Heterogeneous Photodiodes on Silicon Nitride Waveguides with 20 GHz Bandwidth

Qianhuan Yu[1 *], Junyi Gao[1], Nan Ye[1], Boheng Chen[1], Keye Sun[1], Linli Xie[1], Kartik Srinivasan[2], Michael Zervas[3], Gabriele Navickaite[3], Michael Geiselmann[3], and Andreas Beling[1]

[1]*Department of Electrical and Computer Engineering, University of Virginia, Charlottesville, VA 22904, USA*
[2]*Microsystems and Nanotechnology Division, National Institute of Standards and Technology, Gaithersburg, MD, USA*
[3]*LIGENTEC SA, EPFL Innovation Park, Bâtiment C, CH-1015 Lausanne, Switzerland*
**qy5pg@virginia.edu*

Abstract: We demonstrate InGaAs/InP modified uni-traveling carrier photodiodes on Si_3N_4 waveguides with 20 GHz bandwidth and record-high external (internal) responsivities of 0.8 A/W (0.94 A/W) and 0.33 A/W (0.83 A/W) at 1550 nm and 1064 nm, respectively. Balanced photodiodes have 10 GHz bandwidth.

1. Introduction

The silicon nitride (Si_3N_4) photonic platform has attracted wide attention in recent years due to its low propagation loss from the visible to the mid-infrared range, optical frequency comb generation in micro-resonators, and CMOS compatibility [1,2]. In order to build photonic integrated circuits with enhanced functionality, heterogeneously integrated active components have the potential to complement the Si_3N_4 platform which lacks monolithic actives. For light detection, so far, only a few photodiodes (PDs) have been demonstrated on Si_3N_4 waveguides (table 1). In our previous work [3], we demonstrated heterogeneous InGaAs/InP PIN photodiodes with high fiber-coupled external responsivity. The high responsivity was enabled by using a bonding window on the Si_3N_4 waveguide with reduced SiO_2 top cladding thickness. In contrast to PIN PDs, the modified uni-traveling carrier (MUTC) photodiode can achieve higher bandwidth since the carrier transit time component of the bandwidth is mainly based on fast electrons. High-performance waveguide MUTC PDs on native substrate were reported in ref. [4].

In this paper, we demonstrate MUTC PDs heterogeneously integrated on Si_3N_4 waveguides that achieve record-high responsivity and a high bandwidth of 20 GHz. Balanced photodiode pairs have a bandwidth of 10 GHz and over 40 dB common mode rejection ration (CMRR).

Table. 1 PDs on Si_3N_4 waveguide at 1550 nm reported in the literature. *: Estimated internal responsivity.

PD structure	Measured external responsivity (A/W)	Bandwidth (GHz)	Ref.
h-BN/MoS2/graphene	0.24	28	5
InGaAs/InP MUTC	0.15	3.5	6
InGaAs/InP PIN	0.36	30	7
InGaAs/InP PIN	0.68*	25	8
InGaAs/InP PIN	0.68	7	3
InGaAs/InP MUTC	**0.8**	**20**	**This work**

2. Experimental

The Si_3N_4 waveguide cores with a thickness of 400 nm and widths of 1 or 2 µm were deposited by low pressure chemical vapor deposition (LPCVD). The Si_3N_4 strip was buried in SiO_2 with 3 µm top and 4 µm lower cladding as shown in fig. 1(a). In the bonding window, the SiO_2 top cladding was selectively reduced to <100 nm (fig. 1b). Based on our previous results [3], such cladding layer thickness is thin enough for efficient optical coupling from the Si_3N_4 waveguide into the PD. A schematic view of the PD is shown in fig. 1(c). The PD epitaxial layers were grown on semi-insulating InP and consisted of a 150 nm-thick N-doped InP contact layer, a 400 nm P-doped InP contact layer, a depleted InP electron drift layer, and a 450 nm-thick InGaAs depleted and un-depleted absorption layer. The carrier transit time limited bandwidth for this MUTC PD is 40 GHz according to our simulation. Similar to the bonding process described in ref. [3], we used a SU-8 adhesive bonding technique (SU-8 thickness ca. 100 nm) to integrate the InGaAs/InP die onto the bonding window. After substrate removal by wet etch, the MUTC PDs were fabricated as double mesa structures by conventional dry and wet etching techniques. Figures 1 (d) and (e) show microscope pictures of a single photodiode and a balanced PD pair. Typical dark currents were measured to be around 100 nA at 8 V reverse bias.

