Very High-Speed Waveguide Integrated Germanium Photo Detectors

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Abstract *We present a photodiode in which germanium is laterally sandwiched in between complementary in-situ doped silicon layers. We demonstrate optoelectrical 3-dB bandwidth ≥110 GHz with responsivities of 0.6 A/W at 1550 nm, and show, for the first time, results at 1310 nm wavelength.*

Introduction

Progress of silicon photonics technology has been an important enabler for datacenter interconnect or metro applications in recent years. A decisive factor has been the development of devices with optoelectrical (OE) bandwidth exceeding 50 GHz, allowing for generation and detection of signals approaching 100 GBaud. Nevertheless, further enhancement of OE bandwidth is highly desirable in view of anticipated symbol rates of 140-200 GBaud. In this paper we focus on silicon photonic detectors, i.e. waveguide (WG) coupled germanium photodiodes (PDs). Already in 2015, Ge PDs with >67 GHz OE bandwidth and responsivity of >0.9 A/W could be demonstrated [1].

Further Ge PD improvement has been impeded since and 67 GHz OE bandwidth remained the benchmark up to the first demonstration of our PIC/EPIC compatible Ge PDs with OE 3-dB bandwidths exceeding 110 GHz [2]. Thus, Ge PDs are approaching the performance of state-of-the-art III-V photodiodes [3, 4]. Here, we show for the first time bandwidth and responsivity measured at 1310 nm wavelength as well, obtained from PDs fabricated in a follow-up lot.

Ongoing heterodyne measurements on photodiodes based on our novel design approach indicate that the high-speed performance goes way beyond the reported data from [2]. However, investigations are still ongoing and require further verification which is why in this work we focus on devices analogous to those from [2] and present first measurement results at 1310 nm wavelength.

In our novel Ge PD design complementary in-situ doped Si layers laterally sandwich an intrinsic Ge region, forming a lateral drift-field p-i-n diode, shown in Fig. 1. By this approach we entirely circumvent ion-implantation into Ge, with the goal to reduce the impact of minority carrier diffusion.

In [1, 5] the negative impact of minority carrier diffusion on the frequency response of Ge PDs has been discussed. Two methods have been identified to reduce this contribution and increase the PD bandwidths:

(1) Manipulation of minority carrier lifetimes by incorporation of non-doping elements and
(2) Reduction of the fraction of carriers that are subject to diffusion by shrinking the doped Ge regions, such that less photo carriers are generated in doped regions and more photo carriers are generated in the intrinsic region.

As our prior PD relies on ion-implantation into Ge [1], the negative impact of minority carrier diffusion could not be diminished easily.

Our novel photodiode design approach not only allows to omit ion-implantation and thus suppress minority carrier diffusion effects. In contrast to vertical drift field PDs it also leaves the Si WG below the Ge un-doped, which shall be beneficial for the responsivity. Similar to the prior PD, the lateral Si offshoots allow for low-ohmic contacting utilizing state-of-the-art silicide processes and allow for placing the metal contacts at a certain distance to the optical mode. The vertically aligned Si offshoots aside the Ge ensures very homogenous electrical field distribution. Details on the fabrication of these novel devices can be found in [2].

Measurement and Discussion

In [2] we demonstrated measurement results of our novel devices for the first time, while we focussed on 1550 nm wavelength, due to available grating couplers in the first fabrication run. In a follow-up lot, we equipped the Ge PDs with couplers for 1310 nm for the first time.

It is worth to note, that the PDs from this follow-up lot were fabricated with some changes in the processing, e.g. nickel-silicide (NiSi) was used instead of cobalt-disilicide ($CoSi_2$). Thermal

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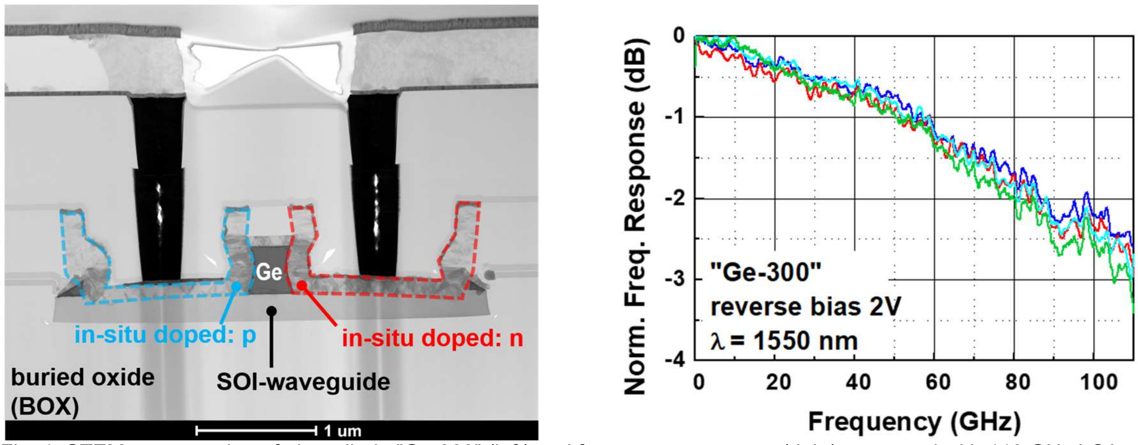

Fig. 1: STEM cross section of photodiode ”Ge-300” (left) and frequency responses (right) measured with 110 GHz LCA at 1550 nm wavelength (four chips from the same wafer).

