High-speed, zero-biased silicon-germanium photodetector 🐵

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ABSTRACT

We report high-speed performance for a photodetector operating at zero bias—with zero dark current and zero DC electrical power dissipation. Photocurrent generation is achieved through phonon-assisted absorption in a silicon microring resonator embedded with silicongermanium, resulting in a responsivity of 0.35 and 0.043 A/W at wavelengths around 1180 and 1270 nm, respectively. We measure a 3 dB bandwidth of 14 GHz, the fastest reported to date for a zero-biased ring-resonant photodetector and which represents a 7× improvement with respect to previous work. We explore the source of such improvement through TCAD simulations and conclude that the optimization of the doping profile significantly decreases the effective carrier lifetime by limiting the impact of the photogenerated carriers drifting into the outer circumference of the resonator, with a low electric field. Using experimental data, we also extract both the free carrier and the phonon-assisted silicon-germanium absorption coefficient, showing good agreement with literature data. High-speed operation at temperatures up to 150 °C is also demonstrated.

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The development of high-speed, low-power near-infrared optical receivers is crucial for the realization of high performance optical interconnects, which promise to meet the ever-growing bandwidth and power dissipation demands of practical communication systems.^{1,2} Particularly attractive are receiver-less detection schemes that do not require power-hungry transimpedance amplifiers or integrating circuits.^{1,3} In such architectures, the electrical power dissipation under reverse bias associated with the DC current flowing through the device can be a significant contributor to the overall receiver power consumption.⁴ Thus, operation of photodetectors under zero bias or in the photovoltaic mode is necessary to minimize power dissipation. The use of ring-resonant photodetectors in optical receivers is beneficial because they result in enhanced responsivity due to their longer effective absorption length, they result in low device capacitance (and hence high bandwidth) due to their small footprint, and most importantly, they provide wavelength selectivity, which allows for simpler wavelength division multiplexing (WDM) systems.⁵ Nevertheless, few examples of silicon photonic ring photodetectors exist in the literature,⁶⁻⁹ and they require high reverse bias operation to achieve high responsivity and fast operation: while speeds over 20 GHz are achievable under reverse bias

operation,^{6,8,9} the maximum bandwidth reported under zero bias is limited to below 2 GHz.⁷ Thus, the realization of fast zero-biased ring-resonant silicon photonic detectors, while necessary to reach the ultimate limits of power dissipation in optical receivers, is still outstanding.

In this Letter, we report a silicon-germanium (SiGe) resonant photodetector with such high-speed performance under zero bias. By comparing our device to a previously reported design realized in the same fabrication process⁷ (which we will refer to as the *Gen1 design* from now on) both through TCAD simulations and experimental characterization, we uncover the importance of junction design and electric field distribution to avoid drifting of photogenerated carriers into device regions with a low electric field. At zero bias, we measure a bandwidth of 14 GHz (7× improvement over previous work) with a responsivity of 0.35 A/W at a wavelength of 1185.9 nm.

We fabricate our device using a 45 nm silicon-on-insulator (SOI) CMOS microelectronics process (GlobalFoundries 45RFSOI), which allows for the close integration of photonic and electronic components in the same substrate, reducing parasitics and thus improving the bandwidth and power dissipation.^{3,10,11} Individual



FIG. 1. CMOS photodetector configuration and layout. (a) Optical micrograph of the device. (b) Device layout. Azimuthally interleaved p- and n-doped spokes form a ring resonator with 10 μ m outer diameter. A 300 nm wide SiGe band generates photocurrent through phonon-assisted below-bandgap absorption. Electrical contact is provided through metal vias located at the inner end of the spokes. The inset shows the intensity distribution of the whispering gallery optical mode supported by the microdisk. (c) and (d) Closeup of the T-junction doping configuration optimized to minimize parasitic capacitance. In Gen1 designs,⁷ the SiGe band is undoped and Si is doped with 1× doping concentration (c). In this work, implants with 2× larger doping concentration are used, and SiGe is doped with the same implants as Si (d).

photonic components with state-of-the-art performance (including waveguides,¹² grating couplers,¹³ optical modulators,^{14,15} and photodetectors⁷), as well as systems integrating hundreds of photonic components and millions of transistors,^{16–18} have been demonstrated over the last decade in this process.