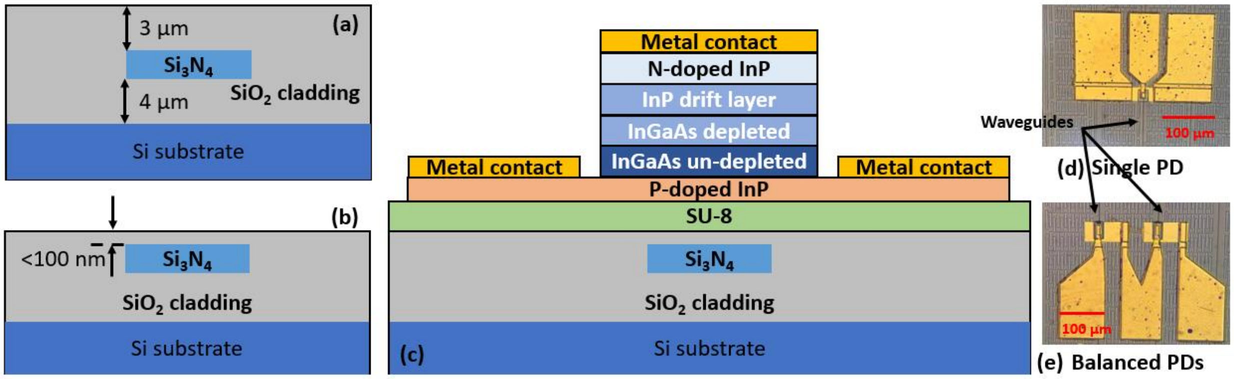

Fig. 1 Cross-sectional views of (a) Si_3N_4 waveguide, (b) Si_3N_4 waveguide in bonding window, and (c) heterogeneous PD. Single PD (d) and (e) balanced PDs.

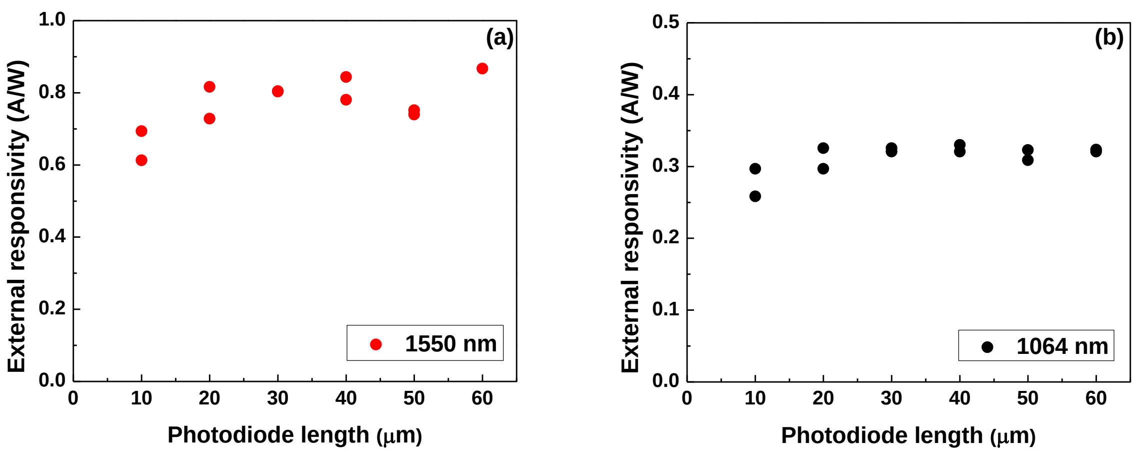

Fig. 2 Measured external responsivity for PDs of various lengths at (a) 1550 nm and (b) 1064 nm wavelength at 8 V reverse bias and 1 mA photocurrent.

