Development of zero-bias photodiodes, segmented waveguide photodiodes, and heterogeneous photodiodes on silicon nitride.

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1. Introduction

My research centers around high-performance integrated photodetectors with applications in many fields such as optical fiber communications, microwave photonics, quantum optics, and integrated silicon photonics. In these applications photodetectors with low dark current, high responsivity, high bandwidth, and low power consumption are always required. A bias free photodetector with zero DC power consumption has applications in radio frequency links and photonic antenna remoting. In my work, a zero bias photodetector with over 40 GHz bandwidth is demonstrated. I also designed and fabricated a novel segmented waveguide photodetector with high quantum efficiency to be potentially used as a photon number resolving (PNR) detector. As in silicon photonics, heterogeneous integration is a promising method to integrate III-V photodiodes on low-loss photonic platforms. For the use in a direct on-chip digital optical synthesizer (DODOS), I also have demonstrated high performance waveguide photodiodes heterogeneously integrated on a silicon nitride platform.

1.1 Zero-bias photodetectors

High power and high-speed photodiodes (PDs) are key components in ultra-broadband analog photonic applications [1-2]. To achieve large bandwidth and high RF output power conventional PDs usually necessitate a bias circuitry and are driven under a high external reverse voltage. Together with large photocurrents, this can lead to device heating and eventually thermal failure. To reduce thermal stress on the PD and to minimize system complexity, zero-bias operation of the PD is desired. Previously, Umezawa et al. have reported a bias free InGaAs/InP uni-traveling carrier PD (UTC-PD) with an output power of -7 dBm at 100 GHz [3]. Jin-Wei Shi et al. have reported a GaAsSb/InP UTC-PD with -13.9 dBm at 160 GHz in ref. [4].

In chapter 2, I present a zero-bias GaAsSb/InP PD with 40 GHz bandwidth and high saturation power -2.8 dBm.

1.2 High Quantum Efficiency Waveguide Segmented PDs

High speed and high quantum efficiency photodiodes are key devices in optical communications, sensing, and microwave photonics. To overcome the well-known bandwidth-efficiency trade-off in normal incidence PDs, side-illuminated or waveguide-photodiodes have been developed [5-6]. Waveguide PDs provide high responsivity and short carrier transit time since electrical and optical transports are not collinear. As most waveguide PDs are butt- or evanescently coupled, their responsivity primarily scales with the length of the absorption layer which can negatively impact the bandwidth and dark current in high-responsivity PDs.

In chapter 3, I describe a novel monolithically integrated InP-based p-i-n segmented waveguide photodetector consisting of 6 PDs that are coupled to one waveguide. Optical coupling from the waveguide into the PD absorber and back into the waveguide was accomplished by using a vertical directional coupler design. Light that is not absorbed
by the first PD couples back into the waveguide and is absorbed in one of the following PDs. We show that the segmented photodetector can achieve near-unity quantum efficiency by using an array of 32 μm long photodiodes with an absorber thickness as small as 30 nm. This type of photodetector has applications in velocity-matched travelling wave PDs [7] and low dark-count photon-number resolving detectors [8] which require minimized absorber volumes and high quantum efficiency.

1.3 High-performance III-V photodiodes on silicon

Heterogeneous silicon photonics is a promising platform for integrated microwave photonics applications that require high-performance active devices. For the integration of III-V photodiodes on silicon, various integration approaches have been reported, including adhesive wafer bonding [9], direct molecular wafer bonding [10], and direct III-V material growth on Si [11]. Among the bonding techniques, SU-8 bonding is attractive since it requires a low-temperature process and can tolerate a considerable amount of surface roughness.

In chapter 4, I demonstrate back-illuminated high-power modified uni-traveling carrier PDs on silicon using a thin SU-8 bonding layer for the first time. The measured RF output power levels of 5.8 dBm at 9 GHz and 4 dBm at 18 GHz compare favorably to published results from top-illuminated uni-traveling carrier type germanium PDs on Si (3.7 dBm at 3 GHz, [12]) and III-V PDs that were directly grown on Si (-3.4 dBm at 8 GHz, [11]).

1.4 High-Responsivity Photodiodes Heterogeneously Integrated on Silicon Nitride Waveguides

The silicon nitride (Si₃N₄) photonic platform is known for its low propagation loss, broad optical transparency window from near-UV to mid-IR, high performance passive components, and optical frequency comb generation in micro-resonators [13]. However, and in contrast to silicon-on-insulator (SOI), the silicon nitride platform lacks monolithic active components, which are necessary to build photonic integrated circuits with enhanced functionality. To date, only few heterogeneous integrations with group III-V waveguide photodiodes (PDs) have been demonstrated [14, 15]. In ref. [15], an intermediate tapered silicon coupler between the Si₃N₄ waveguide and the PD active region was used, and the fiber-coupled responsivity was 0.36 A/W at 1550 nm wavelength.

