Silicon-germanium p-i-n photodiodes with double heterojunction: high-speed operation at 10 Gbps and beyond

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ABSTRACT

We present recent results on high-speed waveguide p-i-n photodetectors with lateral hetero-structured Silicon-Germanium-Silicon (Si-Ge-Si) junctions monolithically integrated on Silicon-on-Insulator substrates. Optical photodetectors leverage a unique integration strategy, combining butt-waveguide-coupling and lateral Si-Ge-Si p-i-n hetero-junctions. Fabrication is then easier, more robust and fully compatible with available Si-foundry processes. Under a low-voltage operation, 1 μm wide devices have dark currents of at most 150 nA, high responsivity of 1.2 A/W, and -3dB cut-off frequency of 12 GHz. Furthermore, an errorless detection is experimentally achieved for a conventional 10 Gbps data rate, with power sensitivity down to -13.9 dBm with a bit-error-rate (BER) of 10^{-9}. Moreover, under avalanche operation, a 0.8 μm wide p-i-n diode offers attractive improvements in opto-electrical performances. In particular, initial results show that device responsivity is enhanced from 0.42 A/W up to 2.79 A/W thanks to an avalanche multiplication gain of 6.7. The cut-off frequency remains larger than 17 GHz with a gain of 10.6, resulting in a gain-bandwidth product greater than 180 GHz. These promising results also yield error-free communication at 10^{-9} with 28 Gbps signal, providing power sensitivities down to -12.7 dBm at 10^{-9} BER. These results make hetero-structured p-i-n photodetectors appealing choice for high-bit-rate systems in integrated silicon nanophotonics.

Keywords: germanium photodiodes, silicon-on-insulator platform, high-speed optical communications

1. INTRODUCTION

Germanium (Ge) photodetectors (PDs) integrated on silicon (Si) waveguides are key devices in group-IV nanophotonics, including emerging areas such as sensing, interconnects, or communications, to name a few. Leveraging the maturity of Si-foundry processes and epitaxial Ge integration, group-IV PDs are presently well-mastered building blocks and their performances are rather good [1]. A large number of homo- [2-4] and hetero-junction [5-9] p-i-n devices have been proposed, fabricated, and demonstrated over the years. Si-Ge-Si p-i-n diodes benefit from a much better control over the intrinsic Ge region, a simpler and robust fabrication and improved opto-electrical performances compared to full-Ge PD architectures. Despite those promises, regular p-i-n diodes provide only a limited responsivity, suffer from a modest power sensitivity and require additional circuit electronics for use in transmission systems. As an alternative, avalanche photodiodes (APDs) with an internal multiplication gain can advantageously be used to meet the emerging demands for improved performances in Si nanophotonics [10-14]. Recently, different Si-Ge APD structures were designed and elaborated, tackling low-voltage operation at 10 Gbps [11-13] and 25 Gbps [14] bit rates, respectively.

In this work, we present recent results on waveguide-integrated p-i-n PDs with lateral Si-Ge-Si hetero-junctions operated under low-bias ("*p-i-n regime*") and high-bias ("*avalanche regime*") conditions, respectively. Cross-sectional schematics of the Si-Ge-Si PD investigated here are shown in Fig. 1(a). PDs were fabricated within CEA LETI's facilities on 200 mm wafers with industrial-scale manufacturing tools Details on design, fabrication, and comprehensive opto-electronic characterization steps can be found in Refs. [7-9].

2. P-I-N REGIME

Figure 1(b) shows the photo-responsivity versus applied reverse voltage for PDs with 1 μm wide intrinsic Ge regions and different lengths. Responsivities of 0.19 A/W and 1.2 A/W were assessed at -0.5V for the shortest and the longest designs from current-voltage measurements. Corresponding dark-currents were 7 nA to 150 nA, respectively. Beyond -0.5V, the responsivity remains neatly flat without any observable bias dependency. Indeed, the strong built-in electric field is already present at low-biases. This shows that PDs with Si-Ge-Si hetero-junction are able to sweep out a major part of photo-generated carries within their lifetime [8].

