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High-performance III-V photodetectors on a monolithic InP/SOI platform

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Integrating light emission and detection functionalities using efficient III-V materials on Si wafers is highly desirable for Si-based photonic integrated circuits. To fulfill the need of high-performance photodetectors (PDs) monolithically integrated on Si for Si photonics, we demonstrate III-V PDs directly grown on a InP/Si-on-insulator (SOI) platform parallel to the Si device layer in a variety of device dimensions. Device characteristics including a 3 dB bandwidth beyond 40 GHz, open eye diagrams at 40 Gb/s, a dark current of 0.55 nA, a responsivity of 0.3 A/W at 1550 nm, and 0.8 A/W at 1310 nm together with a 410 nm operation wavelength span from 1240 nm to 1650 nm are achieved. We further simulate the feasibility of interfacing the III-V PDs with the Si waveguide by designing waveguide-coupled PDs with butt coupling schemes. These results point to a practical solution for the monolithic integration of III-V active components and Si-based passive devices on a InP/SOI platform in the future. © 2021 Optical Society of America under the terms of the OSA Open Access Publishing Agreement

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1. INTRODUCTION

The ever-growing communication traffic is pushing the conventional electronic interconnection to the limit. Silicon (Si) photonics is regarded as a highly competitive technology to solve this pressing issue with its high-speed and large bandwidth capability, as well as low-cost, scalable, and high-throughput manufacturing [1,2]. As crucial optical building blocks in Si photonic integrated circuits (PICs), high-performance photodetectors (PDs) are required with the following characteristics: high responsivity, low dark current, large bandwidth, operation over a wide wavelength band, efficient light coupling with Si waveguides, and CMOS compatibility. These criteria have been achieved or partially realized on Si using two different material systems: Ge-based PDs and III-V-based PDs. Ge PDs are currently deployed in Si-based PICs due to their Si-photonics compatibility, decent responsivity within 1550 nm, and a large 3 dB bandwidth [3-7]. However, lattice mismatch between Ge and Si induced threading dislocations lead to large dark currents and thereby degrade the sensitivity, especially at high frequencies, and the band structure of Ge limits its absorption coefficient, especially for wavelengths beyond 1600 nm. As a counterpart, III-V PDs have long been deployed in InP-based PICs because of their superior device performance, including high responsivities within a wide operation band, large bandwidth, and low dark currents [8-11]. Recently, interest on III-V PDs grown on Si started to flourish, complementing the research on integrating III-V lasers on Si and the eventual goal of having high-performance III-V photonics integrated on the Si-photonics platform. Blanket hetero-epitaxy of III-V PDs on Si yields extremely low dark currents [12-16]. However, the thick buffer layers for defect reduction make it challenging for light coupling with Si waveguides, and the 3 dB bandwidths of these PDs often fall in the range of sub-10 GHz. Alternatively, selective hetero-epitaxy of III-V PDs on Si results in bufferless PDs because of its unique defect management and promotes efficient light coupling into Si waveguides [17-19]. Simultaneously, high-speed performance can also be significantly improved with an associated size reduction. Techniques such as vertical aspect ratio trapping (ART) and nano-ridge engineering (NRE) produce III-V PDs with a vertical configuration, while methods such as template-assisted selective epitaxy (TASE) and lateral ART construct PDs with an in-plane configuration [20–23]. Although vertical III-V PDs grown on Si by the vertical ART and NRE approaches exhibit both low dark currents and high responsivities, the height difference between III-V and Si hampers the light coupling efficiency. Furthermore, having electrical paths through the defective III-V/Si interface for carrier collection also limits the high-speed performance of these devices [24-26]. In contrast, III-V materials grown on SOI by the TASE and lateral ART approaches feature an in-plane configuration with the Si device layer, and the defective III-V/Si hetero-interface is excluded from the p-i-n device structure. Recently, using the TASE method, Mauthe et al. demonstrated III-V nanowire PDs operating in the O band with a 3 dB bandwidth of over 25 GHz [27]. Impressive as the high-frequency results are, the device dimension in deep sub-wavelength scale limits the amount of generated photocurrent

and makes it challenging for subsequent light interfacing with Si waveguides.