In chapter 5, I demonstrate a novel integration method which maximizes evanescent light coupling into the photodiode’s absorber by using a thin (100 nm) bonding layer in a bonding window with reduced thickness of the waveguide top cladding. Fiber-coupled responsivities of 0.68 A/W and 0.24 A/W were measured at 1550 nm and 1064 nm, respectively, for a 25 μm long photodiode. Balanced photodiodes of this type have a bandwidth of 7 GHz and over 40 dB common mode rejection ratio (CMRR).
2. Zero-bias photodetectors

2.1 Device design

To achieve high output power and large bandwidth at zero bias we designed the epitaxial layer structure shown in Fig. 1. In contrast to the high-power InGaAs/InP modified uni-traveling carrier (MUTC) PD in ref. [16], here we used GaAsSb instead of InGaAs as the absorber material. This eliminates the discontinuity in the conduction band between the absorber and the InP drift layer which is known to impede electron transport across the interface at high photocurrent levels [16]. The epitaxial structure was grown on InP and consists of a 300 nm-thick lightly graded doped InP drift layer for space-charge compensation and a 250 nm-thick graded doped GaAsSb absorber. The

![Figure 1. Epitaxial structure of the PD. All layers are lattice-matched to InP.](image)

![Figure 2. Simulated band diagram at 0 V at different photocurrents.](image)
simulated band diagrams at different photocurrents are shown in Fig. 2. In order to provide high bandwidth and high saturation power under zero-bias, the doping concentrations were carefully designed to achieve electron velocity over-shoot in the drift layer. The PDs were fabricated as double-mesa photodiodes by using conventional dry etching techniques. The PDs were connected to gold-plated coplanar waveguide (CPW) RF pads through an air-bridge.

2.2 Characterization

The microscope picture of a 10 μm diameter PD and the dark currents of fabricated PDs with different diameters are shown in Fig. 3. We measured dark currents in the range of 100 nA at a bias of -3 V. The responsivity was measured at 1550 nm wavelength and 0 V bias and was 0.2 A/W. We expect that a responsivity of 0.27 A/W can be achieved once a single-layer anti-reflection coating is applied.

Figures 4 and 5 show the measured frequency responses for different photocurrents at 0 V and -1 V bias, respectively. At 0 V bias, the bandwidth is 40 GHz up to 2 mA, and 35 GHz at 5 mA. The decrease of bandwidth with higher photocurrent can be explained by the space charge effect. At -1 V bias, the bandwidth remains over 50 GHz for all measured photocurrents. The capacitance of a 10 μm diameter PD measured at 0 and -1 V bias was 72 fF and 55 fF, respectively, corresponding to an RC-limited bandwidth of 44 GHz and 57 GHz assuming a 50 Ω load. The fact that the bandwidth is limited by RC implies that a higher bandwidth can be expected by reducing the PD area.

Figure 3. Top-view of a fabricated PD (inset) and dark current versus voltage for PDs with different diameters.
Figure 4. Measured frequency responses of 10 μm diameter PD at zero bias.

Figure 6 shows the saturation characteristics of a 10 μm diameter PD measured at 40 GHz at different voltages. We measured -2.8 dBm, 9.3 dBm, 12.5 dBm and 13.2 dBm at 0 V, -1 V, -2 V and -3 V, respectively. At a forward bias of 0.2 V we obtained -14.1 dBm at 40 GHz. The saturation current of the PD is 7.5 mA under zero bias. The results indicate that the output power is mainly limited by the space charge effect in the depletion region.

Figure 5. Measured frequency responses of 10 μm diameter PD at -1 V bias voltage.

Figure 6. RF output power and RF compression at different bias voltages.
2.3 Conclusion

By optimizing the doping concentration in a GaAsSb/InP modified uni-traveling carrier PD we demonstrated a 10 μm diameter PD with 40 GHz bandwidth, 7.5 mA saturation current and -2.8 dBm RF output power at zero-bias.

