Extrinsic photodiodes for integrated mid-infrared silicon photonics: supplementary material

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Details of our experimental setup, error analysis, fabrication procedure, and additional results are provided as supplementary information to “Extrinsic photodiodes for integrated mid-infrared silicon photonics”, <http://dx.doi.org/10.1364/optica.1.000264> © 2014 Optical Society of America

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1. MEASUREMENT SETUP

Our measurement setup is shown in Fig. S1. An external cavity $\text{Cr}^{2+}:\text{ZnSe}$ tunable laser (IPG Photonics) passes through an isolator (ISO) and is free-space coupled to a single-mode fiber (SMF) using a fiber collimator (FC). The SMF is also connected to a polarization rotator (PR) followed by a single-mode lensed-tapered fiber (LTF) designed for a $2.5\ \mu\text{m}$ spot-size and working distance of $14\ \mu\text{m}$ at $\lambda = 1.55\ \mu\text{m}$ (Oz optics). The LTF couples into a $5\ \mu\text{m} \times 220\ \text{nm}$ fan-out tapered silicon waveguide, which adiabatically decreases in width over a length of $450\ \mu\text{m}$ to a $520\ \text{nm} \times 220\ \text{nm}$ channel waveguide. The PR is used to ensure that only the quasi-TE (QTE) mode of the waveguide is being excited, which produces maximum photocurrent as the overlap with the Zn^+ implanted region is larger than that of the quasi-TM mode. The channel waveguide adiabatically tapers into a rib/ridge waveguide with a $50\ \text{nm}$ ridge and the same channel dimensions over a length of $100\ \mu\text{m}$, which then enters the Zn^+ implanted-silicon-waveguide photodiode. Reverse-bias voltage is applied and current is measured using a Keithley 2400 Source/Meter through electrical probes, which are landed on Al contact pads. Power transmitted through the photodiode is out-coupled in an identical manner to the input coupling,

and passes through an SMF patch cable to a Yokogawa AQ6375 optical spectrum analyzer.

2. DETERMINATION OF ERROR BARS

Error bars are determined by uncertainties in losses from the measurement setup, which include lensed-tapered fiber (LTF) losses and single-mode fiber transmission/bending losses. Additionally, uncertainty in the waveguide facet loss from fan-out tapers couplers have also been taken into account and as well as temporal fluctuations in the laser output as tracked by the transmitted power.

The total fiber-to-fiber transmission loss is measured by aligning two lensed-tapered fibers at their focal distance with the sample removed, and is defined in dB as $P_{F2F} = P_{\text{laser}} - P_{\text{OSA}}$, where P_{laser} and P_{OSA} are shown in Fig. S1. This loss is averaged over four measurements to determine the mean and standard deviation, $\bar{P}_{F2F}$ and σ_{F2F} , respectively. The transmission loss through the connecting fiber in dB is found as $P_{CF} = P_T - P_{\text{OSA}}$, and is also averaged over four measurements to find the mean and standard deviation $\bar{P}_{CF}$, σ_{CF} . The loss due to transmission through a single LTF is calculated as $\bar{P}_{LTF} = \frac{1}{2}(\bar{P}_{F2F} - \bar{P}_{CF})$ and the standard deviation is found by propagation of error $\sigma_{LTF} = \frac{1}{2}\sqrt{\sigma_{F2F}^2 + \sigma_{CF}^2}$.

Facet loss was determined by coupling both LTFs to the on-chip $5\ \mu\text{m} \times 220\ \text{nm}$ fan-out tapers, and averaging over 14 transmission measurements through straight waveguides to find $\bar{P}_{FL} = \frac{1}{2}(\mathbb{E}\{P_{\text{laser}} - P_{\text{OSA}}\} - \bar{P}_{F2F})$, resulting in the mean, $\bar{P}_{FL}$, and standard deviation $\sigma_{FL} = \frac{1}{2}\sqrt{\text{var}\{P_{\text{laser}} - P_{\text{OSA}}\} + \sigma_{F2F}^2}$ shown in Fig. S2.

