1310 nm quantum dot waveguide avalanche photodiode heterogeneously integrated on silicon

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ABSTRACT

We demonstrate quantum dot (QD) waveguide avalanche photodiodes (APDs) on silicon at 1310 nm with a record high gain-bandwidth product of 240 GHz. A 3-dB bandwidth as high as 15 GHz and gain as high as ~45 were achieved. Open eye diagrams up to 12.5 Gb/s were taken and a sensitivity of -11 dB were demonstrated for the first time for any QD APD on silicon. Temperature studies were also made on these APDs, exhibiting high performance up to 60° C, and showing that these APDs can be practically used in an uncooled, WDM system on a silicon photonic platform.

Keywords: optoelectronics, avalanche photodiodes, silicon photonics, quantum dots, optical interconnects.

1. INTRODUCTION

Future high-performance computers and data centers need to be able to keep up with future high-demanding, data-driven applications such as machine learning, virtual reality, and Internet of Things (IoT). Silicon (Si) integrated photonics provides a solution for low-power, high-bandwidth interconnects that are compatible with low cost complementary metal-oxide semiconductor (CMOS) electronic processors and memory chips. We have developed all the key components for a Si photonic integrated circuit including lasers, modulators, and photodetectors. To further reduce power consumption and enhance high-temperature operation robustness, we recently successfully demonstrated quantum dot (QD)-based comb and microring lasers on our heterogeneous photonic platform. Furthermore, by using avalanche photodiodes (APDs), lasers are allowed to operate with smaller output optical power and still be detected with high sensitivity due to the APD's internal gain.

Silicon-germanium (Si-Ge) avalanche photodiodes (APDs) have shown significant potential in providing highly sensitive receivers on silicon photonic integrated circuits. However, these APDs generally require two selective area growths for Si and Ge thin films, which complicate the fabrication process and increase the cost of heterogeneous III-V-on-Si lasers that are fabricated on the same wafer [1]. One solution to this is to use the same epitaxial layers for the lasers and the photodiodes. In this paper, we report the first QD APDs heterogeneously integrated on a Si substrate, made using the same epitaxial layers and fabrication process for a recent 1310 nm hybrid QD silicon comb laser with error-free operation for 14-channels [2]. These APDs demonstrate an avalanche gain of up to ~45 and a gain-bandwidth product of 240 GHz, which are the highest for any QD APDs on Si. A maximum 3-dB bandwidth of 15 GHz and open eye diagrams up to 12.5 Gb/s were achieved, and temperature-dependent studies were conducted to exhibit high performance up to 60˚ C.

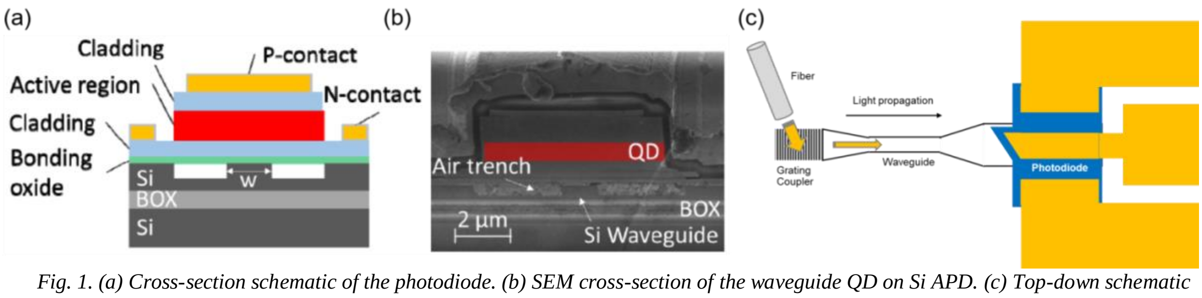

Fig. 1. (a) Cross-section schematic of the photodiode. (b) SEM cross-section of the waveguide QD on Si APD. (c) Top-down schematic of the photodiode with a fiber coupled to the input waveguide with a grating coupler.

2. DEVICE DESIGN AND FABRICATION

Fig. 1 shows a cross-section and top-down view schematic diagram as well as a SEM cross-section of the device. We couple a 1310 nm laser light from a cleaved fiber through a grating coupler, which then directs the light along a Si waveguide and finally evanescently couples light into the APD above the waveguide. First, grating couplers and passive silicon waveguides were etched onto an SOI substrate. Then, a GaAs-based p-i-n eptaxial structure with an active region of 8 layers of InAs QDs, totaling 320 nm in thickness, was bonded directly to the SOI substrate [3]. The waveguide-type lasers and photodiodes were etched, passivated, and metallized during the same process steps. The full detailed fabrication process for these APDs, as well as QD comb and microring lasers made on the same wafer, can be found at [4].

