Demonstration of an Ultra-High-Responsivity All-Silicon Avalanche Photodetectors

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Abstract: We demonstrate an all-Si 20 Gb/s microring avalanche photodiodes with a responsivity of more than 65 A/W. This is the first all-Si APD that can compete with current commercial Ge and III-V photodetectors.

1. Introduction

Starting from the mature CMOS manufacturing techniques, cost-effective and large-scale integrated silicon (Si) photonics is well developed and already provides engines for high-speed optical interconnects and the future generation of data processors [1]. However, due to the inherent indirect and large bandgap structure, it is difficult to utilize silicon for photodetectors in common optical communication band. Currently, commercial receivers (Rxs) use heteroepitaxial growth of Germanium (Ge) or heterogeneous integration of III-V materials to detect light with added material costs and process complexity [2,3]. This accounts for ~ 40% of the overall Rx chip costs. Recently, all-Si photodiodes (PDs) have attracted a lot of interests for power monitoring and datacom applications. Si avalanche photodiodes (APDs) based on two-photon absorption (TPA) and photon-assisted tunnelling (PAT) can absorb sub-bandgap wavelengths, while they are limited by the weak absorption mechanisms and low responsivity [4-7]. Optical resonant enhancement effect in the microring resonator (MRR) makes it possible to improve responsivity compared to waveguide APDs. The all-Si MRR APDs have the inherently advantages of low dark current, compact size, and the ability of wavelength-selective photodetection as a demultiplexer (DEMUX) in a wavelength division multiplexing (WDM) system. Despite these advantages, all the reported all-Si MRR APDs have limited responsivity of < 1.5 A/W [4], which is much less than the current Ge and III-V photodetectors. In here, we report a 20 Gb/s all-Si microring APD with an ultra-high total responsivity of up to ~ 65 A/W and a low dark current of ~ 2 nA just before the breakdown.

2. Device design

The silicon microring APD consists of a 14.2 µm radius ring resonator with a PN junction. The rib WG is 500 nm in width, 310 nm in height and 65 nm in slab height. A racetrack configuration was adopted to realize ~2.1 % power coupling between the microring and bus WG with a coupling gap of 200 nm. A low-doped PN junction and low coupling coefficient are designed for low optical loss, high quality factor (Q) and high cavity resonance enhancement for better total responsivity (R). The high Q microring enables low crosstalk and more available wavelength division multiplexing channels, making all-Si APDs ideal to be used as a DEMUX. Figure 1(b) shows the simulated electric field distribution at -7.36 V in the microring and the field is mainly focused at the center of the junction to have a better overlap with mode. The highest electric field is 7.7×10^7 V/m, which is sufficient for impact ionization.

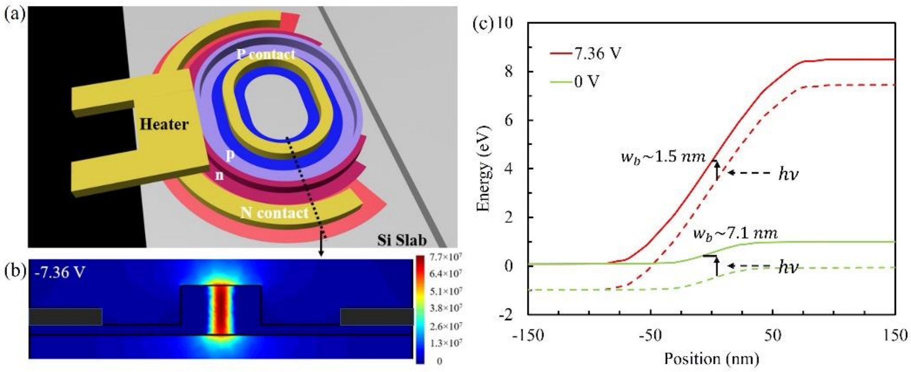

Fig. 1. (a) Schematic, (b) simulated electric field at -7.36 V and (c) energy band of Si PN junction based microring resonator

The energy band diagram of the Si PN junction is shown in Fig. 1(c) at 0 V and -7.36 V. Applying a high bias voltage across the PN junction, the spatial distance between the conduction and valence band will be shortened due to the strong electric field. The electrons in the valence band can tunnel into the conduction band in a process called photon-assisted tunneling. At 1310 nm (corresponding to ~0.95 eV photons), the effective barrier width w_b decreases from ~ 7.1 nm at 0 V to ~ 1.5 nm at -7.36 V and the reduced w_b increases the tunneling probability (T) exponentially to 25 % according to [8]:

$$T \approx \exp\left(-\frac{4\sqrt{2m^*}}{3\hbar}\sqrt{E_b}w_b\right). \tag{1}$$

where m^* is the effective mass of electrons in single crystalline Si and E_b is the potential barrier height. Therefore, the PAT, cavity enhancement and avalanche gain contribute the overall sub-wavelength total responsivity at high reverse bias voltage.