Figure 1(c) presents frequency responses of 1 μm wide and 40 μm long PDs, probed at different reverse biases. The -3dB cut-off frequencies at 0V, -1V, and -2V biases were equal to 1 GHz, 7 GHz, and 12 GHz, respectively. PD bandwidth is always small at 0V due to a comparatively long transit time of carriers and the weak built-in electric field. By contrast, higher bias voltage considerably improves bandwidth characteristics. This agrees well with the improved device responsivities at non-zero reverse voltages. Bandwidth properties of PDs with different lengths were examined as well [7,8]. The bandwidth of Si-Ge-Si PDs with the same intrinsic Ge width and various lengths remained unchanged. This suggests that the PD frequency response is not limited by RC-delay. The main limiting factor of the frequency response is instead the transit time of carriers. Indeed, the PD bandwidth was shown to be inversely proportional to the width of the intrinsic Ge region [7]. As a result, narrower PDs yield faster frequency responses (well beyond 50 GHz), at the expense of responsivities, which are lower, then (typically less than the 1.2 A/W value demonstrated above) [9]. the inset of Fig. 1(c) shows clearly open eye diagram retrieved at a transmission bit rate of 10 Gbps. The device was probed at -1V bias.

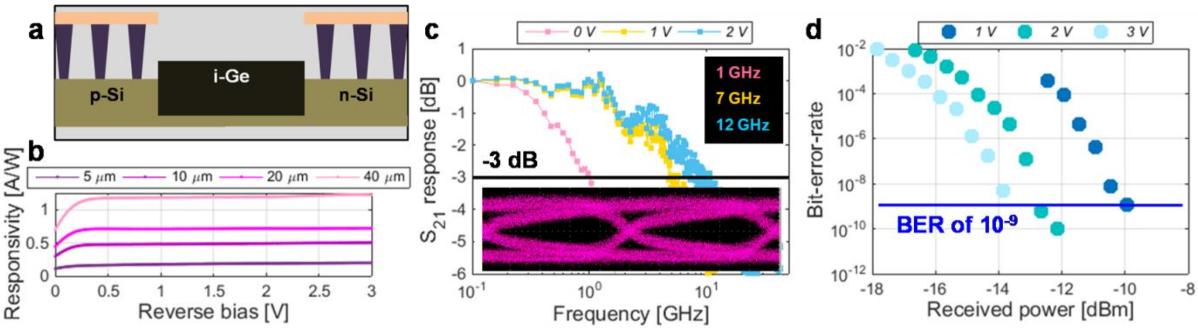

Figure 1. 1 μm wide and 40 μm long PD at low-bias operation. *(a) Transversal schematic of a p-i-n PD with a lateral Si-Ge-Si hetero-junction. (b) Responsivity-voltage characteristic for Si-Ge-Si PDs with different intrinsic Ge lengths. (c) RF traces of S_{21} parameter probed at different biases. Inset: 10 Gbps eye diagram aperture at -1 V bias. (d) BER versus received power for a 10 Gbps signal and different reverse biases.*

Figure 1(d) shows the bit-error-rate (BER) versus received optical power measured with a pseudo-random binary sequence at 10 Gbps bit rate and different biases. PD sensitivities of -10 dBm, -12.8 dBm, and -13.9 dBm were achieved at a BER level of 10^{-9}. In addition, the energy consumption of hetero-structured Si-Ge-Si PDs, biased at low-voltages and operated with 10 Gbps signals, remained reasonably low, typically with a few tens of fJ/bit [9]. This makes Si-Ge-Si diodes good candidates for use in energy-efficient Si-based optical interconnects.

3. AVALANCHE REGIME

Simple p-i-n diodes operated at low-biases typically provide low electrical output levels. This can be overcome by biasing PDs at higher voltages in order to initiate an impact ionization process [1]. This is responsible for an avalanche multiplication effect, which consequently amplifies the generated current and yields improved device performances. To this end, hetero-structured Si-Ge-Si PD with 0.8 μm wide and 40 μm long intrinsic Ge region was considered for an avalanche operation. Figure 2(a) shows a gain-voltage curve, as determined from current-voltage tests (inset of Fig. 2(a)) and the ratios of net-light currents. They were assessed at a wavelength of 1.55 μm and an input power of -9.25 dBm. Low-bias PD responsivities at 0V and -0.5V were 0.42 A/W and 0.74 A/W. The multiplication gain of 6.7 significantly enhances the responsivity up to 2.79 A/W near the avalanche breakdown. The dark-current is still lower than 1 μA at low-bias voltages. It increases progressively with reverse bias up to 600 μA.

