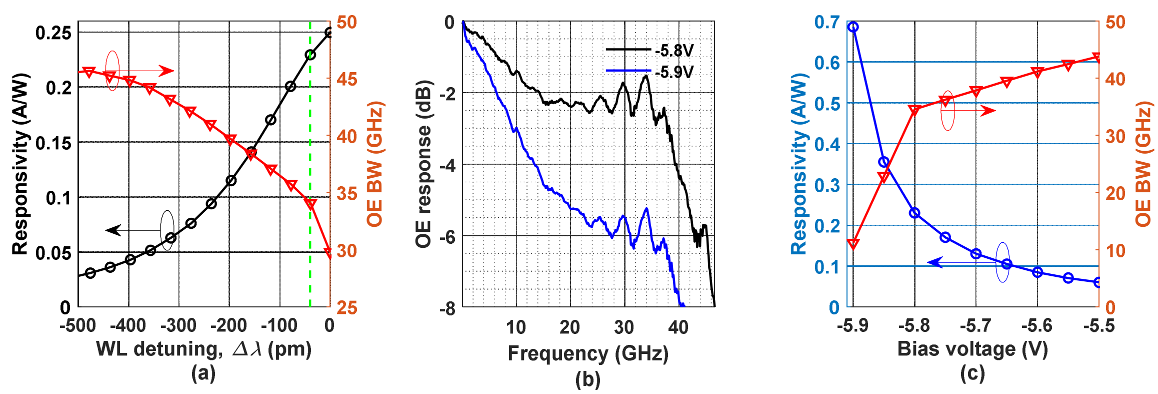


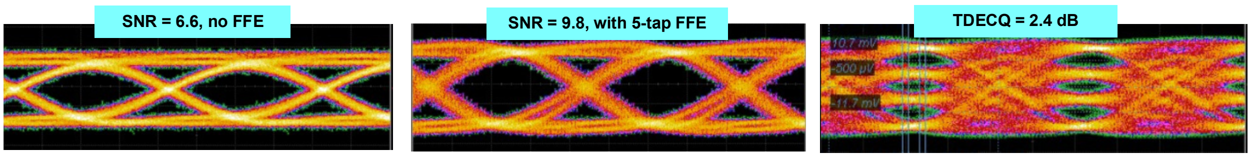
Fig. 3. Measured performance of the silicon MRPD (a) responsivity and OE bandwidth as a function of wavelength detuning $\Delta\lambda$ at -5.8V bias (b) S21 response and (c) responsivity and OE bandwidth as a function of bias voltage at 40 pm wavelength detuning.

3. High-speed time domain measurement results

The input modulated optical signal was generated by a 37 GHz bandwidth Mach-Zehnder Modulator (MZM) driven by a PRBS-13 electrical signal at 56 Gb/s from a 92 GS/s arbitrary waveform generator (AWG) amplified by a 55 GHz linear RF amplifier. The optical signal is coupled into the ring PD through a grating coupler. The time domain response of the Si MRPD was measured using a GS probe. A bias-T was used to supply the DC bias and extract the RF signal. The RF signal produced from the Si MRPD at the output of the bias-T was amplified by a 67 GHz linear amplifier with an RF gain of 11 dB and noise figure of 8 dB. The performance of the output electrical signal was evaluated by a digital communication analyzer (DCA) with a low noise remote electrical sampling head.

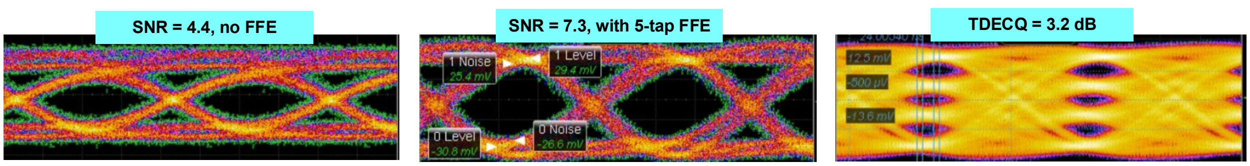
The time domain response of the Si MRPD at -5.8 V bias and received optical power of 3.5 dBm is presented in Fig. 4. We obtained a clear open eye diagram with SNR of 6.6 shown in Fig. 4(a). With a linear 5-tap feed forward equalizer (FFE), the measured SNR was improved to 9.8 as shown in Fig 4(b). Next, we evaluated the performance of the MRPD with PAM4 signals at 112 Gb/s. The measured TDECQ with IEEE 802.3bs TDECQ equalizer was 2.4 dB as shown in Fig. 4(c). The ECP was less than 1.0 dB by comparing the TDECQ of the input optical signal measured using a 65 GHz reference optical receiver. This shows the suitability of the silicon MRPD for >100Gb/s PAM4 signaling.