3. Segmented waveguide photodetector with 90 % quantum efficiency

3.1 Device design

In collaboration with Professor Olivier Pfister’s group in physics, our group has proposed a novel PNR detector which is based on segmented waveguide PDs sharing same waveguide while achieving high quantum efficiency in total. In such design, light should be absorbed in these segmented PDs separately with low radiation loss. Fig. 7 (a) shows the proposed photodiode cross-section. The passive waveguide (WG1) is embedded between two lower index cladding layers and serves as the input waveguide of the photodetector. The upper cladding layer is used to separate WG1 from the second waveguide, the absorption waveguide (WG2). Adding these extra layers does not sacrifice bandwidth performance because they serve as electron drift region similar to the collection layer in dual-depletion region [17] and uni-traveling carrier PDs [18]. The light coupling process in and out of the PD can be recognized as a co-directional coupler problem as illustrated in Fig. 7 (b). To ensure complete coupling, the goal is to achieve phase match, i.e. matching the propagations constants of the modes in WG1 and WG2.

Fig. 7 (a) Cross-section of waveguide photodiode; (b) Light propagating in the segmented waveguide photodetector; (c) Intensity distribution of the symmetric (even) and anti-symmetric (odd) supermodes in the cross-section.

Fig. 7 (c) shows the intensity distribution of the symmetric (even) and anti-symmetric (odd) supermodes in the cross-section. Based on the theory of mode coupling [19-20], the field distribution $\phi_1(z)$ in WG1 and $\phi_2(z)$ in WG2 can be represented by adding the even mode field $\varphi_e$ and the odd mode field $\varphi_o$ [21]:

$$
\phi_1(z) = a_1 \varphi_e \exp(-i\beta_e z) + a_2 \varphi_o \exp(-i\beta_o z)
$$
\[ \varphi_2(z) = a_3 \varphi_e \exp(-i \beta_e z) + a_4 \varphi_o \exp(-i \beta_o z) \] (1)

Where \( \beta_e \) and \( \beta_o \) stand for the corresponding propagation constants of these two modes and \( a_1, a_2, a_3, \) and \( a_4 \) are the coupling coefficients. When light is launched into WG1 at \( z=0 \), it follows:

\[ \varphi_2(0) = a_3 \varphi_e + a_4 \varphi_o = 0 \] (2)

In order to ensure low radiation loss, light has to completely couple back from WG2 into WG1 at the rear facet of the PD, hence it is necessary to make \( \varphi_2(l_{pd}) = 0 \). Combining with the initial conditions (eq.2), the propagation constant of the odd and even modes should follow:

\[ \exp[-i(\Delta \beta)l_{pd}] = 1 \] (3)

Here \( \Delta \beta \) is the difference between the even and odd mode propagation constants defined as: \( \Delta \beta = \beta_e - \beta_o \). Defining \( \Delta \beta_r \) and \( \Delta \beta_i \) to be the real and imaginary parts of \( \Delta \beta \), eq. (3) becomes:

\[ \exp(\Delta \beta IL_{pd}) \cdot \exp(-i \Delta \beta_r l_{pd}) = 1 \] (4)

In order to satisfy above equation, it is imperative to make \( \Delta \beta_i = 0 \). This means, that the propagation constants of the odd and even modes have the same imaginary part. Or, in other words, only when even and odd modes attenuate at the same rate, a complete transfer of optical power between WG1 and WG2 is possible. Moreover, the PD length \( l_{pd} \) is concluded to be multiples of the beat length \( l \), defined as:

\[ l = 2 \cdot \pi / \Delta \beta_r \] (5)

### 3.2 Simulation

To calculate the field distributions and propagation constants, I used the commercial software Fimmwave. In the design process I started from the simplified structure as shown in Fig. 7(a). Since changing the thickness of the cladding layer between WG1 and WG2 will change \( \beta_o \) and \( \beta_e \) simultaneously, we kept this parameter to be 220 nm to ensure sufficient field overlap between WG1 and WG2. At the same time the thickness of WG1 should be thick enough to ensure minimal field overlap with the highly doped n-contact layer and to prevent free-carrier absorption. However, a thick WG1 layer decreases the coupling efficiency from WG1 to WG2 owing to a better mode confinement. In the design I chose a 500 nm thick WG1 that can provide both, a low free-carrier absorption and a strong coupling. For moderate absorption in the first PD, the thickness of InGaAs in WG2 cannot be too thick. Sandwicking an only 30-nm thin InGaAs layer between the two InGaAsP layers results in a similar propagation constant of WG1 and WG2 with a low effective absorption coefficient in WG2.
Fig. 8 (a) Real part of propagation constant and mode beat length vs. WG2 thickness. (b) Imaginary part of propagation constants vs. WG2 thickness.