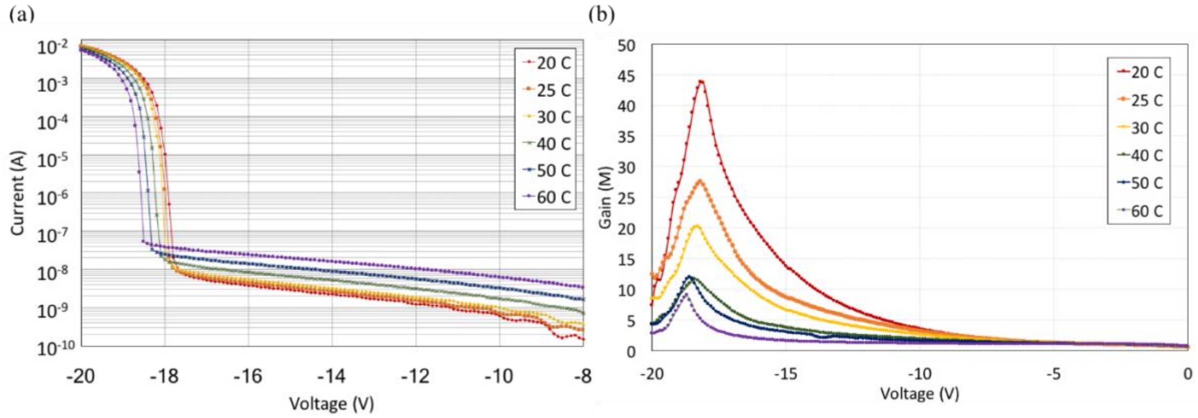

Fig. 2. (a) Dark current vs. temperature and (b) gain vs. voltage for a 11 µm × 60 µm device.

3. RESULTS

Fig. 2(a) plots the I-V curves of a 11 µm × 60 µm photodiode at different temperatures. The temperature dependence on the breakdown voltage reveals that impact ionization of free carriers is the primary physical mechanism behind the breakdown of the device. The dark current was as low was 10 pA at -1V, the lowest for any QD PD on Si to our best knowledge, and 50 µA at a bias right below breakdown voltage [5].

The gain of the device was measured and is shown in Fig. 2(b). The external responsivity at unity gain and with 8 dBm optical input power at room temperature is 0.06 A/W, and the maximum external responsivity at room temperature is 2.7 A/W. A temperature dependence on the gain, as well as a decrease in gain at high biases, have been observed and are due to the increase of dark current with temperature and bias. A maximum gain of ~45 was seen at room temperature, with avalanche gain seen up to a temperature of 60 ˚C, displaying the temperature robustness of the devices. We believe that the avalanche multiplication process occurs in the GaAs spacer layers in between the QDs and that the QDs may also be partially contributing to the multiplication gain [6].

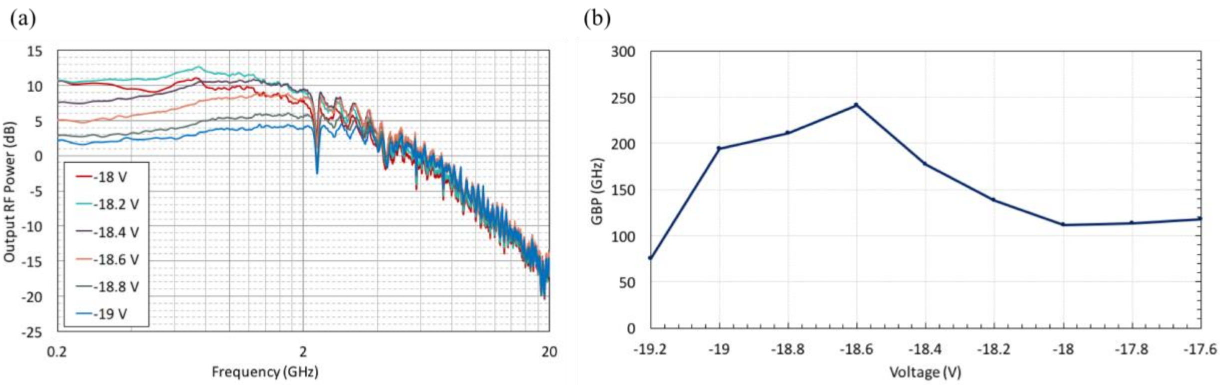

Fig. 3. (a) Frequency response of a 11 µm × 90 µm APD between -18 V and -19 V. (b) Gain bandwidth product of a 11 µm × 90 µm APD.