Here, we report high-performance III-V PDs grown on a monolithic InP/Si-on-insulator (SOI) platform that fulfills the aforementioned criteria for PDs in Si photonics. We first created a monolithic InP/SOI platform with both InP sub-micrometer bars and large-dimension InP membranes through synergizing both the TASE and lateral ART schemes. Built from this InP/SOI platform, we then designed and fabricated III-V PDs with a variety of dimensions. These PDs manifest a 3 dB bandwidth exceeding 40 GHz, a responsivity of 0.3 A/W at 1550 nm and 0.8 A/W at 1310 nm, a dark current of 0.55 nA, and a wide operation band from 1240 nm to 1650 nm. The photocurrents can be adjusted for various applications by designing the length of the PDs. Finally, we simulated the feasibility of interfacing the PDs with Si waveguides through designing waveguide-coupled PDs.

2. SELECTIVE GROWTH AND DEVICE FABRICATION

The III-V PDs are built on a monolithic InP/SOI platform, where both InP bars and InP membranes are selectively grown on (001) SOI wafers. Figures 1(a) and 1(b) schematically depict the concept of our growth scheme. The Si device layer with a thickness of 480 nm was patterned into Si segments with identical width and different lengths spanning from 0.5 µm to 100 µm. The Si segments were then encapsulated by a thin layer of oxide followed by the definition of the template opening. Afterward, the patterned SOI was selectively undercut using anisotropic wet etching, resulting in lateral oxide trenches with a width of around 7.0 μ m. InP segments were then grown from the (111) Si surface and evolved laterally following the lateral oxide trenches [Fig. 1(b)] [28,29]. We define InP segments with lengths smaller than 1.0 µm as sub-micron bars, while those with larger lengths are defined as membranes. Figures 1(c)-1(e) present the top view optical images of the InP bars with a pattern length of 1.0 µm and InP membranes with a pattern length of 5.0 μ m, respectively. The InP bars and membranes feature a unique "InP-on-insulator" characteristic, and consequently it constitutes an ideal InP/SOI platform for



Fig. 1. (a) Predefined patterns with different lengths and 7.0 μ m wide undercut for III-V material growth; (b) InP/SOI template with 6.0 μ m wide InP bars and membranes; (c) top view optical image of the arrayed InP bars on SOI with 6.0 μ m width and 1.0 μ m length; (d) and (e) optical photo and SEM image of the InP membranes with 6.0 μ m width and 5.0 μ m length, respectively.



Fig. 2. (a) SEM image with 52° tilted view of as-grown InGaAs PD; (b) 52° tilted view SEM photo of as-grown QW PD; (c) room temperature PL tested from an InGaAs PD with 2.0 μ m length; (d) optical image and zoom-in SEM photo of the fabricated device with 2.0 μ m length; (e)–(h) fabrication process flow including top oxide cladding removal, BCB planarization and etch-back, and metallization.