After adopting two InGaAsP layers sandwiching a 30 nm InGaAs layer as WG2, the relationships between real part of the propagation constants ($\beta_r$) and thickness of WG2 are shown in Fig. 8 (a). Here, the WG2 thickness is the total thickness of the InGaAs absorption layer and the InGaAsP layers. The $\beta_r$ of the odd and even mode are both linear with the thickness of WG2. Using eq. (5), the beat length determined by the difference of the even and odd modes’ propagation constants is also shown in Fig. 8 (a). The beat lengths range from 23 $\mu$m to 33 $\mu$m when the thickness of WG2 changes from 0.3 $\mu$m to 0.55 $\mu$m. In order to ensure that light couples back from WG2 to WG1, the PD length can only be an integral multiple length of the beat length. For the 30 nm thick InGaAs layer being sandwiched by two 220 nm thick InGaAsP layers, each segmented PD element should be around 30 $\mu$m. Fig. 8 (b) shows the simulated imaginary part of propagation constant ($\beta_i$) of the odd and even modes. We found that $\beta_i$ of the even mode increases with WG2 thickness while the odd mode behaves vice versa. When the thickness of WG2 is 470 nm, both modes exhibit the same $\beta_i$, i.e eq. (4) is satisfied. According to Fig. 8 (a), the beat length is 32 $\mu$m in this situation.

Fig. 9 (a) shows the complete epitaxial layer structure of the segmented waveguide photodetector that was grown on InP substrate by metal organic chemical vapor deposition. The 300 nm thick Si-doped InP layer serves as the n-type contact layer followed by an intrinsic 300 nm thick InP layer as the lower cladding. I used a 500 nm
thick intrinsic InGaAsP layer as WG1 and a 220 nm thick intrinsic InP cladding layer to separate WG1 and WG2. Two InGaAsP layers sandwich the 30 nm thick InGaAs absorption layer to form WG2. The p-type contact layer is composed of a 500 nm thick highly doped InP and a 50 nm thick top InGaAs layer. Layers of InGaAsP Q1.1 layers were used to reduce the band-discontinuities at the heterojunction interfaces between the InP and InGaAsP Q1.4 layers [16]. Fig. 9 (b) shows the simulated total power in the segmented photodetector with 3 elements. It can be seen that in each PD, the light power decays exponentially. Assuming a lossless WG1, the power remains constant in the regions between PD segments. The simulation also predicts that, the light couples completely back into WG1 at each PD’s rear end.

### 3.3 Fabrication and characterization

A double mesa process was used to fabricate the PDs. To address the tight alignment tolerance between feeding waveguide and photodiode mesa, I developed a process that defines both features in one step. The fabrication flow is summarized in Fig. 10. After blanket deposition of the p-metal, we patterned a SiO₂ hard mask and formed a ridge structure. The first mesa etch stopped at the InP n-contact layer to define WG1. Then, the n-metal was deposited. Next, a second hard mask was used to form WG2 and the n-mesa. By this way, we achieved that WG1 and WG2 have a uniform width. AuGe/Ni/Au and Ti/Pt/Au were used for n-metal and p-metal contacts, respectively. Photodiodes were connected to gold-plated pads through air-bridges, as shown in Fig. 11 (b). I also fabricated single PDs with coplanar waveguide RF pads to characterize the bandwidth. Finally I cleaved the waveguide facet for input light coupling.

![Fabrication process](image)

To account for uncertainties of the material refractive indices in the simulations arrays with photodiode’s lengths ranging from 20 μm to 40 μm were fabricated. All PDs in an array were probed individually. I measured uniform I-V characteristics with dark currents of 1 μA at 3 V reverse voltage. I expect that the dark current can be further reduced with an appropriate side wall passivation.

The frequency responses of single PDs are shown in Fig. 11 (c). The data was obtained under large-signal modulation by using an optical heterodyne setup at 1550
nm. It can be seen that a smaller PD area leads to higher bandwidth owing to the reduced capacitance. A photodiode with an active area of 15 x 20 μm² reached a bandwidth of 20 GHz.

Fig. 11 (a) Microscope picture of fabricated segmented waveguide photodetector, (b) SEM pictures of PD and waveguide, (c) Bandwidth measurements of single photodiodes with different areas from the same wafer.

Using a lensed fiber with 2.5 μm spot size diameter, the quantum efficiency was measured as a function of PD length in single waveguide photodiodes. First we measured several 300 μm long single PDs to characterize the coupling loss from the fiber to the waveguide. According to our simulation, a 300 μm long PD should have an internal QE of 99%. Based on the measured external QE of (35±2) %, the coupling loss from the fiber into the waveguide was calculated to be 4.5 dB. In the analysis, 1.5 dB loss are attributed to reflection at the facet since no anti-reflection coating was used. The remaining loss of 3dB agrees with the simulated coupling loss due to mode mismatch from the fiber mode to the waveguide mode.