2. Device characterization

We prove the feasibility of the all-Si APD in a standard Si photonics process at the LETI foundry. An optical micrograph of the APD is shown in Fig. 2(a). From the spectrum, the microring APD exhibits a free spectral range (FSR) of ~ 4.65 nm, a DC extinction ratio (ER) of ~ 9 dB, and a full width at half-maximum (FWHM), δλ, of ~ 0.05 nm. The quality factor Q can be calculated as ~ 26000, the finesse F is ~ 93, the total cavity loss coefficient is ~ 0.064 and the corresponding cavity enhancement factor is ~ 20. The negligible crosstalk can enable >10 channels operation as a DWDM link. The photon lifetime-limited bandwidth of the microring APD can be determined by the Q value to be 10 GHz.

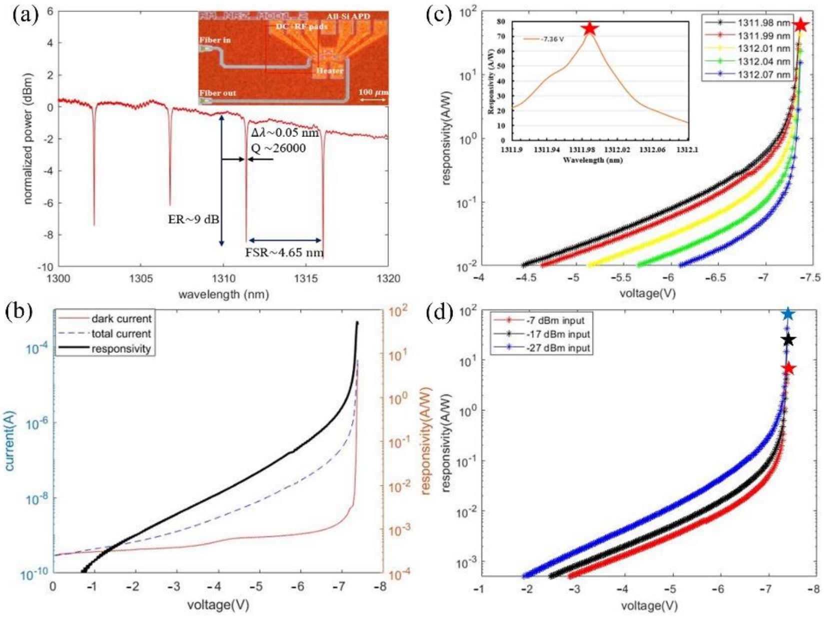

Fig. 2. (a) Normalized transmission spectrum at zero bias voltage, (b) measured total and dark current, (c) measured responsivity versus wavelength and (d) measured responsivity at resonance with different WG power

The measured I-V characteristics are illustrated in Fig. 2(b), where the solid black line is the responsivity. Thanks to the mature Si process, the all-Si APD demonstrates a very low dark current of only ~ 2 nA before breakdown and ~ 0.2 µA when responsivity is 30 A/W at -7.34 V. The value is 2 to 3 orders of magnitude smaller than conventional Si-Ge APDs, which means the induced noise can be largely suppressed. The highest responsivity is ~ 65 A/W at -7.36 V at 1311.98 nm, which is much higher than the record 1.5 A/W for all-Si APD previously reported [4]. The responsivity is comparable to the conventional Si-Ge and III-V APDs [2,3]. The responsivity at different wavelength is shown in Fig. 2 (c) and inset demonstrates the responsivity at -7.36 V. The resonance wavelength stays at 1311.98 nm except at -7.36 V due to the thermal induced red shift. The highest responsivity at 1311.99 nm reaches up to 75 A/W. It should be noted that the device is designed as a two-segments modulator, whereas the PN junction only occupies ~ 50% of the ring circumference. If the rest of the microring is utilized, the responsivity can be >100 A/W. It can also be observed that the responsivity is higher for the weaker input. This phenomenon is the same as the avalanche gain saturation in conventional APDs [9].