To determine error bars for the responsivity, the on-chip power entering the PD is determined in milliwatts, $\bar{P}_{in}[\text{mW}] = 10^{(\bar{P}_{\text{laser}} - \bar{P}_{FL} - \bar{P}_{LTF})/10}$ and the propagation of error is approximated by a Taylor series expansion $\sigma_{in}[\text{mW}] \approx \bar{P}_{in} \frac{\ln 10}{10} \sqrt{\sigma_{\text{laser}}^2 + \sigma_{FL}^2 + \sigma_{LTF}^2}$. The mean responsivity is calcu-

Fig. S1. Experimental setup. ISO = isolator, FC = fiber collimator, PR = polarization rotator, LTF = lensed tapered fiber.

lated as $\bar{\mathfrak{R}} = \frac{I_{ph}}{\bar{P}_{in}}$ resulting in a standard deviation of $\sigma_{\mathfrak{R}} \approx \bar{\mathfrak{R}} \frac{\sigma_{\bar{P}_{in}}}{\bar{P}_{in}}$.

The error bars for the modal absorption coefficient in Fig. 4 of the main text are determined by measuring the optical power transmission through the PD $\bar{T} = \mathbb{E}\{P_{in} - P_{OSA}\} - 2\bar{P}_{FL} - \bar{P}_{F2F}$ through a PD of length $L = 250 \mu\text{m}$, with the modal absorption coefficient being defined as $\bar{\alpha} = -\bar{T}/L$. The standard deviation is determined by propagation of uncertainty to be $\sigma_{\alpha} = \frac{1}{L} \sqrt{\text{var}\{P_{laser} - P_{OSA}\} + 4\sigma_{FL}^2 + \sigma_{F2F}^2}$. This calculation is repeated with measurements from an un-implanted diode, and the modal absorption coefficient due to Zn^+ implantation is defined as $\bar{\alpha}_{eff,Zn} = \bar{\alpha}_{eff,tot} - \bar{\alpha}_{eff,par}$ with standard deviation $\sigma_{\alpha,Zn} = \sqrt{\sigma_{\alpha,tot}^2 + \sigma_{\alpha,par}^2}$.

Fig. S2. Measured system losses with error bars.

3. DEVICE FABRICATION

Un-implanted *p-i-n* SiWG diodes were fabricated on the CMOS line at MIT Lincoln Laboratory as described in [1] using SOI with a $3 \mu\text{m}$ BOX and with the device dimensions given in Fig. 1(b) of the main text. Subsequently, contact photolithography was used to define a Shipley S1811 implantation mask at Brookhaven National Laboratory, and Zn^+ ion implantation was performed in the Ion Beam Laboratory, State University of New York at Albany. An acceleration voltage of 260 keV was used, corresponding to a stopping range of 118 nm into the waveguide as calculated by SRIM software [2], resulting in the maximum

overlap between the induced defect concentration and the fundamental quasi-TE mode of the waveguide (see Sec. 4). The ion beam was launched 7° from normal incidence to the sample surface, and implantation current densities of $1 \text{ nA}/\text{cm}^2$ and $3\text{-}7 \text{ nA}/\text{cm}^2$ were used for the 10^{12} cm^{-2} and 10^{13} cm^{-2} implantation doses, respectively.

Post implantation, the devices were annealed in atmosphere at 250°C for 10 minutes. Subsequently, a series of anneals were performed with increasing temperatures in 50°C steps for 10 minutes per step. Photocurrent and transmission measurements were taken between each step, and the device performance was found to improve with each annealing cycle. The modal absorption coefficient for the 10^{12} cm^{-2} Zn^+ dose PD at each annealing step is shown in Fig. S3. The absorption peak associated with the E_{d2} to conduction band transition located between $2.325 \mu\text{m}$ and $2.350 \mu\text{m}$ can be seen to emerge with increasing anneal temperature. The annealing temperature was limited to 350°C , since the 100 nm thick Al contacts were found to reflow above this temperature.

Fig. S3. Modal absorption coefficient versus annealing temperature for Zn^+ dosage = 10^{12} cm^{-2} . Each subsequent annealing step was performed in atmosphere for 10 minutes.

4. ESTIMATION OF ZINC AND DEFECT CONCENTRATIONS AFTER IMPLANTATION

The SRIM calculated dose profile is shown in Fig. S4. The averaged Zn concentration in the waveguide is estimated by

integrating the Gaussian fit over the 220 nm length of the silicon device layer, and multiplying by the dose. The ion stopping range is adjusted by changing the acceleration voltage. For the PDs explored here, an acceleration voltage of 260 keV was used to place the stopping range in the center of the Si device layer such that the fundamental quasi-TE mode of the SiWG (Fig 1(b), main text) had maximum overlap with the resultant trap-states.

Fig. S4. SRIM calculated Zn^+ implantation profile for an acceleration voltage of 260 keV.