implementing photonic functionalities. Details of the growth and characterization of the InP/SOI platform will be reported elsewhere. Based on our monolithic InP/SOI platform, we designed PDs with lateral p-i-n structures (Fig. 2). N-InP, i-InP, i-InGaAs, and p-InGaAs were grown laterally in sequence. The width of the *i*-InGaAs is around 300 nm, and the *n*-InP and *p*-InGaAs are designed to be over 2.0 µm for an easier metal patterning process. We fabricated devices with different lengths ranging from 0.5 µm to 20 µm. To explore PDs with lower dark current, we also grew quantum well (QW) PDs on the same platform. In the QW PDs, five periods of InGaAs/InP QWs instead of bulk InGaAs were used as the absorption layer. Also, we can get insight into the potential demonstration of QW modulators on the same platform. Figures 2(a) and 2(b) illustrate the as-grown p-i-n structures with bulk InGaAs and QW as absorption layers. A flat III-V/oxide interface and sharp InP/InGaAs interface can be clearly observed. Figure 2(c) presents the room temperature photoluminescence (PL) from an InGaAs photodiode with a length of 2.0 µm. The peak of the PL spectra locates at 1.5 μ m, and the sharp drop at 1.6 µm is due to the detection limit of the InGaAs detector in the PL system. The as-grown sample was fabricated into top illuminated PDs with the fabrication process started from the top oxide removal [Fig. 2(d) and 2(e)]. Before metal contact definition, benzocyclobutene (BCB) was coated, cured, and etched back to serve as a planarization layer [Fig. 2(f)]. Note that the BCB layer here also acts as an effective passivation layer [30-32]. Finally, the p and *n* contact metals were deposited atop the *p*-InGaAs and *n*-InP, respectively [Fig. 2(g)]. The overview of the fabricated PD is shown in the optical image in Fig. 2(h). As exemplified by a device with 2.0 µm length, the zoom-in SEM photo reveals well-controlled planarization and metal contact conditions.

3. RESULTS AND DISCUSSION

We first carried out static characterizations of the fabricated PDs including dark current, photocurrent, and operation wavelength.

Considering the spot size ($\sim 4 \,\mu m$) of the lensed fiber used in the measurement, PDs with 0.5, 1.0, 2.0, and 5.0 µm lengths were characterized. Excitation of the tunable laser was shone on the PDs with a tilted angle of 12° through a lensed fiber, and the generated photocurrent was measured by the source measure unit (Keithley 2400). We measured the photocurrent at 1310 nm and 1550 nm with identical incident power for a fair comparison. Figure 3(a)plots the dark current and photocurrent of a device with 2.0 µm length under the illumination of 1310 nm and 1550 nm at reverse bias from -2 V to 0 V. The large photo-to-dark current ratio is evident for the photo-response at 1310 nm and 1550 nm. Figure 3(b) plots the dark current at -1 V for PDs with various lengths. The dark current increases linearly at short lengths but superlinearly for the 5.0 µm length. A lowest dark current of 0.55 nA was measured from PDs with a length of $0.5 \,\mu$ m. The photocurrent distributions at 1310 nm and 1550 nm for devices with a variety of lengths were presented in Fig. 3(c). The devices with different lengths were tested under identical excitation laser power, which resulted in the increase of the effective incident power (excitation power incident on the InGaAs absorption layer) with the expansion of PD absorption area. Thus, a clear trend of rising photocurrent with the longer PD was observed. For all of the measured devices, the photocurrent at 1310 nm is higher than that at 1550 nm. The stronger absorption at 1310 nm can be attributed to the larger modal absorption coefficient and stronger multiple reflections at 1310 nm [33]. We also investigated the power and bias dependence of the photoresponse by illuminating the PD with elevated excitation powers and recorded the corresponding photocurrent at various bias from -2.5 V to 0 V. When the effective incident power is higher than 3μ W, the photocurrent shows no obvious dependence on the bias [Fig. 3(d)]. Therefore, the PDs can provide a large photocurrent at a small electrical bias, which is desirable for lower energy consumption [34]. Benefiting from the larger device dimension and high sensitivity, a saturation photocurrent exceeding 0.3 mA was achieved on the PD with 2.0 µm length. The PD with 5.0 µm