The responsivity of PDs with different lengths were characterized at wavelengths of 1550 nm and 1064 nm, respectively. The waveguides were illuminated by a single mode tapered fiber with a spot size of 2.5 µm. For a 30 µm long PD we measured external (fiber-coupled) responsivities of 0.8 A/W and 0.33 A/W at 1550 nm and 1064 nm, respectively. Part of the difference in the external responsivities at these two wavelengths can be explained by the strong wavelength dependence of the fiber-chip coupling loss. Once we take the coupling loss of 0.7 dB at 1550 nm and 4 dB at 1064 nm into account, the internal responsivities were 0.94 A/W and 0.83 A/W corresponding to 75 % and 96 % internal quantum efficiency at 1550 nm and 1060 nm, respectively. From the figures 2(a) and (b), it can be seen that the responsivity has only a weak dependence on PD length between 20 µm and 60 µm. For a 10 µm-long PD, the responsivity can be as high as 0.68 A/W at 1550 nm which suggests that most of power was absorbed in the first 10 µm.

Using an optical heterodyne setup at 1550 nm with modulation depth close to 100 %, the frequency responses of single and balanced PDs were measured. As shown in fig. 3a, a single PD with an active area of 10×30 µm^2 has 20 GHz bandwidth. To measure the balanced photodetector, the optical heterodyne signal was split into two branches before being launched into the waveguides of both PDs through a fiber array. We used variable optical delay lines in both branches to adjust the radio frequency (RF) phase of the modulated optical signal to be either in phase (common mode) or out of phase (differential mode). As shown in fig. 3(a), the bandwidth in differential mode was 10 GHz which is expected due to the doubled PD capacitance. To measure CMRR we replaced the optical heterodyne source by an optical modulator. CMRR was calculated by subtracting the measured power in common mode from the power in differential mode. Figure 3(b) shows the RF powers in common and differential modes at 10 GHz as measured with an electrical spectrum analyzer indicating a high CMRR of 40 dB.

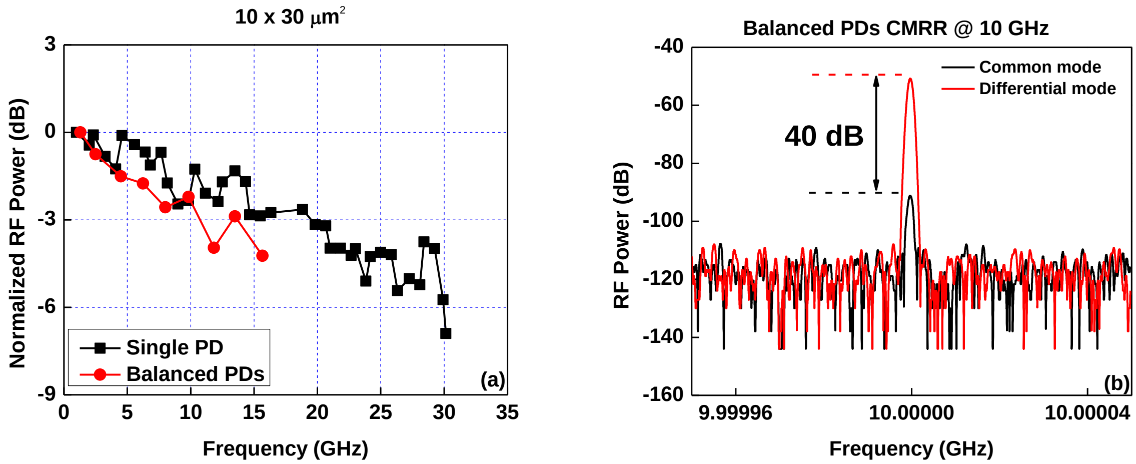

Fig. 3 (a) Frequency response measurements of a single 10 x 30 μm² PD (black) and a pair of balanced 10 x30 μm² PDs in differential mode (red) at 8 V reverse bias and 2 mA photocurrent. (b) CMRR of balanced PDs at 10 GHz with 8 V reverse bias and 2 mA photocurrent for each PD.

3. Summary

MUTC photodiodes heterogeneously integrated onto Si_3N_4 waveguides were fabricated and characterized. The internal responsivities of a 30-μm long PD with 20 GHz bandwidth are as high as 0.94 A/W and 0.83 A/W at 1550 nm and 1064 nm wavelength, respectively. For balanced PDs, 10 GHz bandwidth were achieved with over 40 dB CMRR. Based on their excellent performance, we believe that our devices are promising candidates for high-speed Si_3N_4 photonic integrated circuits.

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