The configuration and layout of our resonant photodetector are depicted in Fig. 1. A micrograph of the device, which shows the ring resonator as well as the vertical grating couplers and tapers providing optical access to the device, is shown in Fig. 1(a). Figure 1(b) shows the layout of the resonator. A microdisk with 5 μ m outer radius and 1.2 μ m width is etched into the crystalline silicon layer, which is conventionally used to realize the transistor body. Such a structure supports a whispering gallery optical mode [inset of Fig. 1(b)], which is concentrated in the outer edge of the disk, allowing for the placement of metal contacts at the inner edge [black regions in Fig. 1(b)] without incurring high optical losses.¹⁹ Azimuthally interleaved p- and n-doped spokes [yellow and orange shaded regions in Fig. 1(b), respectively] provide electrical contact to the active area where there is optical absorption and carriers are generated.

Optical absorption is achieved through sub-bandgap, phononassisted mechanisms in SiGe,^{7,20} which is natively present in CMOS microelectronics processes for the improvement of hole mobility in p-FET transistors.^{21–23} In our device, a 300 nm wide SiGe ring [shaded area in Fig. 1(b)] is epitaxially grown in shallow pockets etched into the crystalline silicon (see Ref. 24 for a representative cross section). Based on experimental characterization, SiGe has a Ge content around 20%. Figures 1(c) and 1(d) show a closeup of the junction design, with a T-like shape aimed at the minimization of the parasitic capacitance and therefore the maximization of the device bandwidth.¹⁴ In the Gen1 design,⁷ all doping steps are performed before the SiGe deposition, resulting in SiGe being close to intrinsic [Fig. 1(c)]. In contrast, our new (*Gen2*) design uses a doping implant that is applied after the SiGe deposition, therefore doping SiGe as well as Si [Fig. 1(d)]. Furthermore, the doping implants used in the Gen2 design have a $2 \times$ larger doping concentration compared to the implants used in the Gen1 design.

The changes in the doping characteristics between the Gen1 and the Gen2 design [(1) using $2 \times$ doping concentration and (2) using the doping implants that dope both SiGe and Si] change the device performance remarkably. This is because the Gen2 design improves the speed of the two main processes, limiting the photodetector bandwidth, as depicted in Fig. 2: the RC (charging) process [Fig. 2(a)] and the drift or diffusion of the photogenerated carriers into areas with no collecting electric field [Fig. 2(b)].



FIG. 2. Bandwidth-limiting processes in resonant photodetectors. (a) RC limit associated with the finite resistance and capacitance between the metal contacts and the optical absorption region (outlined by the blue dashed lines). (b) Drift of photogenerated charges to areas with a low electric field. Such charges are not readily collected by the contacts and therefore have longer lifetime, limiting the device speed.

Concerning the RC process, the use of 2× higher doping concentration with respect to the Gen1 design significantly decreases the resistance of the access spoke [R_{access} in Fig. 2(a)], while the total capacitance [C_{access} in Fig. 2(a)] is approximately the same as it is mostly determined by the width of the intrinsic region between the p- and n-doped spokes (salmon areas in Figs. 1 and 2). As a result, the characteristic RC time constant of the device is notably decreased in the Gen2 design, resulting in an enhanced bandwidth as we have reported previously.²⁵

More interesting (and not recognized in our previous work²⁵) is the study of how the Gen2 doping configuration affects the drift and/or diffusion of the photogenerated carriers into areas with a low electric field. It has been previously recognized that the optical absorption that generates carriers in regions with a low electric field can appreciably slow down the dynamics of photodetectors because these carriers have to either move through (slow) diffusion or recombine, in which case the limiting time constant becomes the minority carrier lifetime and not that associated with the RC process.^{26–28}

