Metal-semiconductor-metal ion-implanted Si waveguide photodetectors for C-band operation

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Abstract: Metal-semiconductor-metal Si waveguide photodetectors are demonstrated with responsivities of greater than 0.5 A/W at a wavelength of 1550 nm for a device length of 1 mm. Sub-bandgap absorption in the Si waveguide is achieved by creating divacancy lattice defects via Si+ ion implantation. The modal absorption coefficient of the ion-implanted Si waveguide is measured to be \( \approx 185 \text{ dB/cm} \), resulting in a detector responsivity of \( \approx 0.51 \text{ A/W} \) at a 50 V bias. The frequency response of a typical 1 mm-length detector is measured to be 2.6 GHz, with simulations showing that a frequency response of 9.8 GHz is achievable with an optimized contact configuration and bias voltage of 15 V. Due to the ease with which these devices can be fabricated, and their potential for high performance, these detectors are suitable for various applications in Si-based photonics integrated circuits.

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OCIS codes: (040.6040) Silicon; (040.5160) Photodetectors; (130.3120) Integrated optics devices.

References and links

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1. Introduction

Ion-implanted Si waveguide photodetectors (PDs) have recently been incorporated into numerous photonic integrated circuits and systems [1–14]. By implanting Si with a selected atomic species, photodetection from 1550 nm to beyond 1900 nm has been achieved [1–10], opening up the ability to incorporate detectors for the telecom band and beyond in integrated Si systems. These devices have been demonstrated with bandwidths greater than 35 GHz and responsivities up to 10 A/W [1] along with error-free data transmission at wavelengths of 1550 nm [2] and 1900 nm [3]. Multiple configurations have been used to enhance detector responsivity, including resonant-cavity-enhanced detectors [4] and avalanche-multiplication.
detectors [5,6]. These ion-implanted waveguide PDs have been incorporated in Si photonic
devices for power monitoring [11], wavelength monitoring [12], thermal tuning [13], and
variable optical attenuation [14].

The majority of these devices are based on reverse biased \( p-i-n \) rib waveguide diodes,
similar to the structure shown in the bottom inset of Fig. 1(a). These \( p-i-n \) diodes require
multiple masking and alignment steps, and have significant junction capacitance [1,15]. An
alternative metal-semiconductor-metal (MSM) structure, commonly used in planar geometries [16],
has been proposed and demonstrated for carrier removal in 2D Photonic Crystal (PC) cavities [15] as well as for Ge [17] and InGaAs [18] photodetectors integrated on Si. Where a \( p-i-n \) PD relies on a reversed bias \( p-i-n \) junction, the MSM structure relies on
back-to-back Schottky barriers. By applying a bias across the Schottky contacts, carriers
generated in the semiconductor region are swept out to the contacts while the barrier height
prevents current across the device, unlike internal photocemission devices where carriers are
excited over the barrier to generate photocurrent [19]. The MSM PD has a simplified
fabrication procedure as well as having a lower capacitance when compared with \( p-i-n \) diodes
of similar dimensions [15]. The lower capacitance/length makes the MSM ideally suited for
the longer low-absorption-coefficient ion-implanted Si waveguide PDs. Additionally, the lack
of contact doping makes the MSM useful for carrier removal [15] in nonlinear four-wave
mixing devices [20]. However, the top contact MSM design used in [17,18] creates
significant parasitic optical loss resulting in substantially reduced responsivity. To decrease
parasitic loss, the metal-semiconductor Schottky contacts are moved to the “wings” of the PD
structure, as shown in Fig. 1(a).

In this paper, we demonstrate MSM PDs based on a Si rib-waveguide geometry as shown
in Fig. 1(a). The absorbing region of the PD is formed by implanting Si \(^+\) ions to introduce
divacancy defects that absorb at 1550 nm. Device responsivity of > 0.5 A/W is achieved
along with a frequency response of 2.6 GHz for a 50 V bias. Bias voltage is a strong function
of contact separation and can be reduced to =15 V with reduced contact spacing. Analysis
shows that the frequency response is not limited by the MSM-contact configuration, but is
likely due to reduced low-field mobility as compared to intrinsic Si. Simulation of an
optimized device shows an increased frequency response of =9.8 GHz at 15 V, making it
suitable for a broad array of Si photonic integrated circuit applications.