length demonstrated a higher saturation photocurrent over 0.7 mA (limited by excitation power). The photocurrent of the PD with 2.0 µm length is plotted as a function of the incident power in Fig. 3(e). By fitting the data with incident power larger than 4 μ W, we can find that the photocurrent scales linearly with the incident power at various reverse bias, indicating a trap-free feature of the PDs [35]. To demonstrate the ability to operate over a wide wavelength range, we measured the PD at different wavelengths from 1240 nm to 1650 nm under identical incident power. Figure 3(f)shows the responsivity at various wavelengths and biases. The responsivity was calculated by dividing photocurrents by the effective incident power, which was achieved by considering the overlap of the illuminated InGaAs absorbing area and the Gaussian beam from the lensed fiber, with the assumption that the two centers coincide. The responsivity at 1310 nm and 1550 nm when taking both the *i*-InGaAs and *p*-InGaAs regions into consideration is calculated to be 0.8 A/W at 1310 nm and 0.3 A/W at 1550 nm. We obtained an operation wavelength span of over 400 nm covering the O, E, S, C, and L bands. The responsivity first peaked at 1.3 µm and gradually decreased to 0.3 A/W at 1.6 µm. The responsivity exhibits no dependence on the bias for all of the wavelengths measured. The missing data from 1380 nm to 1450 nm is due to the limited tuning range of the excitation laser.

With the criteria of high responsivity, low dark current, and wide operation wavelength range fulfilled, we also investigated the 3 dB bandwidth of our PDs through impulse-response measurements and further evaluated the viability of the PDs for optical communication in a 10, 15, and 40 Gb/s system. The test setup of the impulse-response measurement is summarized in Fig. 4(a). We coupled the optical pulse with a full width at half-maximum (FWHM) of 100 fs from the 1550 nm femtosecond fiber laser (Toptica FemtoFErb 1560) to the PD under test and observed the electrical pulse from our PDs on a 70-GHz-bandwidth sampling oscilloscope (Tektronix 80E11). An electrical pulse with 10 ps FWHM was generated by the PD with a length of 2.0 μ m, as



Fig. 3. (a) Dark current and photocurrent at 1310 nm and 1550 nm of a PD with a length of 2 μ m; (b) dark currents at -1 V measured from the PDs with lengths of 0.5, 1.0, 2.0, and 5.0 μ m; (c) photocurrent at 1310 nm and 1550 nm of devices with various lengths; (d) photocurrent of the PD with 2.0 μ m length at 1550 nm under elevated effective incident power from 1 μ W to 400 μ W; (e) photocurrent of the PD with 2.0 μ m length at various reverse bias as a function of the effective incident power; (f) responsivity at different wavelengths from 1240 nm to 1650 nm.



Fig. 4. (a) impulse-response measurement setup; (b) output electrical pulse measured from the 2.0 μ m long device with FWHM of around 10 ps; (c) frequency response obtained by Fourier transform; (d) data transmission experimental setup, VOA, variable optical attenuator; (e) Measured eye diagrams at 10, 15, and 40 Gb/s for the PD with 2.0 μ m length.

shown in Fig. 4(b). The tail may stem from the reflections at the III-V/oxide interface underneath the III-V segments. Limited by the analog bandwidth of the setup, no improvement of the FWHM of the output pulse was observed when increasing the bias or on devices with smaller dimensions. The 3 dB bandwidth is then calculated to be 40 GHz according to the time-bandwidth product $\Delta f \cdot \Delta t = 0.441$, where Δf is the 3 dB bandwidth of the PD, and Δt is the FWHM of the output pulse [36]. Figure 4(c) shows the 3 dB bandwidth of around 40 GHz extracted by the Fourier transform of the measured time-domain data. We then characterized the data communication performance of the PDs at 1550 nm. The non-return-to-zero on-off keying pseudo-random bit sequence data pattern was generated by the pulse pattern generator at 10, 15, and 40 Gb/s due to the available electrical clock sources in the lab. Figure 4(d) illustrates the experimental setup of the eye-diagram measurements. Light from the laser went through the fiber polarization controller, Mach-Zehner modulator, and erbium-doped fiber amplifier (EDFA) before being coupled to the PD under test. The converted electrical signal was boosted by a radio-frequency amplifier and captured by the sampling oscilloscope. Eye diagrams obtained at 10, 15, and 40 Gb/s for the PDs with a length of 2.0 μ m are presented in Fig. 4(e). The clearly open eye diagrams demonstrate the high-speed feature of our PDs and prove their capability of practical applications in optical communications. Similar to the impulse-response measurement,