To study the impact of such an effect in our devices, we developed a 2D model of both Gen1 and Gen2 designs using Synopsys TCAD.²⁹ Due to the periodic nature of the device, we simulated a single p–n spoked junction. Figures 3(a) and 3(b) show the constructed 2D model for both designs, with periodic boundary conditions in the *y* direction. We assume a uniform carrier generation rate (due to optical absorption) in the SiGe region [dotted area in Figs. 3(a) and 3(b)] and consider the generation in the Sionly areas negligible (Sec. 1 of the supplementary material). Despite the existing differences between the model and the actual physical device, the qualitative and relative predicted performance is consistent with experimental data, validating the model (Sec. 2 of the supplementary material).

Figures 3(c) and 3(d) show the static electric field distribution in the x direction (E_x) obtained with the model under 1 μ W illumination at 0 V bias for the Gen1 and Gen2 designs, respectively. Outstanding differences are observed that result in the Gen1 design being more sensitive to carriers not directly collected by the electric field. In fact, it is clear from looking at Fig. 3(c) that while photogenerated holes readily drift toward the inner p-doped spoke through the existing electric field, most of the photogenerated electrons drift toward the outer silicon region. Since no strong electric field is present in this region, these electrons need to either recombine or slowly diffuse into the *n*-doped regions contacting the metal vias at the inner edge of the spokes. As a result, the photodetector response is considerably slowed down, resulting in a low bandwidth as measured experimentally. In contrast, the electric field distribution for the Gen2 design, shown in Fig. 3(d), results in only a small fraction of photogenerated holes (those generated right at the outer edge of the SiGe region) drifting into the outer Si region, therefore notably reducing the impact of these carriers on the frequency response. Although not as significant, the changes between the Gen1 and Gen2 designs also result in a different E_{ν} field distribution (Sec. 3 of the supplementary material).

Another important drawback of the Gen1 design, which was observed experimentally, is the strong dependence of the bandwidth on the input optical power to the device. For instance, at a bias voltage of -4 V and an average photocurrent of 10 μ A, the device bandwidth was measured to be about 2 GHz, whereas when the



FIG. 3. TCAD simulation of the device. (a) and (b) The developed 2D TCAD models for the Gen1 (a) and Gen2 (b) designs, which simulate a single junction and apply periodic boundary conditions along the boundaries in the *y* direction. A uniform carrier generation rate due to the incident light is applied to the SiGe region (dotted area). The color scheme depicts the spatial doping implant profile. In the Gen1 design (a), SiGe is slightly p-doped uniformly, whereas in the Gen2 design (b), SiGe is doped in a T-junction configuration. (c) and (d) Simulated electric field distribution in the *x* direction (*E_x*) for the Gen1 design (c) and the Gen2 design (d) at 0 V bias and 1 μ W illumination. Clearly, a greater fraction of the photogenerated carriers is pushed away from the active area in the Gen1 design. (e) Simulated *E_x* at 0 V bias as a function of the input optical power for the Gen1 (violet) and Gen2 (dark green) designs. As shown in the inset, *E_x* is recorded along the outer boundary between the Gie and Si regions. A strong dependence of *E_x* on power is observed for the Gen1 design, which explains why the bandwidth is sensitive to the input power. No dependence is observed for the Gen2 design.

average photocurrent was increased to 100 μ A (i.e., the input power was increased by 10×), the bandwidth increased to 5 GHz.⁷ This is of course detrimental as large input optical powers are required to achieve the best performance, reducing the sensitivity of the detector

and thus that of the whole system. Our TCAD model can be used to discern the physical mechanism leading to such power dependence. Figure 3(e) shows the distribution of E_x at the outer edge of the SiGe region [depicted by the red dashed line in the inset of Fig. 3(e)] under different input optical powers. As is readily observable, increasing optical powers result in a notable decrease in the magnitude of E_x for the Gen1 design (purple lines). This suggests that the observed bandwidth dependence is due to changes in the electric field distribution with input power (caused by the accumulation of electrons in the outer Si region), which, in turn, affect the impact of the slow diffusion/recombination of carriers into the outer Si region. On the contrary, the electric field distribution for the Gen2 design (dark green lines) shows no optical power dependence, suggesting that this issue is solved.