Fig. 1. (a) Device cartoon with lower inset showing the cross-section of a \( p-i-n \) device from [4]
and upper inset giving the cross-section of our MSM structure. (b) SEM image of 250 \( \mu \)m
device.

2. Device design and fabrication
2.1 Device design

Previous MSM waveguide PDs based on Ge [17] or InGaAs [18] utilized Schottky contacts
directly on top of the waveguide allowing for low operating voltage and high frequency
response. Due to the lower absorption coefficients of 8 – 200 dB/cm associated with Si ion-
implanted waveguides [1,8,9], the parasitic loss from such a design is significantly greater
than the defect-mediated absorption coefficient, resulting in poor responsivity. The alternate design presented here utilizes a rib-waveguide structure similar to $p-i-n$ devices in [1,8,9] with the contacts on either side of the waveguide, creating Schottky barrier contacts with the wings, as shown in Fig. 1(a). The wings provide the necessary electrical connection between the waveguide and contacts as well as alter the distribution of the electric field so as to facilitate carrier transport. The tight confinement of the rib-waveguide mode allows for the contacts to be placed close to the channel section, thus reducing the operating voltage and increasing the frequency response.

Fig. 2. Simulated parasitic loss verses waveguide-contact gap for 750 × 220 nm waveguide with wing heights of 50 nm and 150 nm at $\lambda = 1550$ nm. (Insets) Mode intensity for the quasi-TE guided mode for both 50 nm (lower) and 150 nm (upper) wing heights. The lower modal confinement of the 150nm-wing height increases the required contact gap for a given amount of parasitic loss. For devices reported here, the waveguide-contact gap is 2.3 $\mu$m.

Using finite element method (FEM) analysis, the amount of parasitic loss in the device is found to be strongly dependent on wing height and contact spacing. Contact structure can also impact parasitic loss, but is not examined here. Sellmeier equations were used for the Si and SiO$_2$ indices of refraction, while free-carrier effects in Si were modeled based on the data from [21] and Ti/Au contacts were modeled using data from [22]. The FEM results for quasi-TE modes are shown in Fig. 2 for wing heights of 50 nm and 150 nm with 15 nm/150 nm Ti/Au Schottky contacts. Increasing the wing height decreases the modal confinement, resulting in a reduced modal overlap with the implanted region and an increased parasitic loss from the contacts. Moving the contacts further apart can reduce this parasitic loss, but will also increase the required bias voltage, along with the carrier transit time. Ideally, for minimal parasitic loss, a wing height of ~50 nm is desired. We note that other metals such as Cu and Al [19] may be used in place of the Ti/Au combination for CMOS compatibility.

Fan-out tapers are utilized to couple between a lensed-tapered fiber (LTF), and the Si waveguide detector. These fan-out tapers are designed for a ~6 dB coupling loss per facet by mode-matching between Gaussian profile of the LTF with a spot size of 2.5 $\mu$m [23] and a coupler width of 3.85 $\mu$m. The coupler adiabatically tapers down to the 750 nm wide channel waveguide input to the PD over a length of 100 $\mu$m.

