A high-responsivity photodetector absent metal-germanium direct contact

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Abstract: We report a Ge-on-Si photodetector without doped Ge or Ge-metal contacts. Despite the simplified fabrication process, the device shows a responsivity of 1.14 A/W at −4 V reverse bias and 1.44 A/W at −12 V, at 1550 nm wavelength. Dark current is less than 1µA under both bias conditions. We also demonstrate open eye diagrams at 40Gb/s.

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References and Links


1. Introduction

High-speed communication is critical to modern society. Silicon photonics is a promising technology for high-speed fiber-optic communication with low energy consumption and low cost. The last decade has witnessed a dramatic improvement of silicon photonics devices. High-quality hybrid integrated lasers with sub-MHz linewidth, modulators and photodetectors supporting 40 Gb/s or higher data rates have all been demonstrated [1–6]. Transceivers and switch fabrics monolithically integrated with electronics were reported [7–9]. Coherent long-haul communication at 112 Gb/s was also demonstrated [10]. Foundry services, which open access of advanced fabrication facilities to academic labs and startups, will further speed up research and development of photonic integration on silicon [11, 12].

One bottleneck that emerges during the design of silicon-photonics-based data links is the constraint on link power budget. A typical link power budget is around 9 dB. For example the IEEE 802.3 40GBASE-LR4 has 6.7 dB allocated for channel insertion loss and 2.3 dB for penalties. Due to the large mode mismatch between glass fibers and submicron silicon waveguides, on-and-off chip coupling loss is usually quite high, over 1 dB in a mature commercial process [13]. On-chip devices tend to be lossy too. For example, insertion losses of state of the art silicon modulators reported in both [3, 4] are over 5 dB. In some cases, device insertion loss could be significantly reduced by design optimization, such as the y-
junction, waveguide crossing and grating coupler reported in [14–16]. However, in other cases, insertion loss and device efficiency are orthogonal. For example, in silicon electro-optic modulators, higher doping results in higher modulation efficiency, but also increases insertion loss at the same time. A photodetector with high responsivity could compensate for some of the channel insertion loss, and help satisfy the required link power budget.

Germanium can be epitaxially grown on silicon and is CMOS-compatible, and has thus become the preferred light-absorbing material in silicon photonics. Waveguide-coupled $p$-$i$-$n$ detectors have attracted extensive attention due to their high bandwidth, good responsivity and low dark current. Ge-on-Si detectors with lateral and vertical $p$-$i$-$n$ junction configuration are illustrated in Fig. 1. Attractive Ge-on-Si detector performances have been reported, with typical responsivity around 0.8 A/W and bandwidth high enough for 40 Gb/s operation [5–8, 10, 17–21].

As shown in Fig. 1, both types of devices require heavily-doped germanium to form the junction, as well as the direct contact of germanium with metal via plugs. Germanium processing received far less research attention than silicon, and is therefore much less well understood and characterized. While silicon modulators have been optimized for efficiency [22], similar TCAD models remain elusive for germanium detectors. Hence a photodetector that does not require doping or metallization of germanium is highly desirable.

In this paper, we report a Ge-on-Si photodetector without doped Ge or Ge-metal contacts. The device was measured to have a responsivity of 1.14 A/W at $-4$V reverse bias, at 1550 nm wavelength. We also show that responsivity can be increased to 1.44 A/W with $-12$V reverse bias. The detector dark current remains below 1 µA for both bias conditions. 40Gb/s operation is demonstrated.

2. Device design

A schematic illustration of the floating germanium photodetector is shown in Fig. 2(a). Compared to the conventional detector configurations shown in Fig. 1, the germanium is free of defects caused by ion implantation damage and metallization. Furthermore, we note that creating metal via-plugs is a complicated multi-step process in CMOS, requiring implantation, annealing, contact hole opening, silicide formation, diffusion barrier deposition, metal deposition, patterning, and planarization [23]. The proposed floating germanium detector configuration significantly simplifies the silicon photonic process flow and will ultimately reduce the cost of building silicon-based photonic integrated circuits (PICs). Since this diode design shares exactly the same doping levels and metallization procedures of a silicon modulator, the only extra step needed to build the device is germanium epitaxy. Incidentally, a similar device, independently designed from this work at approximately the same time, was presented at the Optical Fiber Communications Conference (OFC) recently by Liow et al [24]. The device in [24] was designed as an avalanche photodetector (APD) with low electric field strength in germanium, separated absorption and multiplication region, and was characterized at 1.3 µm wavelength, while our device is an enhanced $p$-$i$-$n$ detector...
with relatively high electric field strength in germanium to effectively sweep out photo generated carriers at high speed, and we report device performance at 1.55 µm wavelength.