In summary, the developed TCAD model suggests that the Gen2 doping distribution results in a strong suppression of the slow diffusion/recombination of the photogenerated carriers into areas with no electric field. This is achieved through a change in the electric field distribution, which minimizes the number of carriers pushed toward these areas (in our device, this area is the Si region at the outer edge of the microdisk). Combined with a reduction in the RC time constant, because we are using $2 \times$ higher doping concentration, we expect the Gen2 designs to have a significantly higher bandwidth and to show a reduced dependence on the input optical power.

To confirm the model results, we fabricated and experimentally characterized the Gen2 photodetector. Figure 4 shows the responsivity characterization at two different operating wavelength ranges: around 1270 nm (black lines) and around 1180 nm (orange lines). Figure 4(a) shows the I-V curve of the device under illumination at both wavelengths (black and orange curves) and in dark conditions (blue curve). The dark current is ≈ 30 pA at -2 V bias, which is remarkably lower than that of Ge-based photodetectors.^{30–33} This is a result of the high material and fabrication quality, as well as the fact that employing a resonant structure allows for the use of a smaller volume of active material compared to non-resonant configurations. Such low dark currents result in our device developing large open circuit voltages for low input powers: as seen in Fig. 4(a), an input optical power of 2 μ W at λ = 1180 nm is enough to develop an open circuit voltage $V_{oc} > 0.65$ V, and 7.5 μ W is required at λ = 1270 nm to generate V_{oc} = 0.58 V. These voltage levels are enough to drive a CMOS transistor without the need for amplification or a load resistor (which is required in conventional receiver-less detectors³). Thus, our device has the potential to realize a low power (since the detector is unbiased, there is no electrical power dissipation), high sensitivity (low input powers generate large photovoltages, and there is no extra noise from the load resistor), and high-speed receiver-less optical link.

Figure 4(b) shows the measured responsivity as a function of bias voltage at both wavelengths. The responsivity at 1180 nm (≈ 0.35 A/W at 0 V bias) is considerably higher than that at 1270 nm (≈ 0.043 A/W at 0 V bias) due to higher optical absorption at lower wavelengths (the photon energy is closer to the SiGe bandgap at 1180 nm). Figures 4(c) and 4(d) show the normalized transmission (top) and generated photocurrent (bottom) as a function of wavelength for $\lambda \approx 1270$ nm [Fig. 4(c)] and $\lambda \approx 1180$ nm [Fig. 4(d)]. As expected, a Lorentzian-like resonant response is observed at both wavelengths, with the resonance wavelength λ_0 set by the



FIG. 4. Experimental characterization of the Gen2 photodetector responsivity. (a) I–V curves under no illumination (blue line) and illumination at 1180 nm (orange line) and 1270 nm (black line) wavelengths. (b) Responsivity vs bias voltage at 1180 nm (orange line) and 1270 nm (black line) wavelengths. Larger responsivity is measured at 1180 nm because the photon energy is closer to the SiGe bandgap. (c) and (d) Normalized optical transmission (top) and generated photocurrent (bottom) as a function of wavelength around 1270 nm [(c) black line] and 1180 nm [(d) orange line]. As expected, a resonant behavior is observed. (e) Extracted absorption coefficients and comparison to literature data. The SiGe absorption (the table in green) and free carrier absorption (FCA, the table in blue) coefficients experimentally extracted from the Gen1 (circles) and Gen2 (crosses) designs are shown at the two studied wavelengths ($\lambda_1 = 1180$ and $\lambda_2 = 1270$ nm). Dashed lines correspond to literature data. The process to extract the absorption coefficients at λ_1 and λ_2 is included. The process to extract the absorption coefficients is detailed in Sec. 4 of the supplementary material.