The electrical characteristics of the PD are modelled using the RSoft LaserMod package from Synopsis [24]. The static electric field produced by applying a bias voltage across the contacts was modelled using a Poisson solver, while the Boltzmann transport equations are solved numerically to determine the carrier-transit-time. Frequency response was determined by simulating an optical impulse function incident on the device and performing a Fast-Fourier Transform on the resultant current transient response.
2.2 Device fabrication

The devices shown in Fig. 3 were fabricated at Brookhaven National Laboratory on SOITEC [25] silicon-on-insulator (SOI) wafers with a 220 nm 14-22 $\Omega$ cm resistivity $p$-type Si layer and a 3 $\mu$m buried oxide layer (BOX) layer. The waveguides were defined using electron beam lithography with a 90 nm hydrogen silsesquioxane (HSQ) hard-mask. The mask was developed with a 1% wt NaOH/4% wt NaCl aqueous mixture, followed by an inductively coupled plasma etch utilizing HBr and Cl chemistry to define the waveguide, while leaving $\approx 60-64$ nm of the top Si layer. A second mask utilizing MaN-1410 negative photoresist defined the wing sections of the PD and the remaining Si layer was etched away, leaving a Si-nanowire waveguide adiabatically coupled to a Si rib waveguide, as shown in Fig. 1(a). The NaOH/NaCl development process is known to provide very high contrast [26] while the inductively coupled plasma etch provides clean side walls with roughness on the order of 3 nm [20]. Contact windows were patterned using a single layer of Shipley S1811 resist for liftoff, followed by a 1min O$_2$ plasma clean. The contacts were deposited via electron-beam deposition of a 15nm layer of Ti for adhesion followed by a 150nm layer of Au for the contact pads. Devices were subsequently masked to open a 1mm window and implanted at the Ion Beam Laboratory, at the State University at Albany with $1 \times 10^{13}$ cm$^{-2}$ Si$^+$ ions at an implant energy of 195 keV, beam current density of 7nA/cm$^2$ beam current density, and beam diameter of $\approx 4$mm. The implantation energy and dose were based on prior reports of ion-induced defects [1,8,9] and Stopping Range of Ions in Matter (SRIM) calculations [27]. After implantation the devices were annealed in steps of 50°C starting at 150°C, for 10 minutes at each step. Results reported here were after the 250°C anneal, which corresponded to the maximum responsivity. The final device dimensions are shown in Fig. 3. Waveguide width and contact spacing are 763 nm and 5.4 $\mu$m, respectively.

![Fig. 3. SEM images of fabricated devices. (a) View of the waveguide sidewalls showing no measurable roughness over the length of 1 $\mu$m. (b) Top view of waveguide with wings and contacts; the contact separation is 5.4 $\mu$m. (inset) High-magnification view of the waveguide showing waveguide width of 763 nm.](image)

3. Results and discussion

3.1 Responsivity and internal quantum efficiency

To determine the detector responsivity and internal quantum efficiency, coupling loss is first determined at 1550 nm by measuring insertion loss through the devices prior to implantation and utilizing the cutback method on various PD lengths. Loss is measured for PD lengths of 0 $\mu$m, 250 $\mu$m, 500 $\mu$m, and 1mm as part of a total device length of 3 mm. The insertion loss is measured to be 16.6 dB with a standard deviation of 1 dB. Analysis of variance showed no significant difference in insertion loss versus device length. This is expected due to the low wing height and adiabatic taper, which minimizes scattering and parasitic losses between the waveguide and PD. Scattering loss between the coupler and device is lumped into the insertion loss, and scattering loss along the device was negligible based on the cutback
measurements. For responsivity and internal quantum efficiency measurements, coupling loss (including scattering loss before and after the device) is assumed to be half the measured insertion loss, equating to 8.3 dB, matching well with a simulated loss of 6 dB.

Responsivity is found by subtracting the dark current $I_{dark}$ from the photocurrent under illumination $I_{ph}$ and dividing by the incident power on chip, $\mathcal{R} = (I_{ph} - I_{dark}) / P_{inc}$. Figure 4(a) shows the measured responsivity and standard deviation over a bias range from 0 to 50 V for the ten 1 mm length devices. The high bias voltage is not intrinsic to the MSM contact configuration; rather, it is required for the large contact spacing of our devices. Based on Poisson solver calculations, a reduction in contact separation from 5.4 µm down to 1.5 µm reduces the bias voltage required for 0.51 A/W from 50 V to less than 15 V. Increasing bias voltage increases responsivity with no photocurrent plateau, similar to the results of [6]. The smooth increase in responsivity above 30V is unlikely due to avalanche multiplication, as the simulated DC fields in the device were significantly less than required for avalanche breakdown. The increase is believed due to improved carrier collection arising from an increase in carrier velocity. The frequency response measurements in the following section indicate the carriers are far from saturation velocity, resulting in significant increase in carrier velocity with increased bias. Alternatively the increase may be from other forms of carrier multiplication seen MSM PDs [16,28]. Figure 4(b) shows the responsivity decreasing with wavelength by 50% from 1550 nm to 1610 nm.

