Low-Dark Current III-V Photodiodes Grown on Silicon Substrate

Keye Sun[1], Daehwan Jung[2], Chen Shang[3], Alan Liu[3], John Bowers[2,3], and Andreas Beling[1]

1 Department of Electrical and Computer Engineering, University of Virginia, Charlottesville, VA 22904, ks2kz@virginia.edu
2 Electrical and Computer Engineering Department, University of California Santa Barbara, CA 93106
3 Materials Department, University of California Santa Barbara, CA 93106, USA

Abstract: InAlGaAs/InP p-i-n photodiodes epitaxially grown on silicon substrate with a dark current density as low as 1.3 mA/cm^2 at -3 V are demonstrated. Responsivity, bandwidth, and output power at 1-dB compression are 0.76 A/W, 8 GHz, and -3.4 dBm, respectively.

1. Introduction

Heterogeneously integrated silicon photonics has drawn a lot of interest since it can leverage the mature Si CMOS technology to reduce manufacturing costs while exploiting III-V materials to achieve high-performance devices. To date, integration technologies include hybrid integration [1], wafer bonding [2, 3] and heterogeneous epitaxy [4-6]. In contrast to hybrid integration, which involves optical alignment steps, and wafer bonding with its stringent requirements for the interfaces, heterogeneous epitaxy offers a wafer-level solution for high-yield mass production. In this paper, we demonstrate that epitaxially grown III-V photodiodes on Si can achieve performance comparable to their counterparts on native InP substrate.

2. Experimental

The InP-on-Si template consists of a 500 nm Ge layer, 1 μm GaAs layer, 1.1 μm InAlAs linearly graded buffers, and 0.5 μm InP virtual substrate by molecular beam epitaxy (MBE) as shown in Fig. 1 (a). Atomic force microscope measurement shows smooth surface morphology with a RMS roughness of 2.5 nm from a 5 × 5 μm^2 scan. The p-i-n device structure was then regrown at UCSB by MBE after oxide desorption under As_2 overpressure. The InAlGaAs grading layers were used to smooth the band discontinuities on both sides of the InGaAs absorber. A thin p+ InGaAs layer served as the p-contact layer.

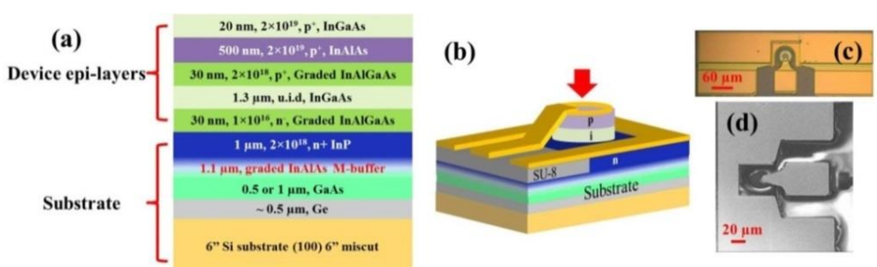

Fig. 1. (a) Layer structure, (b) schematic, (c) top-view optical image and (d) SEM image of the PD.

The PDs were fabricated using contact photolithography and dry etching processes. A ring contact was used for top illumination. The RF pads were deposited on a 2 μm-thick layer of SU-8. In this region we removed the 1 μm n$^+$-InP layer to reduce the pad stray capacitance. An air-bridge was used to connect the top ring contact to the RF pad (Figs. 1 (b-c)). Fig. 2 (a) shows that the dark current varies from 4 to 400 nA at 3 V reverse bias for PDs with mesa diameters between 20 μm and 100 μm. Since the dark current depends quadratically on the mesa diameter, we conclude that it is dominated by bulk effects (inset of Fig. 2 (a)). The dark current density is 1.3 mA/cm^2 at -3 V which is lower than previously reported in [4] and [5]. It should be mentioned that control devices on native InP substrate showed a similar dark current density for diameters below 60 μm. The C-V characteristics show that the absorber is depleted at a reverse bias voltage above 2.5 V (Fig. 2 (b)). The measurement results agree with the theory after subtracting the 67 fF stray capacitance. The responsivity at 1.55 μm is 0.76 A/W and is linear up to 10 mW optical input power (Fig. 2 (c)). No difference in responsivity was found from the control device.