Using 4.5 dB as the coupling loss, Fig. 12 (a) shows the internal QE of single PDs of different length. The data shows that the QE only depends weakly on PD width. For a fixed width, longer PDs consistently show higher QE owing to the longer absorption length. As expected and due to mode beating phenomena, the QE scales in a non-linear fashion with PD length. This explains the flat region around the calculated beat length of 30 μm in Fig. 12 (a), which indicates that in this region the QE does not increase as light couples back into WG1.

Fig. 12 (a) Simulated and measured internal QE of single PDs with different widths vs. PD length, (b) Total internal QE of the segmented waveguide photodetector. The error bars come from the uncertainty in determining the input coupling loss.
The total QE of a 6 element segmented waveguide photodetector is shown in Fig. 12 (b). To determine the internal QE we added the photocurrent of the first 4 PDs in the array that were measured simultaneously, and corrected for the 4.5 dB input coupling loss. As expected from simulation, the contributions from the 5th and the 6th PDs in the array were negligible. The results show that the total internal QE increases for PD lengths larger than are 20 μm. At 32 μm PD length, the QE reaches its peak value around 90% corresponding to 1.13 A/W. For longer PDs, the radiation loss prevails leading to a decrease in total QE. The black line in Fig. 12 (b) shows the total QE by simulation. It can be seen that the measurement agrees well with the simulation within the error bars. The fact that the measurement exhibits excess loss can be explained by the following reasons. First, the refractive indices that we used in the simulation may not be accurate. Together with small variations in the epitaxial layer thicknesses this may lead to a mismatch of the propagation constants of WG1 and WG2. Moreover, I did not include any waveguide loss between PD segments in the simulations.

### 3.4 Conclusion

A novel segmented waveguide photodetector based on a directional coupler design has been demonstrated. By matching the imaginary parts of the propagation constants of the even and odd modes in the design, a 6 element photodiode array achieves an internal responsivity as high as 1.13 A/W in agreement with simulations. We believe that this design finds applications in travelling wave PDs and in recently proposed photon number resolving detectors that benefit from near-unity quantum efficiency and minimized active volumes.
4. High-performance III-V photodiodes on silicon

4.1 Experimental

Adhesive bonding is one of the possible methods for III-V on silicon photonics heterogeneous integration. Here we used SU-8 as bonding media to bond an III-V die on silicon. Then we processed the PD fabrication afterwards. Figure 13 (a) shows the layer structure of the modified uni-traveling carrier photodiode bonded onto silicon after substrate removal. The III-V epitaxial structure was grown on InP by MOCVD and consists of a 700 nm graded doped p-type InGaAs absorber, a 150 nm depleted InGaAs absorber and a 950 nm InP drift layer. The quaternary InGaAsP layers were designed to reduce the bandgap discontinuity at the heterojunction interface between the InP and InGaAs layers [16]. The die bonding process was adopted from [22] in collaboration with Prof. Weikle’s group and includes SU-8 spin coating, soft bake at 110°C, UV exposure followed by a 40-minute outgas, and curing at 130°C under 10 Psi for 30 min. The final adhesive layer of SU-8 was approximately 250 nm thick (Fig. 13 c). After using HCl to selectively etch the InP substrate, I fabricated double-mesa photodiodes using conventional wet and dry etching techniques. Microwave probe pads were deposited on SU-8 and connected to the PD n-contacts through air-bridges (Fig. 13 (b) and (d)).

Typical dark currents were 5 μA at 5 V reverse bias. Since these PDs were not passivated, we expect that the dark current can be further reduced in future runs with an appropriate side wall passivation. Using a fiber collimator for back-illumination through the silicon substrate we measured a responsivity of 0.49 A/W at 1550 nm wavelength (no anti-reflection coating).
Fig. 14 (a) Measured frequency responses of 10-μm and 20-μm diameter PDs at 8 V reverse bias and 10 mA average photocurrent. (b) Frequency responses under different photocurrents for a 20-μm diameter PD at 8 V reverse bias.

The PD frequency responses shown in fig. 14 (a) were obtained under large-signal modulation using an optical heterodyne setup at 1550 nm wavelength. At 8 V reverse bias and 10 mA, we measured bandwidths of 18 GHz and 11 GHz for a 10 μm and 20 μm diameter PD, respectively. The frequency responses of the 20 μm diameter PD under different average photocurrents are shown Fig. 14 (b). We observed a bandwidth enhancement effect from 5 GHz to 11 GHz when the photocurrent increases from 1 mA to 20 mA which can be attributed to the self-induced field in the un-depleted absorber [23].

Fig. 15 RF output power and compression curve versus average photocurrent at (a) 9 GHz for a 20-μm PD; and (b) 18 GHz for a 10-μm PD.