The initial dark current prior to annealing is 10’s of nanoamps. However, the dark current increases with successive annealing steps and levels off in the 10’s of microamps after 200°C, which is higher than those reported for $p-i-n$-based ion-implanted devices [1,6,8,9]. We attribute this behavior to contact degradation during annealing since Ti is known to diffuse into Au between 200°C-400°C [29]. Contact degradation has also been shown to be a source of unusually high dark current in $p-i-n$ devices [10]. We expect that this dark current can be reduced by using a diffusion barrier such as Pt. The defect states in the wings may also contribute to the higher than expected dark current, therefore we expect limiting implantation to the channel region of the waveguide, should reduce dark current as well.

In order to determine the detector internal quantum efficiency, $\eta = 1.24 \left( I_{ph} - I_{dark} \right) / (\lambda P_{abs})$, where $P_{abs}$ is the absorbed power in detector and $\lambda$ is the free space wavelength in micrometers, the absorption losses for the devices are first calculated by subtracting out the insertion loss measured prior to implantation from the measured insertion loss after ion implantation. Using this technique a modal absorption coefficient of 185 ± 70 dB/cm at 1550 nm is measured, matching well with other ion-implanted detectors in the
literature [8,9]. Utilizing the average absorption coefficient of 185 dB/cm for the 1mm devices, \( \eta \) is found to be between 42 ± 8% at a 50 V reverse bias. This result is significantly higher than previous reports of 16% [1,8,9] for devices annealed at 300°C. We hypothesize that the different annealing and implantation conditions impact the quantum efficiency by changing defect distribution and concentration, as the quantum efficiency matches closely with previous results seen under similar annealing conditions in \( p-i-n \) Ar\(^{+} \) ion-implanted devices [30]. Additionally, MSM PDs have been known to exhibit gain [16,28], attributed to either induced tunneling currents caused from built up charges at the cathode and anode of the device or to photoconductive gain from long life-time traps [16].

The modal absorption coefficient \textit{versus} wavelength for a typical device is shown in Fig. 5(a). An increase in absorption with wavelength is expected for divacancy absorption centers in ion-implanted bulk Si [31], which is consistent with our measurements. Since the calculated changes in parasitic loss and confinement factor are negligible in this wavelength range, the decrease in responsivity with wavelength shown in Fig. 4(b) is due to a reduced internal quantum efficiency at longer wavelengths, which is consistent with observations of [3].

![Absorption Coefficient vs Wavelength](image1)

![Photocurrent vs Optical Power](image2)

Fig. 5. (a) Measured modal absorption coefficient \textit{versus} wavelength from 1530 nm to 1610 nm. The data was smoothed to reduce noise in our measurement setup and thus obtain a general trend. (b) Linearity of device with input optical power at \( \lambda = 1550 \) nm from 0.015 mW to 13 mW, corresponding to power incident on detector 2.2 \( \mu \)W to 2 mW.

To measure device linearity with signal power, an erbium doped fiber amplifier is used to provide a variable signal source of up to 13 mW, corresponding to a maximum PD input power of \( \approx 2 \) mW. With this variable source, linearity is measured over approximately three decades with a slope of 1.03 in Fig. 5(b), matching well with previous results [6,9] and demonstrating that these ion-implanted devices operate via a single-photon absorption process.