The amorphization threshold is taken to be the dose for which the concentration of implantation-induced lattice defects accounts for 10% of the total available Si lattice sites. This corresponds to a defect concentration of $5 \times 10^{21} \text{ cm}^{-3}$ for Si. Based on the SRIM calculations the threshold dose for amorphization is $2 \times 10^{13} \text{ cm}^{-2}$; however, these calculations do not take thermal effects into account. Thus, the SRIM estimation is an underestimate of the amorphization threshold dose. Even so, this conservative estimate shows that the doses explored here are below the amorphization threshold.

5. EXTRACTION OF THE MODAL ABSORPTION COEFFICIENT

Transmission measurements were performed Zn^+ implanted PDs, and were repeated for an un-implanted diode (having identical p and n implants and contact metallization as the Zn^+ implanted PD) of the same length. Using these measurements, the effects of parasitic absorption in the Al contacts is taken into account by calculating the modal absorption coefficient, $\alpha_{eff} = -T/L$ [dB/cm], where T is the power transmission in dB and $L = 250 \mu\text{m}$. By subtracting the parasitic absorption coefficient $\alpha_{eff,par}$, measured from an un-implanted diode, from the absorption coefficient of a Zn^+ implanted PD, $\alpha_{eff,tot}$, the absorption coefficient due to defects shown in Fig. 4 of the main

text is determined: $\alpha_{eff,Zn} = \alpha_{eff,tot} - \alpha_{eff,par}$. The contact absorption becomes dominant for $\lambda > 2.325 \mu\text{m}$, resulting in the loss of responsivity with increasing wavelength seen in Fig. 3(b) of the main text.

The transmission measurements used to find the modal absorption coefficients can also be used to determine the fraction of power absorbed in the PD that is due to Zn^+ implantation. Using the parasitic absorption coefficient, $\alpha_{eff,par}$, and the absorption coefficient of a $p\text{-Si}:\text{Zn}-n$ PD, $\alpha_{eff,tot}$, the fraction of power absorbed by Zn^+ implantation can be found by noting that

$$P_{abs,Zn} = \alpha_{eff,Zn} P_{in} \int_0^L \exp(-\alpha_{eff,tot} z) dz = \frac{\alpha_{eff,Zn}}{\alpha_{eff,tot}} P_{abs,tot} \quad (\text{S1})$$

The fraction of absorption due to Zn^+ implantation is shown in Fig. S5 (with error bars determined as described in Sec. 2), and is calculated as:

$$\frac{P_{abs,Zn}}{P_{abs,tot}} = \frac{\alpha_{eff,Zn}}{\alpha_{eff,tot}} = 1 - \frac{\alpha_{eff,par}}{\alpha_{eff,tot}} \quad (\text{S2})$$

Fig. S5. Fraction of total power absorption due to Zn^+ implantation, $\alpha_{eff,Zn}/\alpha_{eff,tot}$, for a Zn^+ dose = 10^{12} cm^{-2} and (b) Zn^+ dose = 10^{13} cm^{-2} .

6. DATA FROM 3 mm-LENGTH PHOTODIODES

Measurements of 3 mm-length Zn^+ -implanted SiWG PDs are shown in Fig. S6 for implantation doses of 10^{12} cm^{-2} and 10^{13} cm^{-2} . Photocurrent was measured beyond a wavelength of $2.35 \mu\text{m}$; however, transmitted power could not be measured at these wavelengths due to the longer PD length, and thus error bars could not be determined for the responsivity.

Fig. S6. (a) Responsivity as a function of reverse bias voltage for 3 mm length PDs. Inset: dark current as a function of reverse bias voltage for an un-implanted diode (black dashed line) and PDs with Zn^+ doses of 10^{12} cm^{-2} (red solid line) and 10^{13} cm^{-2} (blue solid line). (b) Responsivity as a function of wavelength for 3 mm-length PDs. Photocurrent was measurable above $2.35 \mu\text{m}$; however, the transmitted power was not sufficient for determining error bars for the responsivity

7. NOISE EQUIVALENT POWER

The noise equivalent power (NEP) in $\text{W}/\sqrt{\text{Hz}}$ is defined as the on-chip optical power required to achieve a unity signal-to-noise ratio in a detection bandwidth of 1 Hz [3]. Based on our dark current measurements, the two dominant potential sources of noise in our PDs are thermal noise from leakage current and shot