RF output power and compression were measured at a fixed beat frequency and different reverse voltages (Fig. 15). For the 20-μm and 10-μm diameter PDs, we recorded RF output power levels at the 3 dB cut-off frequencies as high as 5.8 dBm and 3.9 dBm, respectively. For the 10 μm PD, the saturation currents at 1 dB compression were 12 mA, 10 mA and 7.5 mA at 8 V, 6 V and 4 V, respectively. The saturation current reached 20 mA at 8 V for the 20 μm diameter PD. It should be mentioned that no thermal device failure was observed during these measurements.

To characterize photodiode linearity, I used an optical three-tone setup with each laser modulated by a Mach-Zehnder modulator. I determined the equivalent two-tone output third order intercept point (OIP3) from the measured intermodulation distortions.
(IMD3) [24]. At 15 mA, the OIP3 reached 28.5 dBm and 22.5 dBm at 1 GHz and 9 GHz, respectively (Fig. 16a). The OIP3 versus photocurrent for a 20-μm diameter PD is summarized in Fig. 16 (b). Consistent with previous measurements from uni-traveling carrier type PDs we found that the OIP3 increases with higher photocurrents [9].

![Fig. 16 20 μm diameter device (a) 1 GHz and 9 GHz IMD3 with different photocurrent; (b) OIP3 at 1 GHz and 9 GHz versus different photocurrent.](image)

### 4.2 Summary

InP-based modified uni-traveling carrier photodiodes heterogeneously integrated on silicon substrate using a low-temperature SU-8 bonding process are demonstrated. The photodiodes reach bandwidths up to 18 GHz, large saturation currents up to 20 mA, and an OIP3 as high as 28.5 dBm at 1 GHz.

### 5. High-Responsivity Photodiodes on Silicon Nitride Waveguides

#### 5.1 Experimental

Complex photonic systems that use a multitude of devices based on different material systems benefit from heterogeneous integration. In the DODOS project, our group has been tasked with the development of balanced PDs on Si$_3$N$_4$ waveguides with one pair PDs of high responsivity at 1064 nm and the other pair of PDs over 15 GHz bandwidth at 1550 nm. A promising approach to achieve this goal are heterogeneously integrated PDs on Si$_3$N$_4$ waveguide to make high performance III-V PDs on Si$_3$N$_4$ waveguides. The Si$_3$N$_4$ strip waveguides were deposited using low pressure chemical vapor deposition (LPCVD) with a thickness of 400 nm and widths of 1 or 2 μm (waveguide fabrication by Ligentece). The thicknesses of the top and lower SiO$_2$ claddings were 3 μm and 7 μm, respectively. For bonding the InGaAs/InP photodiode material, the top SiO$_2$ cladding was selectively reduced to 80 nm in an area of 6.5 x 5.5 mm$^2$ which defined the bonding window.
Fig. 1. Schematics of (a) Si$_3$N$_4$ waveguide, (b) Si$_3$N$_4$ waveguide with reduced top cladding, and (c) integrated photodiode; (d) schematic overview of the chip; (e) chip with patterned waveguides, and (f) after InGaAs/InP die bonding; (g) finished chip with heterogeneous photodiodes.

Schematic cross sections and an illustration of the chip are shown in Figs. 17 (a) – (d). The PD structure was grown on a 2" InP wafer and included a 200 nm-thick P-doped InP contact layer, a 1250 nm-thick InGaAs absorption layer, and a 600 nm-thick N-doped InP contact layer. Low-temperature adhesive bonding [25] was used to attach the 5 x 4 mm$^2$ die with the epitaxial photodiode layer stack in the bonding window (Fig. 17 (e) and (f)). The thickness of the SU-8 (refractive index: 1.57 at 1550 nm) bonding layer was around 100 nm resulting in 180 nm distance between Si$_3$N$_4$ waveguide and photodiode layers. After InP substrate removal by hydrochloric acid, I used conventional wet etching techniques to fabricate double mesa single and balanced photodiodes. Microwave probe pads were deposited on SiO$_2$ and connected to the PD contact metals through air-bridges. An image of the fabricated chip is shown in Fig. 17 (g).

![Fig. 17 Schematics of (a) Si$_3$N$_4$ waveguide, (b) Si$_3$N$_4$ waveguide with reduced top cladding, and (c) integrated photodiode; (d) schematic overview of the chip; (e) chip with patterned waveguides, and (f) after InGaAs/InP die bonding; (g) finished chip with heterogeneous photodiodes.](image)

Fig. 18. Measured photocurrent V.S. fiber-coupled input optical power for different PDs with different dimension (width x length). (a) Laser wavelength 1550 nm, (b) Laser wavelength 1064 nm.