We offer a comment on the triangular shape of the germanium. Similar to the anisotropic wet etch of silicon, which naturally stops at the (111) surface due to a much slower etch rate, crystal germanium growth rate is different in different directions. The germanium geometry also depends on the trench angle of the oxide hard mask, and can be projected by the Wulff construction model [25]. The epitaxial germanium was measured to have a 25° sidewall angle versus the silicon surface in the process to build our device. With germanium base width 1.5 µm, the height of the germanium is 0.35 µm.

Despite the simplified fabrication, the floating germanium detector is expected to have higher responsivity than the conventional ones shown in Fig. 1, because metal absorption from the electrodes and free carrier absorption from heavy contact doping are eliminated. The dark current is expected to be lower too because of the preserved crystal quality after epitaxy. To achieve high responsivity, photons should be confined in the intrinsic germanium absorber, and scattering needs to be minimized. The fundamental mode of this germanium silicon hybrid waveguide structure is plotted in Fig. 3(a). The optical mode is well confined to the germanium, with a confinement factor of 88%, ensuring efficient absorption and minimizing detector length, and thus capacitance. A 3 µm long germanium taper from 0.22 µm to 1.5 µm in width was used to adiabatically transfer light from the input silicon waveguide to the hybrid waveguide. A 50 µm long taper used to connect the standard 0.5 µm wide strip routing waveguide and the 1.5 µm rib waveguide detector input, as shown in Fig. 2(b).

Without a \textit{p-i-n} junction formed in germanium, the device relies on the fringe field of the silicon junction to sweep out photo-generated carriers. It has been reported that the fringe field and its corresponding capacitance is a non-negligible part of the 220 nm-thick silicon \textit{pn} junction and must be accounted for in modulator design [26]. As germanium has a much higher permittivity than typical CMOS dielectrics, such as silicon nitride or silicon dioxide, the portion of fringe field in the germanium and the capacitance will be even higher for the same silicon junction. We numerically solved Poisson’s equation and plotted the electric field distribution in Fig. 3(b). The junction’s intrinsic region width in Fig. 3(b) is set to match the mode field diameter in Fig. 3(a). The electric field in most of the germanium is stronger than 10^4 V/cm at –4V reverse bias, high enough for the carriers to drift at the saturation velocity [27]. Slightly higher bias might be needed to drive all photo-generated carriers, due to the non-uniformity of electric field. Note that the \textit{p-i-n} junction extends to the tapered part of the hybrid silicon germanium waveguide to collect photo-generated carriers in the germanium taper, as shown in the layout in Fig. 2(b).
3. Device characterization

We prototyped the aforementioned device by participating in a multi-project wafer (MPW) run offered by the OpSIS foundry. Fabrication occurred at Institute of Microelectronics in Singapore. The floating germanium detector was fabricated using the standard process to create our baseline vertical $p-i-n$ detectors with a 0.5 µm thick germanium slab [21], and no additional process split was needed thanks to the anisotropic epitaxial growth of germanium [25]. The starting substrate was an 8-inch silicon on insulator (SOI) wafer, with 220 nm, 10 ohm-cm $p$-type top silicon film, and 2 µm buried oxide on top of a high resistivity silicon handle. Waveguides and grating couplers were patterned using 248 nm UV lithography followed by dry etching. Boron and phosphorus ions were implanted into silicon, and activated by rapid thermal annealing. Germanium epitaxy followed and then two layers of aluminum metal interconnect were added to complete the fabrication flow.

