Ultra-Low Capacitance, High-Speed Integrated Waveguide Photodiodes on InP

Bassem Tossoun, Jesse Morgan, and Andreas Beling

Charles L. Brown Department of Electrical and Computer Engineering, University of Virginia, Charlottesville, VA 22904, USA

Abstract: We demonstrate integrated waveguide modified uni-traveling carrier (MUTC) photodiodes with dark currents as low as 5 nA at -1 V, capacitance of 1.8 fF, 0.26 A/W external responsivity, and a 3-dB bandwidth of 85 GHz. © 2019 The Author(s)

I. Introduction

High-speed, low-capacitance photodiodes are key components in low-power optical receivers for data communication and processing. According to Miller [1], reducing the photodiode capacitance can help enable a 'receiverless' system, meaning there is no need for a transimpedance amplifier (TIA) following the photodiode. Because the photodiode capacitance is sufficiently small, the self-induced electric field caused by photogenerated carriers will create a strong enough voltage swing to drive the input of a CMOS gate with the incorporation of a high load resistor [2]. This not only simplifies the system, but has the potential to reduce the energy consumption per bit of an optical receiver by over 100x.

In this paper, we demonstrate a modified uni-traveling carrier (MUTC) waveguide photodiode with an ultra-low capacitance of 1.8 fF, 0.26 A/W external responsivity, and a bandwidth up to 85 GHz at -1 V and 50 GHz at zero bias. A newly designed planarization and passivation process was developed and devices as small as 2 µm in diameter were successfully fabricated with reduced device and parasitic capacitances for potential high bandwidth, 'amplifier-less' optical receivers.

II. Device Design and Fabrication

Figure 1 displays the epitaxial layer stack of the photodiode (PD), which was grown with metal-organic chemical vapor deposition (MOCVD). The first step for device fabrication was to deposit Ti/Pt/Au/Ti, the p-contact metal, on top of the sample using electron beam evaporation. Then, silicon dioxide (SiO_2) was deposited as a hard mask for the p-mesa etch. After the p-mesa was etched, then the waveguide and the n-mesa were dry etched. Next, Ti/AuGe/Ni/Au was deposited on top of the n-mesa to serve as the n-contact metal, as well as, the coplanar waveguide (CPW) ground pads. SU-8 was then used to passivate the sidewalls of the device and reduce leakage current, as well as, serve as an insulation pad and interconnect supporting structure for the RF signal pad. After SU-8 was deposited and planarized on the surface of the chip, it was dry etched with O_2 and SF_6 until the p-metal was exposed. Then, 30 nm of Ti and 400 nm of Au were deposited for the CPW signal pad. This novel planarization process eliminates the need for an air bridge and its precise and difficult alignment to the p-mesa. Lastly, the chips were cleaved using a cleaving tool. An SEM photo of a fabricated PD is shown in Figure 3.

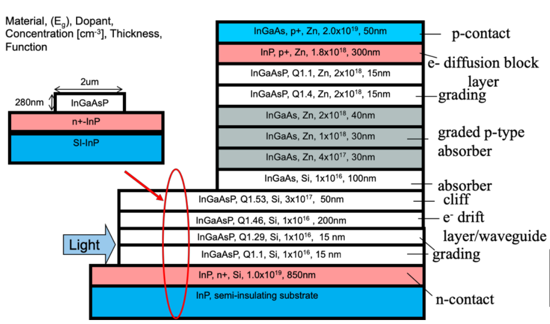

Figure 1: Epitaxial layer stack of the MUTC photodiode

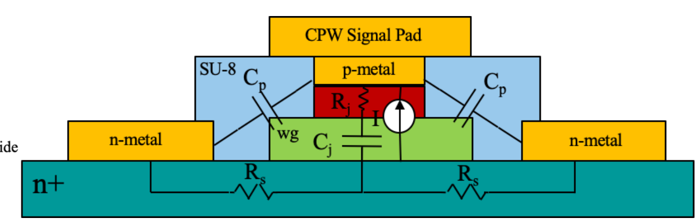

Figure 2: Cross-section with circuit elements of the PD and planarization SU-8.

III. Measurement Results

Firstly, I-V curves were taken of the devices are shown in Figure 4. The dark current is as low as 5 nA at -1 V for a 2 µm x 2 µm photodiode. Capacitance-voltage (C-V) measurements were also taken using a LCR meter showing that the junction capacitance scales linearly with area as shown in Figure 5. A junction capacitance as small as 1.8 fF was measured for a 3 µm x 3 µm device at -1 V, and the parasitic capacitance coming from outside the device, C_p, was measured to be about 1 fF. Due to the new planarization process and optimized CPW designs, the capacitances of these devices were more than 10x lower than the smallest devices fabricated in previous similar designs [3].

Even with a large load resistor, the measured capacitance allows for a high 3-dB bandwidth to still be maintained. Also, since the capacitance is ultra-low, the photogenerated charges in the photodiode produce a large enough voltage swing across the high resistance load resistor to supply a CMOS logic gate, eliminating the need of a TIA.