It is possible to get higher responsivity from the silicon MRPD at the cost of its OE bandwidth and lower SNR. At -5.9 V bias, we obtained a responsivity of 0.7 A/W, dark current of <400 nA and an un-equalized eye SNR of 4.4 as shown in Fig. 5(a). With a 5-tap FFE, we obtained an improved SNR of 7.3 as shown in Fig. 5(b). For a PAM4 signal, we achieved 112 Gb/s open eye with TDECQ of 3.2, corresponding to an ECP of 1.9 dB as shown in Fig 5(c).



(a) (b) (c)

Fig. 4. Measured electrical eye diagrams at -5.8V bias and 0.23 A/W responsivity. (a) 56 Gb/s NRZ OOK eye without any equalization, (b) with a 5-tap linear equalizer, and (c) 112 Gb/s PAM4 eye diagram with IEEE 802.3bs TDECQ equalizer.



(a) (b) (c)

Fig. 5. Measured electrical eye diagrams at -5.9V bias and 0.7 A/W responsivity. (a) 56 Gb/s NRZ OOK eye without any equalization, (b) with a 5-tap linear equalizer, and (c) 112 Gb/s PAM4 eye diagram with IEEE 802.3bs TDECQ equalizer.

4. Conclusion

We have demonstrated for the first time, an all-silicon micro-ring photodetector that can be used for high-speed detection at 112 Gb/s. We obtained a responsivity of 0.23A/W, dark current of <100 nA, and OE bandwidth of 35GHz at -5.8 V bias and 40 pm wavelength detuning. We achieved 112 Gb/s open PAM4 eye with 1.0 dB ECP. With higher bias at -5.9 V, a higher responsivity of 0.7 A/W can be achieved at the cost of increased dark current of up to 400 nA and reduced bandwidth down to 11.2 GHz. Under these conditions we could still achieve open PAM4 eye with ECP of 1.9 dB. Although we only performed the measurements at a wavelength around 1310 nm, by tuning the ring resonances with an integrated heater, we can cover the entire O-band, and can use the silicon MRPD as a demultiplexing PD in a WDM network to detect a specific wavelength channel. A dedicated transimpedance amplifier (TIA) could further improve the high-speed performance of the silicon MRPD. This work proves the viability of using low-cost silicon-based photodetectors as an alternative to Ge or III-V based detectors for photonics integration and high-speed datacom applications.

Acknowledgements

The authors would like to acknowledge Jie Sun and Hasitha Jayatilleka for their early contributions, Gregory Lovell for testing support, Saeed Fathololoumi, Ansheng Liu, Ling Liao, Ganesh Balamurugan, Hao Li, James Jaussi, Bryan Casper, Yuliya Akulova, and Robert Blum for technical discussions, and our device fabrication partners in F11x, Intel Corporation, Rio Rancho, NM, for their high-quality Si photonics processing support.

5. References

[1]R. Jones, *et al.*, "Heterogeneously Integrated InP/Silicon Photonics: Fabricating Fully Functional Transceivers," IEEE Nano Mag. (2019).
[2] I. W. Hsieh, *et al.*, "Two-photon-absorption-based optical power monitor in silicon rib waveguides," Group IV Photonics, 326-328 (2010).
[3] M. Sakib, *et al.*, "Demonstration of a 50 Gb/s all-silicon waveguide photodetector for photonic integration," CLEO (2018).
[4] H. Zhu, et al., "All-Silicon Waveguide Photodetection for Low-Bias Power Monitoring and 20-km 28-Gb/s NRZ-OOK Signal Transmission," JSTQE (2018).
[5] J. You, *et al.*, "Photon-assisted tunneling for sub-bandgap light detection in silicon PN-doped waveguides," OE (2017).
[6] R. Grote, et al., "10 Gb/s Error-Free Operation of All-Silicon Ion-Implanted-Waveguide Photodiodes at 1.55um," PTL (2013).
[7] H. Yu, et al, "Using carrier-depletion silicon modulators for optical power monitoring," Opt. Lett. (2012)
[8] X. Li,. et al, "40 Gb/s All-Silicon Photodetector Based on Microring Resonators," PTL (2015).
[9] M. Casalino, et al. "State-of-the-art all-silicon sub-bandgap photodetectors at telecom and datacom wavelengths," Laser & Photonics Reviews (2016).