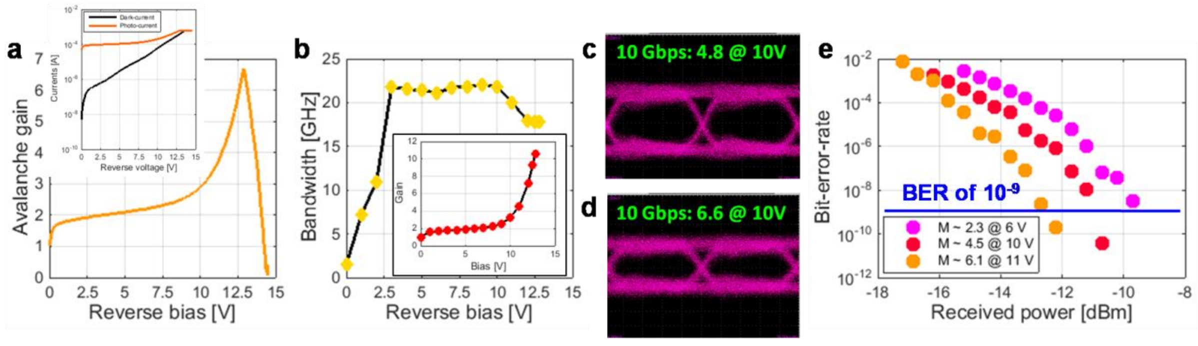

Figure 2. 0.8 μm wide and 40 μm long PD under avalanche operation. *(a) Gain-voltage characteristic. Inset: Current-voltage plot for dark- and photo-currents. Photo-current was generated with an optical power -9.25 dBm at 1.55 μm wavelength. (b) Measured -3dB bandwidth versus reverse bias, with an optical power of -17.5 dBm. Inset: Corresponding gain-voltage characteristic. Eye diagram apertures at 10 Gbps and -10 V bias with gains of (c) 4.8 and (d) 6.6. (e) BER versus received power for a 28 Gbps signal at different biases.*

Figure 2(b) summarizes the bandwidth properties of hetero-structured Si-Ge-Si p-i-n APD, coming from small-signal radio-frequency testing. Bandwidth properties were examined at a wavelength of 1.55 μm and an optical input power of -17.5 dBm. The evolution of the avalanche multiplication gain with the reverse bias is shown in the inset of Fig. 2(b). Cut-off frequencies increases a lot with voltage within the low-bias range (up to -3V), from 1.5 GHz to 22 GHz, step-by-step reaching a high drift velocity. Then, the -3dB bandwidth remains nearly flat up to -10 V, as the photo-generated carriers reached their saturation velocity. Beyond -10V, the cut-off frequency decreases down to 17.8 GHz due to an avalanche built-up time that sets restriction on the device operation speed. In this region, the avalanche gain increases exponentially up to a 10.6 peak. As a result, a gain-bandwidth product greater than 180 GHz was determined. Figures 2(c) and 2(d) show eye diagram apertures for PD working at 10 Gbps and -10V bias, with avalanche gains of 4.8 and 6.6, respectively. Both eye apertures are clearly open under these conditions of avalanche regime without observable degradation in the rise and fall times. Indeed, relative eye closure was observed for device operated with a higher gain (see Fig. 2(d)). This indicates that the studied PD approaches the bandwidth-limited operation regime.

Last, but not least, the potential of hetero-structured Si-Ge-Si APD for high-speed communication links was assessed experimentally through BER measurements. Figure 2(e) shows BER versus received optical power for an 0.8 μm wide and 40 μm long PD operated at 28 Gbps under different avalanche conditions at different biases (-6V; -10V; and -11V), for which multiplication gains were 2.3, 4.5, and 6.1, respectively. Optical power sensitivities of -9.7 dBm, -11 dBm, and -12.7 dBm were associated with those avalanche conditions.

4. CONCLUSIONS

We described recent results on high-speed p-i-n photodetectors with lateral Si-Ge-Si hetero-junctions. Under a low-voltage operation, devices afford low dark current, high responsivity, and fast response, which in turn, enables a bit-error-free operation at 10 Gbps data rate, with power sensitivities down to -13.9 dBm. Additionally, under an avalanche operation, photodetectors provided improved opto-electrical performances. Device responsivity was enhanced from 0.42 A/W to 2.79 A/W thanks to an internal avalanche gain of 6.7. A device response as high as 17 GHz with a gain of 10.6 was achieved, yielding a gain-bandwidth product greater than 180 GHz. These achievements opened up a route for an errorless signal detection at 28 Gbps data rate and a sensitivity as low as -12.7 dBm. These state-of-the-art results definitely extend opportunities for high-speed detection in integrated optoelectronic chips based on mature group-IV nanophotonic technology.

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