Fig. S7. NEP at 0 V and 5 V reverse bias for $250 \mu\text{m}$ length PDs with Zn^+ implantation dosages of (a) 10^{12} cm^{-2} and (b) 10^{13} cm^{-2} .

noise from detected background radiation. Signal shot noise and thermally generated reverse saturation current can be neglected. In a similar manner to [4, 5], the NEP due to thermal noise from leakage current is determined as:

$$\text{NEP}(\lambda, V_R = 0) = \frac{2}{\Re(\lambda)} \sqrt{\frac{k_B T}{R_0}} \quad (\text{S3})$$

where R_0 is the zero-bias incremental resistance defined as $R_0 = \left[\frac{dI_{\text{dark}}}{dV_{\text{bias}}} \right]^{-1} \Big|_{V_{\text{bias}}=0}$, k_B is the Boltzmann constant, and T is the absolute temperature in kelvin. The zero-bias incremental resistance is found from dark current measurements to be $1.2 \text{ G}\Omega$ for a dose of 10^{12} cm^{-2} , and $28 \text{ M}\Omega$ for a dose of 10^{13} cm^{-2} .

With the application of a reverse bias voltage detected background radiation becomes the dominant contributor to dark current, and the NEP can be written as [3, 4]:

$$\text{NEP}(\lambda, V_R > 0) = \frac{1}{\Re(\lambda)} \sqrt{2eI_{\text{dark}}} \quad (\text{S4})$$

where e is the charge of an electron. The calculated NEP under

both of these assumptions is plotted for zero bias and 5V bias in Fig. S7 versus wavelength. The NEP is expected to decrease at longer wavelengths with improved responsivity. In most practical communications systems, the NEP of a link is dominated by the receiver circuit, preamplifier, and laser noise, as would be the case with the PDs demonstrated here. If avalanche multiplication is indeed present in our PDs, gain noise at higher voltages may also increase NEP.

8. COMPARISON TO INTEGRATED PHOTODIODES IN THE LITERATURE

A comparison of device performance for SiWG-integrated mid-infrared PDs using different detection materials is given in table S1. The PbTe photoconductive detectors in [6] were fabricated and simulated, but no measurements were reported. The bias voltage used and dark current measured for Si divacancy defect PDs in [7] were not provided.

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Table S1. Comparison of SiWG-integrated mid-infrared PD technologies

Detector material	Wavelength range	Responsivity	Bias voltage	Dark current	Dimensions	Reference
Si:Zn, 10^{12} cm^{-2}	2.2–2.4 μm	0.52, 8.33 mA/W	5, 20 V	2.1, 76.5 nA	520 nm $\times$ 220 nm $\times$ 250 μm	-
Si:Zn, 10^{12} cm^{-2}	2.2–2.4 μm	1.50, 87.06 mA/W	5, 20 V	0.043, 3.71 μA	520 nm $\times$ 220 nm $\times$ 3 mm	-
Si:Zn, 10^{13} cm^{-2}	2.2–2.4 μm	0.77, 34.2 mA/W	5, 20 V	0.36, 4.63 μA	520 nm $\times$ 220 nm $\times$ 250 μm	-
Si:Zn, 10^{13} cm^{-2}	2.2–2.4 μm	1.22, 42.75 mA/W	5, 20 V	0.42, 6.07 μA	520 nm $\times$ 220 nm $\times$ 3 mm	-
Si divacancy	2.0–2.5 μm	1.5 mA/W*	-	-	4.7 μm $\times$ 3.5 μm $\times$ 6 mm	[7]
GaInAsSb	2.29 μm	0.44 A/W	0.1 V	1.13 μA	9 μm $\times$ 50 μm $\times$ 800 nm [†]	[5]
GaInAsSb	2.3 μm	1.4 A/W	0.1 V	1.8 μA	10 μm $\times$ 700 nm $\times$ 10 μm [†]	[8]
PbTe [‡]	3–4 μm	25 V/W	-	0.1 mA	750 nm $\times$ 100 nm $\times$ 80 μm	[6]
Graphene	2.75 μm	0.13 A/W	1.5 V	13 nA	-	[9]

*Estimated from plots at $\lambda = 2.2 \mu\text{m}$

[†]Dimensions are given for GaInAsSb stack. The stack is bonded with a 258 nm BCB layer to a 3 μm $\times$ 220 nm SiWG.

[‡]Photoconductive detectors on As₂Se₃/GeSbS core/cladding waveguides.