3.1 Optical spectrum

Two sets of characterization structures corresponding to the device cross-section in Fig. 2(a) were designed. Grating couplers were used as optical I/O to a fiber array in both cases. In Set A, transmitted light after the germanium absorber was guided to another grating coupler, which was used to characterize the germanium absorption efficiency and determine the required device length. In Set B, the through port was connected to a $y$-junction [14] with its two branches tied together, which effectively functioned as a broadband mirror, as shown in the device photo in Fig. 2(b). A fiber array was first aligned to the grating couplers in Set A, and the devices were measured using a tunable laser that can sweep from 1500 nm to 1570 nm. The spectra of two devices with different germanium length, as well as a reference grating coupler, are plotted in Fig. 4. The overall parabolic shape is due to the spectral response of the grating coupler. A reduction in power level indicates extra loss added by the germanium strip. No interference fringes were observed on the spectrum, confirming that light stayed in its fundamental mode throughout the structure. Single mode operation prevented a waste of photons from scattering or divergence, and also improved absorption per unit length since the light was tightly confined in the germanium absorber. The capability to couple light upward into germanium and back down into silicon is useful for constructing germanium absorption modulators as well. The lengths of the two detectors in Fig. 4 are 11 µm and 16 µm respectively, including 6 µm for tapers. Stronger absorption at shorter wavelengths is clearly illustrated, because shorter wavelengths are further from the band edge of germanium. At 1550 nm, the 16 µm long germanium had 26 dB of attenuation. With the $y$-junction loop mirror to reflect the transmitted photons back for reabsorption, the 16 µm long detector in device Set B will be able to achieve almost 100% internal quantum efficiency.
3.2 IV characterization

In addition to the optical properties, device performance also depends on the p-i-n junction shown in Fig. 3(b). We probed the device and characterized the IV curve using a semiconductor device analyzer, both for dark operation and with incident light, shown in Fig. 5(a). The dashed line shows a typical diode IV curve. The dark current is only 0.12 µA at −4V, which is an order of magnitude smaller than the dark current of conventional vertical p-i-n detectors fabricated in the same process [21]. We attribute this improvement to the smaller junction area and preserved germanium crystal quality from and after the epitaxy. The dark current increases to 0.29µA, 0.9µA, and 26µA at −8V, −12V, and −16V respectively. Similar traces were observed when light was incident. Photocurrent was extracted by subtracting dark current from the total current. Photocurrent increases with reverse bias voltage and saturates at about −2 V. With less than −2 V, the fringe field is not strong enough to sweep out photogenerated carriers before they recombine. With more than −2 V, essentially all photogenerated carriers are swept out within their lifetime and are collected by the electrodes. Hence the photocurrent in Fig. 5(a) saturates and stays relatively flat until beyond −5 V, where it slowly tails up due to the turn-on of avalanche gain. Different from a typical avalanche photodetector, photocurrent reaches a maximum at −17V and drops when reverse bias is further increased. This is most likely due to the silicon junction beneath the germanium entering its avalanche regime and beginning to conduct a significant amount of current.

Fig. 4. Transmission spectra of floating germanium detectors and a reference grating coupler.

Fig. 5. (a) Device IV curves in darkness and with various incident optical powers; (b) Photocurrent as a function of input optical power at different bias voltages. The slope of the linear fit gives the responsivity for each bias.
From Fig. 5(a), the photocurrent as a function of optical power impinging on the device at each bias voltage can be plotted, as shown in Fig. 5(b). Red dots are measured data points, and colored straight lines are linear fits. The slope of the fitting line gives the responsivity value at the corresponding bias. At −4V, the device works as a normal \textit{p-i-n} detector, the responsivity is 1.14 A/W, comparable to the best state-of-the-art devices [17, 19, 20]. Responsivity further improves as reverse bias increases due to avalanche multiplication. At −12V, responsivity goes up to 1.44 A/W, while the dark current remains below 1 µA. Further increasing bias continues to increase the responsivity, but at the price of higher dark current.

For receivers with \textit{p-i-n} detectors, the noise is typically limited by thermal noise generated from the load resistor. In this case the signal to noise ratio and receiver sensitivity is determined by photocurrent amplitude, which is proportional to detector responsivity. Compared to our baseline detector in [21] with 0.75A/W responsivity, receiver sensitivity, and hence link budget, is improved by 1.82 dB if the floating germanium detector is biased at −4V. At −12V, thermal noise still dominates due to the minimal avalanche multiplication factor, receiver sensitivity benefits from the enhanced responsivity and increases to 2.83 dB better than the baseline PD.