we are not able to demonstrate eye diagrams at a higher speed when measuring smaller devices due to the limitation of the experimental setup. We also performed static and high-speed characterizations of the QW PDs and summarized the comparison with InGaAs PDs with a 0.5 μ m length in Table 1. The QW PDs feature a lower dark current and a similar 3 dB bandwidth. The dark currents of the QW PDs with different lengths are all lower than 2 nA.

To demonstrate the feasibility of interfacing the PDs with Si waveguides, we designed waveguide-coupled PDs and simulated the coupling efficiency, as shown by the schematic in Fig. 5. As the epitaxial InP and the Si device layer feature a co-planar configuration, in our design, we adopted butt coupling schemes to efficiently interface the Si waveguides and the III-V PDs. Waveguides with a width of 600 nm and PDs with a 6.0 μ m width and 5.0 μ m length were applied for this design. The InGaAs absorbing layer was designed to be 400 nm wide to provide a high photo-response. We can also shallow etch the *p*-InGaAs and *n*-InP to form a ridge at the InGaAs absorbing region to further improve the responsivity. The III-V PD and Si waveguide are in the same plane with an identical height of 480 nm, which eliminates the loss induced by the height mismatch. As a result, the coupling efficiency is mainly influenced by the gap between the end facet of the III-V PD and Si waveguide. We simulated the coupling efficiency for various gaps using 3D lumerical finite-difference time-domain (FDTD) solutions. To improve the coupling efficiency, we fill

Table 1. Performance Comparison of QW PD and InGaAs PD with the Same Length of 0.5 μ m

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PD Gain Material	Lowest Dark Current at –1 V (nA)	Responsivity (A/W)	Operation Wavelength Range (nm)	3 dB Bandwidth (GHz)
Bulk InGaAs	0.55	0.8 (1310 nm) 0.3 (1550 nm)	Over 400 (1240–1650)	Beyond 40
InP/InGaAs QW	0.12	0.6 (1310 nm) 0.2 (1550 nm)	Over 400 (1240–1650)	Beyond 40



Fig. 5. Schematic of the designed waveguide-coupled III-V PD and coupling efficiency between the PD and Si waveguide at various gaps.

the gap with oxide in the calculation to reduce the reflections and cover the Si waveguide with oxide cladding to minimize the light leakage into the substrate. By adding the top oxide cladding layer, reasonable coupling efficiency can be achieved at relatively large gaps, which makes it promising for future experimental demonstration. Figure 5 presents the simulated coupling efficiency for gaps between 100 nm to 1000 nm. Efficiency up to 80 % can be achieved when the gap is 100 nm. When the gap broadens to 1000 nm, the coupling efficiency reduces accordingly to about 30%. Inverse tapers can be included in the Si waveguides to further enhance coupling efficiency and add tolerance to coupling gaps.

4. CONCLUSION

In conclusion, we demonstrated high-performance III-V PDs on a monolithic InP/SOI platform with CMOS compatible in-plane structures and flexible dimensions. The PDs feature a 3 dB bandwidth exceeding 40 GHz, a responsivity of 0.3 A/W at 1550 nm and 0.8 A/W at 1310 nm, an operation wavelength span over 400 nm, and a dark current of 0.55 nA. In addition, the PDs can be potentially light interfaced with Si waveguides using butt coupling strategies. These III-V PDs on a monolithic InP/SOI monolithic platform are qualified candidates for future data communications in Si photonics, and the potential of achieving lasers on this platform further paves the way towards fully integrated Si photonics.

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Data Availability. Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

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