The responsivities at 1550 nm and 1064 nm were both measured with single mode tapered fibers with a spot size of 2.5 μm. The fiber-coupled responsivities for a 25 μm long PD were 0.68 A/W and 0.24 A/W at 1550 nm and 1064 nm, respectively. From
Fig. 18 (a) we found that the responsivity at 1550 nm did not have a strong dependence on the PD length implying that even shorter PDs with similar responsivity should be possible. At 1064 nm, the optical mode in the $\text{Si}_3\text{N}_4$ waveguide is more confined which makes the coupling into the absorption layer less efficient than at 1550 nm. This explains why photocurrent scales with photodiode length for a given optical input power in Fig. 18 (b). A maximum responsivity of 0.26 A/W was measured for a $10 \times 70 \, \mu\text{m}^2$ PD. We found no significant difference between PDs on 1 $\mu$m and 2 $\mu$m-wide $\text{Si}_3\text{N}_4$ waveguides in this measurement. The fiber-chip coupling loss was determined from simulations and was 0.7 dB at 1550 nm and 4 dB at 1064 nm. This large difference is due to a stronger mode confinement at shorter wavelengths, which results in smaller mode size and thus larger mismatch with the 2.5 $\mu$m input spot. Once we took the coupling loss into account, the internal responsivities were 0.8 A/W and 0.6 A/W, corresponding to 64% and 69% internal quantum efficiency at 1550 nm and 1064 nm, respectively. The polarization dependent loss was 0.45 dB at 1550 nm and only 0.08 dB at 1064 nm for PDs on 2 $\mu$m wide $\text{Si}_3\text{N}_4$ waveguides.

As shown in Fig. 19 (a), the dark currents of both photodiodes (PD1 and PD2) in a balanced photodetector were 10 nA at 4 V reverse bias. A relatively large series resistance around 1.25 k$\Omega$ can be derived from the curves in forward bias, which is due to a relatively low doping level (1 x $10^{18}$/cm$^3$) in the P-doped contact layer. Nevertheless, and as shown in Fig. 19 (b), a bandwidth of 7 GHz was achieved for both 20 $\times$ 10 $\mu$m$^2$ PDs under large-signal modulation using an optical heterodyne setup at 1550 nm wavelength. A higher bandwidth can be expected once the series resistance is reduced by using a higher doping in the contact layer.

In order to characterize the CMRR at 1550 nm, light was modulated by an optical modulator and split by a fiber-based 3 dB coupler into two branches before being launched into the waveguides of PD1 and PD2 through a fiber array. We used variable optical delay lines in both branches to adjust the RF phase of the modulated optical signal to be either in phase (common mode) or out of phase (differential mode). The CMRR was then calculated by subtracting the measured power in common mode from the power in differential mode. Figure 20 (a) shows the RF powers in common and differential modes at 8 GHz as measured with an electrical spectrum analyzer indicating a CMRR of 42.5 dB. As shown in Fig. 20 (b), the CMRR of the balanced photodetector was characterized from 2 GHz to 15 GHz with 0.1 mA photocurrent and 4 V reverse bias. The differential mode bandwidth agreed well with our bandwidth measurements that were obtained from individual measurements of PD1 and PD2. The CMRR was 50 dB within the 3-dB bandwidth and over 40 dB up to 15 GHz indicating an excellent symmetry of both PDs.
5.2 Conclusion

Heterogeneous InGaAs/InP photodiodes on Si₃N₄ waveguides based on a thin adhesive layer and a reduced-top cladding bonding window are developed. This new integration method improves the efficiency of the light coupling from the waveguide into the photodiode and enables internal responsivities as high as 0.8 A/W at 1550 nm and 0.6 A/W at 1064 nm. Balanced photodiodes of this type have a low dark current and reach a bandwidth of 7 GHz with over 40 dB CMRR from 2 GHz to 15 GHz making this device an ideal candidate for Si₃N₄ photonic integrated circuits.
6. Future work

My future work will mainly focus on optimizing the performance of PDs on the Si$_3$N$_4$ platform. While previous device results have met the requirements in terms of low dark current and high responsivity over a wide spectral range, the bandwidth was lower than expected. The DODOS project calls for balanced PDs with 15 GHz bandwidth while only 7 GHz was achieved up to now. To this end I will design a new epitaxial layer structure aiming for 15 GHz and more than 70% quantum efficiency. Moreover I will develop a wafer epitaxial layer design for 50 PDs PNR system.