### 3.3 Bandwidth

Photocurrent roll-off was characterized by measuring the \textit{s}-parameters using a vector network analyzer (VNA) and a LiNO\textsubscript{3} modulator. S21 traces at different bias voltages are plotted in Fig. 6. At −4V, the 3 dB bandwidth is around 20 GHz, sufficient for detecting 25 Gb/s on-off keying (OOK) signals. The response at −2V matches that of −4V at low frequencies, indicating all photo-generated carriers have been swept out within their lifetime, matching the IV curves in Fig. 5(a), but frequency roll-off is fast due to transit time limitation. At −8V and −12V, the 3 dB bandwidth increases to over 40 GHz, which indicates that carrier transit time limits the device bandwidth at lower bias. At −16 V, bandwidth drops slightly to 30 GHz as the avalanche gain increases.

![Fig. 6. Device S21 at different reverse bias voltages.](image)

Generally the bandwidth of a photodetector is determined either by carrier transit time or device RC time constant. Taking the saturation velocity to be $6.5 \times 10^6$ cm/s [27], and mode field diameter 0.85 µm, the transit time limited bandwidth is estimated to be

$$f_t = \frac{0.44v_{sat}}{L} = 33.6 \text{GHz} \quad (1)$$
which is close to the measured bandwidth. The transit-time-limited bandwidth could be improved by using a narrower germanium strip, which won’t degrade the detector efficiency given the strong absorption of germanium, as shown in Fig. 4.

The device capacitance was determined to be 8 fF, calculated from the phase information of the $s$-parameters. Low capacitance is critical for the device to be used in optical interconnects [28]. Assuming a 50 Ω load impedance, the major contributor of series resistance are the p + and n + doped 90 nm silicon slabs connecting the silicon under the germanium to the metal via. Sheet resistance at this intermediate doping level is 3750 Ω/☐ and 1490 Ω/☐ for p + and n + silicon slab respectively. They are 1.5 µm wide and 16 µm long, leading to around 490 Ω series resistance. Thus the RC time limited bandwidth is

$$f_{rc} = \frac{1}{2\pi C_{pd}(R_{pd} + R_L)} = 36.8GHz$$

Since the light is tightly confined in the germanium, it is safe to use higher doping on these connecting slabs without introducing noticeable optical loss from free carrier absorption. Sheet resistance for p + + and n + + dope slab is 137 Ω/☐ and 60 Ω/☐, which is an order of magnitude smaller than those of p + and n + slab, and will totally remove RC time limit on device operating bandwidth.

We further performed data transmission experiments to verify the detector performance. Light modulated with a 40Gb/s non-return to zero (NRZ) pseudo random bit sequence (PRBS) was launched into the photodetector. The detector RF output was displayed on a digital communication analyzer (DCA). Eye patterns obtained at −4V, −8V, −12V, and −16V bias are shown in Fig. 7. The eye opening at −4V is not as good as those at higher bias voltages due to the bandwidth limitation. Because of the low dark current and small gain factor, the detector noise remains low, confirmed by open eye diagrams, even at −16V. As a compromise between low noise, high responsivity and high bandwidth, −12V is an optimal operating bias voltage, which is a factor of 2 to 3 lower than that required by conventional APDs. At this bias level, a 1.44 A/W responsivity can be obtained, with a dark current of 0.9 µA, which is orders of magnitude smaller than that of Ge/Si APDs [29–31].

![Fig. 7. 40 Gb/s eye diagrams at (a) −4V, (b) −8V, (c) −12 V and (d) −16V bias.](image-url)
4. Conclusion

To conclude, we have demonstrated a novel floating germanium photodetector that significantly simplifies Ge-on-Si detector fabrication process by eliminating the need to dope and contact the germanium. The simplified process has the added advantages of preserving the crystal quality of the germanium, and keeping the optical mode away from metal and heavily doped material. This has allowed for detectors with high responsivities and low dark currents, capable of 40Gb/s operation.

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