ring dimensions and the group index of the optical mode.³⁴ More than $100 \times$ larger photocurrent is generated when the light is onresonance compared to the off-resonance condition, which, as already mentioned, makes resonant photodetectors attractive for wavelength division multiplexing (WDM) applications since they achieve simultaneous photodetection and wavelength selectivity.⁵

Two main absorption mechanisms are present in our device: (1) phonon-assisted optical absorption in the SiGe region $(\alpha_{SiGe})^{35}$ which generates electron-hole pairs and therefore results in a photocurrent, and (2) free carrier absorption (FCA) in both the Si and the SiGe regions $(\alpha_{FCA})^{.36}$ Since FCA does not result in photocurrent (as the photons are absorbed by already existing electrons and holes), in a critically coupled resonator, the external quantum efficiency is set by the ratio between these two absorption mechanisms: η_{ext} = $\Gamma_{SiGe}\alpha_{SiGe}/(\Gamma_{SiGe}\alpha_{SiGe} + \Gamma_{FCA}\alpha_{FCA})$, where Γ_{SiGe} (Γ_{FCA}) is the overlap between the optical mode and the SiGe (FCA) regions. Therefore, as detailed in Sec. 4 of the supplementary material, from the experimentally measured responsivities and resonance *Q* factors [Figs. 4(c) and 4(d)], it is possible to extract these two optical absorption coefficients at each studied wavelength (1180 and 1270 nm in our case), which are shown in Fig. 4(e). As is observable, good matching to literature data is obtained both for the SiGe absorption and the FCA.

The data in Fig. 4(e) help us explain the different responsivities at different wavelengths and for different designs (Gen1 and Gen2). As already mentioned, the responsivity is considerably lower at 1270 nm compared to that at 1180 nm, not only because there is an $\approx 20 \times$ decrease in the SiGe absorption coefficient but also because FCA increases with wavelength. Another important observation is that the responsivity of the Gen1 design is slightly larger than that of the Gen2 design (0.55 vs 0.42 A/W at 1180 nm and -2 V bias, respectively). This is because the Gen1 design uses lower doping concentration implants for Si (1× vs 2×), and therefore, as shown in Fig. 4(e), the FCA coefficient is lower.

The approach to obtain a device with the largest possible responsivity is thus clear: maximizing the optical absorption in the SiGe ($\Gamma_{SiGe}\alpha_{SiGe}$), while at the same time minimizing the FCA ($\Gamma_{FCA}\alpha_{FCA}$). This is of course not straightforward since minimizing FCA requires the use of lower doping concentration implants, but then the frequency response of the device is severely affected due to the increase in R_{access} and thus that in the RC time constant.

We measured the high-speed characteristics of our Gen2 photodetector, and the results are summarized in Fig. 5. The experimental frequency response is shown in Fig. 5(a), yielding a measured 3 dB bandwidth of 14.85 GHz (18.25 GHz) at 0 V (-2 V) bias and 20 μ A average generated photocurrent. This represents a >7× (3×) increase in bandwidth with respect to the Gen1 designs, with a maximum bandwidth of 2 GHz (5 GHz) at 0 V (-4 V) bias. We also measured the device bandwidth in low forward bias (V > 0), which is relevant for the operation of the photodetector in the photovoltaic mode. As shown in Fig. 5(b), bandwidths above 10 GHz are maintained for voltages up to 0.6 V. As can also be observed in Fig. 5(b), we do not observe a strong dependence of the bandwidth on the input optical power (or equivalently, the average generated photocurrent) as our TCAD simulations suggested (<10% change measured).

We recorded high-speed eye diagrams, but the fastest achievable data rate was limited by the bandwidth of the commercial modulator we had available, which was rated up to 10 Gbps. We used a commercial, 50 GHz bandwidth photodetector to record the eye diagram generated by the modulator when operated at a data rate of 15 Gbps, shown in Fig. 5(c). The eye diagram at the same speed but generated with our photodetector at zero bias is shown in Fig. 5(d). No additional slowdown is observed in the eye diagram generated by our device, showing that the photodetector can sustain higher data rates as expected from the bandwidth measurements.