3.2 Frequency response

A lightwave component analyzer (LCA) is used to determine the frequency response of the PD for bias voltages of 40 V and 50 V; the results are shown in Fig. 6 along with simulation results for a reduced carrier mobility as discussed below. Although the results are somewhat noisy, as the photocurrent was measured near the noise floor of the LCA, the 3dB point was well defined over several measurements. The resonance around 200-300 MHz was linked to the overall test setup, and the dip around 1.5GHz in the 50V measurement was attributed to the connection between the bias tee and the probes. The simulated curves are for a device with reduced carrier mobility, which is discussed below. The frequency response of 2.6 GHz at 50 V is significantly lower than that expected from simulation models based on intrinsic Si. For the given bias, the carriers are expected to be close to saturation velocity with a frequency response of \( \approx 20 \) GHz. Capacitance and carrier gain can impact frequency response, but based
on measured PD characteristics and device simulations, we attribute the reduced response to decreased low-field mobility.

A Keithley 590 CV Analyzer was used to measure the total-device and contact-pad capacitance. The measured capacitance of ~70 fF/mm results in calculated RC-limited frequency response of 45 GHz for the 1 mm device (assuming a 50 Ω load). The measured device frequency responses of 2-3 GHz suggest that the response is not limited by capacitance, but by other factors.

![Graph showing frequency response for a 1 mm device at 40-50V along with simulation results for a carrier mobility of 50 V/cm²s.](image)

**Fig. 6.** Frequency response for a 1 mm device at 40-50V along with simulation results for a carrier mobility of 50 V/cm²s.

Furthermore, the nearly three-fold increase in frequency response going from a 40 V to 50 V bias does not match simulations where carriers are near saturation velocity. The increase in response with bias voltage suggests the carriers are far from saturation velocity, indicating a decrease in carrier mobility compared to that in intrinsic Si. Mobility is known to decrease with the incorporation of trap states, in particular those created by divacancy defects [1, 32, 33]. For example, in reference [1], the surface-carrier mobility for implanted devices is shown to be several orders of magnitude lower for both electrons and holes after implantation. Assuming the bulk mobility follows the same trend as the surface mobility [1] a reduced frequency response is expected. Further reduction in low-field mobility is also expected from the degradation of the contacts with annealing, as Au is known to act as a carrier scattering center in Si [34].

In order to study the impact of decreased mobility, simulations at bias voltages of 40 V and 50 V were performed for different electron and hole mobilities and compared with experimental results. A mobility of ~50 V/cm²s matches the measured device frequency response well. Our simulations clearly show that a reduction in carrier mobility can account for the observed frequency responses. Utilizing this reduced mobility a device with a contact spacing of 1.5 μm (gap equivalent to 0.375 μm) was simulated at bias voltages of 10 V, 15 V, and 20 V, resulting in frequency response of 4.7 GHz, 9.8 GHz, and 13.8 GHz, respectively. Further increase in frequency response is expected with an increase in bias voltage as the carriers are not at saturation velocity and further decrease in contact spacing.

### 4. Conclusion

A monolithic ion-implanted Si MSM PD based on a rib waveguide has been demonstrated for the first time to the best of our knowledge. Responsivity is measured to be ≈0.51 A/W at 50 V bias with a frequency response of 2.6 GHz. The calculated quantum efficiency of 42% was...
found to be significantly higher than previously reported values of 16% for Si implanted waveguides, likely due to different annealing conditions. Results from previous ion-implanted detectors coupled with simulation results show an optimized device is capable of frequency responses greater than 9.8 GHz at bias voltages $\approx 15$ V. These devices have the potential to be incorporated into many Si-based photonic integrated circuits due to their high performance and ease of fabrication. The devices can also be made CMOS compatible by replacing the Ti/Au Schottky contacts with Cu.

Acknowledgments

Research carried out in part at the Center for Functional Nanomaterials, Brookhaven National Laboratory, which is supported by the U.S. Department of Energy, Office of Basic Energy Sciences, under Contract No. DE-AC02-98CH10886. The authors also acknowledge support from the Columbia Optics and Quantum Electronics IGERT under NSF grant DGE-1069420.