Fig. 3 shows the measured eye diagrams at -7.2 V and -7.36 V and received optical power is -5 dBm, where the link loss and signal distortion were calibrated at -7.2 V. The optical signal from an O-band tunable laser was modulated by a 65 GHz MZM. All eye diagrams in this work were measured with pseudo random bit sequence 9 (PRBS9) signals, which were generated with a 92 GSa/s arbitrary waveform generator (AWG), and averaged by 64 times to reduce the amplified noise. Thanks to the high gain and low noise, the MRR APD thus can support open eye diagrams of 20 Gb/s NRZ. The eye diagrams can be further improved by adding a trans-impedance amplifier (TIA) after the all-Si APD. If the transceiver consists of 10 wavelength channels, an aggregate bandwidth of 200 Gb/s can be expected. Except for telecommunication, this high-speed Si APD are suitable as the inline monitor for complex circuit.

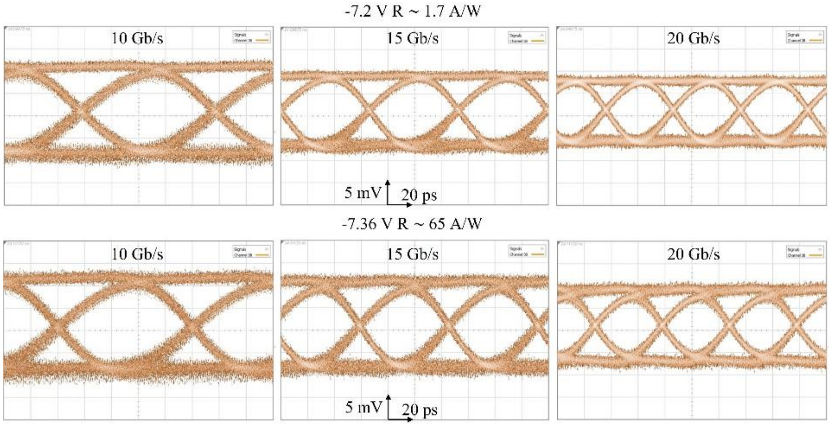

Fig. 3. The 10 Gb/s, 15 Gb/s and 20 Gb/s NRZ eye diagrams of all-Si APDs with R~ 1.7 A/W and 65 A/W

To better understand the performance of our MRR PDs, the comparison of different all-Si PDs/APDs is demonstrated in Table 1. Our APD PDs achieves comparable bit rate and breaks the responsivity limitations of the previous all-Si APDs. To the best of our knowledge, this is the first Si APD can beat conventional Si-Ge and III-V APDs. The Ge-free approach can reduce the technical entrance level for CMOS foundry and suitable for fast-developing optical chip-level integration in the near future.

Table 1. Comparison of APDs

Device	Size	Responsivity	Bit rate	Additional process
All-Si APD (this work)	14.2 μm radius	65 A/W	20 Gb/s NRZ	No
All-Si APD [4]	20 μm radius	1.5 A/W	<1 Gb/s NRZ	No
All-Si APD [5]	10 μm radius	0.7 A/W	56 Gb/s NRZ	No
Si-Ge APD [2]	3 μm × 10 μm	55 A/W	13 Gb/s NRZ	Ge growth & implantation
InAs QD APD [3]	3 μm × 50 μm	47 A/W	8 Gb/s NRZ	Multiple III-V materials growth

4. Conclusion

We have demonstrated for the first time, an all-Si microring APD that can compete with conventional Si-Ge and III-V APDs. We obtained a responsivity of 30 A/W and dark current of <200 nA at low bias voltage of -7.34 V. With bias at -7.36 V, a high responsivity of 65 A/W and open eye diagrams of 20 Gb/s can be achieved. The wavelength-selective photodetection and low channel crosstalk make our microring APD promising in the DWDM Rx application. This work proves the feasibility of using low-cost Si APDs as an alternative to Ge and III-V based APDs to reduce the cost, complexity, and footprint of Si photonics, for high-density and large-scale optical chip-level integration.

5. References

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