FIG. 5. High-speed characterization of the Gen2 photodetector. (a) Experimental electro-optical frequency response. A 3 dB bandwidth of 17.8 GHz at -2 V bias (dark green line) and 14.5 GHz at 0 V bias (olive line) is obtained. (b) Measured 3 dB bandwidth as a function of bias voltage. A high bandwidth over 10 GHz is maintained up to 0.6 V bias. (c) 15 Gbps reference eye diagram taken with a commercial 50 GHz photodetector. (d) 15 Gbps eye diagram taken with our CMOS photodetector at 0 V bias. No significant difference is observed between (c) and (d), showing that our photodetector can operate at speeds beyond 15 Gbps. (e) Eye diagrams at high operating temperatures under 0 V bias (top row) and -2 V bias (bottom row). High-speed operation at 10 Gbps is achieved up to 100 °C (middle column). 5 Gbps operation is demonstrated at 150 °C (right column).

Since zero bias operation is unaffected by dark current, our device is suitable for high-speed photodetection at high temperatures, where conventional reverse-biased detectors suffer from an exponential increase in dark current that can become the dominant source of noise and decrease the sensitivity of the system. Nevertheless, even under conventional, reverse-biased operation, our photodetector can be operated at high temperatures due to its low dark current. With a measured dark current $I_{dark} = 30$ pA [Fig. 4(a)], our device shows $\approx 300 \times$ lower dark current than typical Ge-based photodetectors, with I_{dark} on the order of 10 nA and above.^{30–33}

We experimentally measured the performance of our photodetector at high temperatures up to 150 °C, and the results are

summarized in Fig. 5(e). No noticeable deterioration in the highspeed characteristics of the device was measured up to a temperature of 100 °C [middle column in Fig. 5(e)]. Successful operation was recorded at a temperature of 150 °C [right column in Fig. 5(e)] although we observed a decrease in the maximum achievable data rate. This is likely due to an increase in the junction capacitance of the device as a result of the larger free carrier population (at 150 °C, the intrinsic carrier concentration of both Si and SiGe is larger than the extrinsic concentration coming from the doping implants). The decrease in carrier mobility with rising temperature might also contribute to increased device resistance.³⁷ Consequently, there is an increase in the RC time constant from which a decreased bandwidth ensues.

At 150 °C, we measure a dark current $I_{dark} = 4$ nA, whereas for Ge-based photodetectors, we would expect dark currents on the order of 10 μ A. We also observe a significant increase in responsivity at high temperatures: at 150 °C and $\lambda = 1270$ nm, we measure a responsivity of 0.38 A/W, which is almost a 9× increase with respect to the measured responsivity at room temperature. We attribute this increase to an enhanced phonon-assisted optical absorption due to the reduction in the SiGe bandgap and the increased phonon population.

In conclusion, we have reported a high-speed, zero-biased SiGe photodetector realized in a commercial microelectronics CMOS process. We measure a 3 dB bandwidth of 14.5 GHz, which, to the best of our knowledge, is the fastest ever reported for a zero-biased microring photodetector in any material or fabrication platform. This is achieved through a decrease in the RC time constant (by using doping implants with $2\times$ impurity concentration compared to previous designs) and the suppression of the photogenerated carriers drifting into areas with no electric field (as a result of doping SiGe, causing a more favorable electric field distribution). Combined with the low parasitics resulting from the use of a monolithic electronic–photonic platform, our high-speed detector could enable the implementation of receiver-less link architectures with high speed, high sensitivity, and low power dissipation under zero bias or photovoltaic operation.

The supplementary material describes the approach to model carrier generation due to the incident optical power, the validation of the TCAD model, and the electric field distribution in the y direction E_y obtained with the TCAD model. It also provides a detailed description of the process to extract the relevant absorption coefficients in our device from experimental data.

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D.V.O., J.F., M.W., and R.J.R. are developing silicon photonic technologies at Ayar Labs. The remaining author declares no competing interests.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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