The S21 frequency response was measured at room temperature using an HP lightwave component analyzer (LCA). The frequency response was taken under bias voltages that provide high multiplication gain. The maximum 3-dB bandwidth measured for a 11 µm × 90 µm APD was about 8 GHz and 15 GHz for a 11 µm × 60 µm APD at -12 V bias. An inductive peaking effect was observed between -18 V and -19 V bias, which has been previously explained in other APDs to be caused by the impact ionization in the avalanche region of the device [1]. A maximum gain-bandwidth product (GBP) of 240 GHz was measured at a bias voltage of -18.6 V, as shown in Fig. 4(b). This is higher than most traditional InP-based receivers based on APDs, which is around 100-200 GHz due to their larger impact ionization coefficient *k* value [1]. This number also compares to Ge-on-Si APD counterparts which typically show higher GBP due to the low *k*-value of Si. However, they also often suffer from higher dark currents due to dislocations at lattice-mismatched Ge/Si interface.

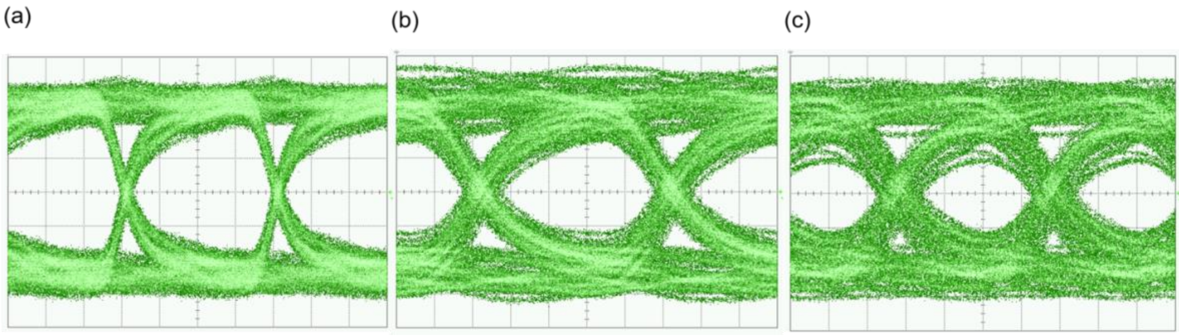

Fig. 4. Eye diagrams at (a) 5 Gb/s, (b) 10 Gb/s, and (c) 12.5 Gb/s.

These APDs provide enough multiplication gain to produce a sufficiently high signal-to-noise ratio and clear eye diagrams without the need of a transimpedance amplifier (TIA). A high-speed pseudo-random binary sequence (PRBS) signal was amplified by a 20 dB high-speed power amplifier. Then, a 1310 nm optical signal couples to an APD that is biased through a RF probe and a bias-T. The output electrical signal is monitored by a DCA86100C sampling scope in the form of an eye diagram. Figs. 4(a)-(c) show the electrical eye diagrams of a 11 µm × 60 µm APD at 5 Gbps, 10 Gbps, and 12.5 Gbps, respectively. At a gain of 40, we have obtained a signal-to-noise ratio greater than 7 dB and 5 dB at 5 Gbps and 10 Gbps, respectively. We have also obtained open eye diagrams at 12.5 Gbps, as shown in Fig. 4(c), where the data rate was limited by the pattern generator.

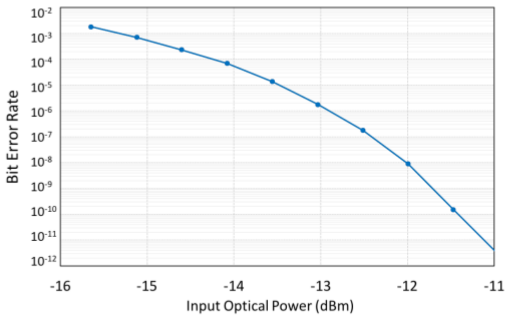

Fig. 5. Bit error rate vs. input optical power of a 11 µm × 90 µm device.

A bit error rate (BER) test was conducted using an Anritsu Bit Error Rate Tester at 10 Gb/s. At a gain of 28, the sensitivity was measured to be about -11 dBm at a BER of 1×10^{-12} and -14.6 dBm at a BER of 2.4×10^{-4}, as shown in Fig. 5. This sensitivity is a few dB higher than that of a typical Ge-on-Si p-i-n PD. Better performance is expected when a TIA is utilized. Furthermore, the epitaxial layer structure can be designed as a separate absorption and multiplication (SAM) structure in order to reduce breakdown voltage and increase multiplication gain in the device.

4. CONCLUSIONS

A QD APD heterogeneously integrated on Si was demonstrated for the first time. A maximum gain of up to 45 and a gain bandwidth product of 240 GHz were observed, which are record high results for any QD APDs on Si. These APDs achieve a low dark current and a sensitivity of -11 dBm, and have demonstrated open eye diagrams up to 12.5 Gb/s. These devices are promising candidates for on-chip monitor PDs and integrated high-speed receivers. They also leverage the same epitaxial layers and processing steps as an on-chip laser, which significantly simplifies the processing for a fully integrated transceiver on Si.

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