6.1 Initial circuit analysis of fabricated PDs

![Smith chart for one balanced PD and simplified equivalent circuit model for such PD.](image)

The measured 3-dB bandwidths of fabricated PIN PDs on Si$_3$N$_4$ waveguide are 3 GHz and 7 GHz for single and balanced PDs, respectively. From the I-V curves, the series resistance can be extracted to be over 1 kΩ. Here in Fig. 21, the red curve shows the measured single device S11 parameter of a pair of balanced PDs. After measuring the capacitance of our PDs, it is possible to fit the S parameter to determine the series resistance. For the balanced PD, I estimated the series resistance to be 260 Ω. With this
resistance, the bandwidth is calculated to be 7.4 GHz as shown in Fig. 22, which is consistent with the bandwidth measurement. In the near future, I plan to measure S11 parameters of single PDs to verify the series resistance.

Fig. 22. Simulated bandwidth with 260 Ω resistance.

6.2 New wafer design for PDs on Si₃N₄ waveguide

As mentioned above, we need to design a new epitaxial structure for higher bandwidth while not sacrificing the responsivity. The modified uni-traveling carrier photodiode as shown in Fig. 2 has been proven to have high bandwidth and high responsivity. Using such a structure for the next run of PD on Si₃N₄ would meet the program requirements.

For the design, I mainly focused on responsivity and bandwidth. For responsivity, the thickness of SU-8 and upper SiO₂ cladding are key parameters affecting the optical coupling. From previous devices, I evaluated the cross-section of PD by SEM-FIB. According to Fig. 24, the SiO₂ cladding and SU-8 are 140-160 nm and 60-120 nm, respectively. Similar to a previous MUTC structure, InP is chosen to be the drift layer and N-contact layer. In the optical simulation, we can treat them as the same layer with the thickness Thick_N as shown in Fig. 24. Figure 25 shows the initial optical
simulation results for 50 μm and 100 μm long PDs with different Thick_N and absorber thicknesses (Thick_I). The power scale bar shows the simulated quantum efficiency. The exact value of Thick_I and Thick_N will be determined by bandwidth the requirements.

Fig. 24. SEM-FIB image for previous PDs on Si₃N₄ and MUTC structure on Si₃N₄ for optical coupling.

Fig. 25. Quantum efficiency simulation with various Thick_I and Thick_N for a 50 μm and 100 μm long PDs.

6.3 Fabricate and characterize new high-speed PDs

Fig. 26 shows the new fabrication flow I designed for the fabrication of the PD on Si₃N₄ waveguide. Based on the fact that SU-8 cannot survive in temperatures higher than 180°C, a SiO₂ hard mask deposited by PECVD cannot be used. Therefore, I used
conventional wet etch to fabricate previous devices. In order to avoid the under-cutting, here I designed such new fabrication flow by using top contact metal as a hard mask. Thick photoresist will be spun onto the chip to protect the passive regions during the following process steps. Moreover, we also could use RF sputtering for SiO$_2$ hard mask deposition which would make the process similar to our group’s conventional dry etching process. However, initial test runs will be required to verify film thickness uniformity and quality.

6.4 Wafer epitaxial design for photon number resolving detector

We have shown the validity of segmented waveguide PDs previously. However PNR system needs not only high quantum efficiency for the whole system but uniform absorption for more than 50 PDs. Based on the previous design, the PD length can only be an integral multiple length of the mode beat length L. Here, 50 segmented PDs are proposed aiming for achieving high photon number resolution. There are twenty PDs with length L, fifteen 2L length PDs, six 4L length PDs, three 6L length PDs and six 10L length PDs as shown in Fig. 27. Different lengths of PDs are designed for achieving similar photocurrent for every PD. We estimated the total radiation losses by simulating the photodetector without including the imaginary part in the absorber layer. From Fig. 27, 50 PDs obtained 7% loss in total. Here I optimized the structure by adding a cladding layer into WG1 for less radiation loss. From Fig. 27, it also can be seen that once making device with length L owing to 2.5% QE, light absorption will be uniform across all 50 PDs. Assuming the implementation of avalanche photodiodes (instead of pin PDs), such kind of design can be used for our photon-number resolution. In my future work, I will design the epitaxial layer structure for segmented PDs with large device count.
List of Publications


[4]. Zhanyu Yang, Qianhuan Yu, Xiaojun Xie, Peng Yao, Christopher Schuetz, Joe C Campbell, Andreas Beling, “High-gain phase modulated analog photonic link using high-power balanced photodiodes.” In Optical Fiber Communication Conference (pp. Th1A-5). Optical Society of America (2017).


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References


[8]. R. Nehra, C. H. Chang, A. Beling, and O. Pfister, University of Virginia, are preparing a manuscript to be called “Photon-number-resolving segmented avalanche-photodiode detectors.”