The external responsivity at 1550 nm was measured using a 2 µm spot size lensed fiber to be about 0.26 A/W for a 5 µm x 7 µm PD. The RF frequency response was also measured at 1550 nm and is shown in Figure 6. We recorded a 3-dB bandwidth as high as 85 GHz at -1 V, and a 3-dB bandwidth of 50 GHz at 0 V for a 5 µm x 7 µm photodiode.

It is worth noting that the photodiode is able to produce high speed RF output power at zero-bias. This is beneficial because of zero leakage current, saving idle power consumption in an optical receiver. It is also advantageous because it simplifies heat sinking, reduces biasing circuit cost, and improves reliability [4].

IV. Summary

An integrated waveguide MUTC photodiode on InP was successfully designed and fabricated. The photodiodes exhibit a low dark current of 5 nA at -1V, a responsivity of 0.26 A/W, and an ultra-low capacitance of 1.8 fF. We also measured a RF frequency response at 1.55 µm with a 3-dB bandwidth of 85 GHz at -1 V, and 50 GHz at 0 V. These photodiodes enable energy-efficient optical receivers without the need of an electrical amplifier or biasing circuity.

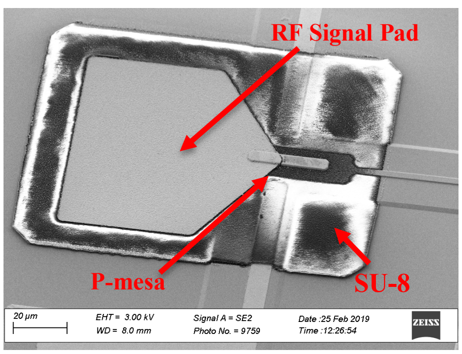

Figure 3: SEM photo of a fully fabricated 5 µm x 30 µm PD.

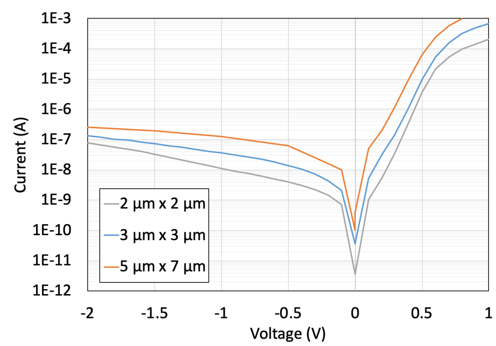

Figure 4: I-V curves of PDs with different active areas.

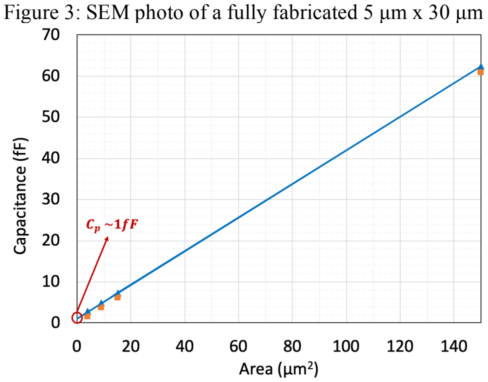

Figure 5: Measured (blue dots) and calculated (orange dots) capacitance vs PD area. The linear represents a linear fit of the measured data.

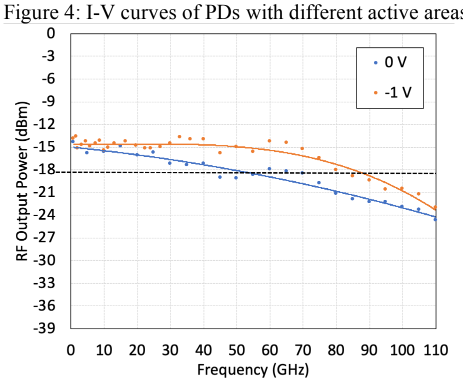

Figure 6: Measured frequency responses of a 5 µm x 7 µm PD at 1 mA. Curves show averaged data.

V. References

[1] D. A. B. Miller, "Attojoule optoelectronics for low-energy information processing and communications," Journal of Lightwave Technology, vol. 35, no. 3, pp. 346-396, February 1, 2017.

[2] K. Nozaki, et al. "Photonic-crystal nano-photodetector with ultrasmall capacitance for on-chip light-to-voltage conversion without an amplifier," Optica, vol. 3, no. 5, 2016.

[3] Q. Li, K. Sun, K. Li, Q. Yu, P. Runge, W. Ebert, A. Beling, J. C. Campbell, “High-Power Evanescently-coupled Waveguide MUTC Photodiode with >105 GHz bandwidth,” IEEE/OSA J. Lightwave Technol., Vol. 35, No. 21, pp. 4752-4757, November 2017.

[4] H. Ito, T. Furuta, S. Kodama, and T. Ishibashi, “Zero-bias high-speed and high-output-voltage operation of cascade-twin uni-travelling-carrier photodiode,” Electron. Lett., vol. 36, pp. 2034–2036, Nov. 2000.