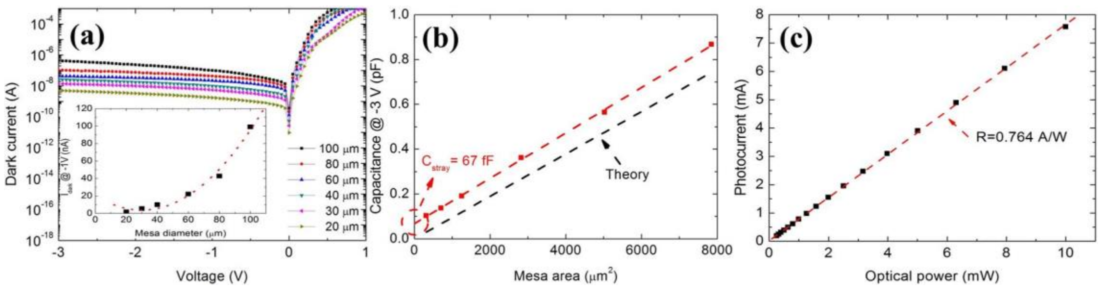

Fig. 2. The (a) I-V, (b) C-V characteristics and (c) responsivity of the PDs grown on Si. The inset of (a) shows dark current vs. PD diameter.

The frequency responses of a 30-μm diameter PD under different bias voltages and photocurrents are shown in Fig. 3 (a). The bandwidth at 1 mA and 3 V is 8 GHz. As the photocurrent increases, we observe a decrease of bandwidth, which can be partly compensated by higher reverse bias. The bandwidth of the PD is somewhat lower than its theoretical prediction which can be explained by substrate dielectric loading effects on the RF pads and a higher n-contact resistance. The RF compression and output power for the same device is shown in Fig. 3 (b). Higher output power can be achieved at higher reverse voltages as the stronger electric field in the depletion region alleviates the space-charge effect. The output power at 1-dB compression was 1.9 dBm at 1 GHz and -3.4 dBm at 8 GHz under 5 V bias.

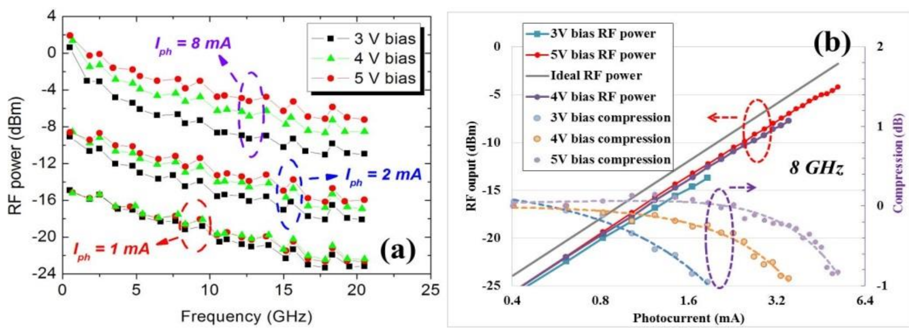

Fig. 3. (a) Bandwidth results of PDs grown on Si under different photocurrents and bias voltages. (b) RF output power and 1-dB compression versus photocurrent at 8 GHz.

3. Summary

We demonstrate photodiodes based on epitaxial III-V material grown on InP-on-Si templates that have a low dark current density of 1.3 mA/cm^2 and a responsivity of 0.76 A/W. The 3-dB bandwidth of a 30-μm diameter PD is 8 GHz and the output power at 1-dB compression is -3.4 dBm. We expect that the bandwidth can be further improved by optimizing contact resistance.

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