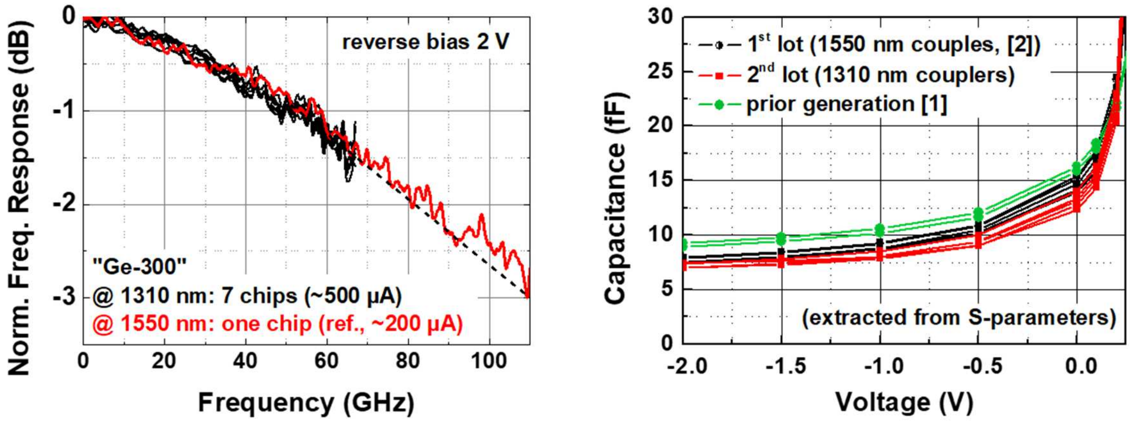

Fig. 2: Frequency responses (left) measured with 67 GHz LCA at 1310 nm (7 diodes from the same wafer from the follow-up lot) and, for direct comparison, 110 GHz LCA measurements at 1550 nm (red curve, measured on wafer from first lot). Capacitance-voltage characteristics from diodes of 2nd lot compared to those from prior photodiodes (right).

budget for silicide formation was thus significantly lower compared to the $CoSi_2$-based process applied in the first lot. However, we compare PDs with identical layout and thus similar Ge width and length (all PDs presented in [2] and here are 20 µm long).

Normalized frequency responses of PDs with an average Ge width of about 300 nm (referred to hereinafter as “Ge-300”) measured at chip level with a Keysight 110 GHz lightwave component analyzer (LCA) are shown in Fig. 1, on the right side (1550 nm wavelength). Clearly, the presented PDs achieve OE 3-dB bandwidths of 110 GHz and above [2]. Unfortunately, the diodes from the follow-up lot with 1310 nm grating couplers could not be characterized with the 110 GHz LCA. Instead, we performed measurements at 1310 nm wavelength with a 67 GHz LCA, shown in Fig. 2 (left), where the black curves belong to 1310 nm measurements. For direct comparison, we additionally show one curve from the prior lot, measured at 1550 nm on the 110 GHz LCA setup (red curve). The diodes from the follow-up lot show similar performance up to 67 GHz, although in tendency, the frequency response curves of the PDs from the follow-up lot seem to decrease slightly faster. Capacitance-voltage characteristics (Fig. 2, right side) indicate that the PDs “Ge-300” (black curves) from the 2nd lot might have slightly wider depletion regions compared to the PDs from the first lot. This could explain the slightly faster decreasing frequency response curves and could be either attributed to differences in the actual Ge width but also to reduced dopant out-diffusion from the Si-layers into the Ge. Note, that in the follow-up lot we deployed the aforementioned NiSi-process. Investigations on this effect are still ongoing.

Compared to the prior Ge PD generation (green curves) [1], our new PDs exhibit certainly lower capacitances (black and red curves) although the latter ones feature significantly narrower i-regions by means of the drawn layout (length and height of the PDs are similar for all diodes). This strengthens our assumption, that there is significant dopant diffusion in the prior PD generation which is efficiently suppressed in our novel PD design.

Dark- and photo-currents at 1310 nm are shown in Fig. 3 (left). Moderate dark currents in the range of 20-100 nm at -2 V are achieved.

External and internal responsivities are obtained

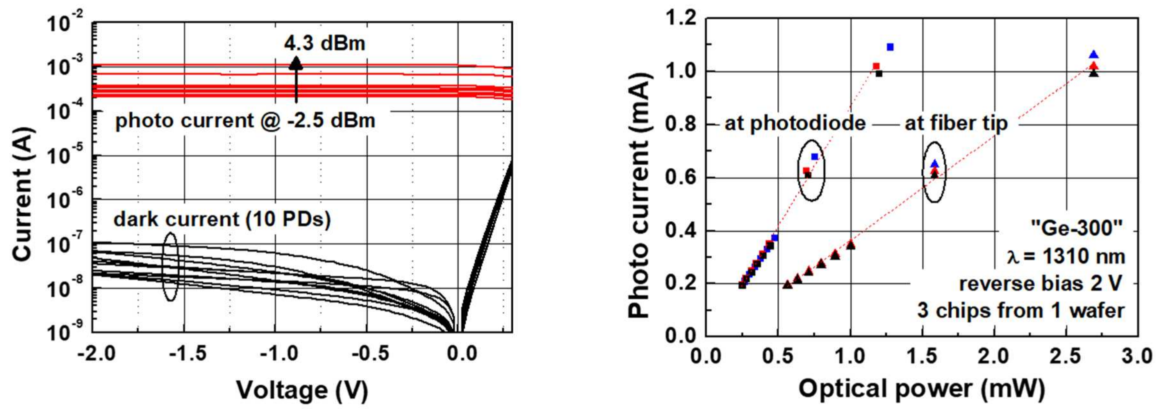

Fig. 3: Dark- (10 PDs) and photo-currents (one PD) at 1310 nm (left); Photo-current vs. optical power for the estimation of external (at fiber tip) and internal (at PD) responsivties (right). All measurements: PDs "Ge-300" on chips from the same wafer.

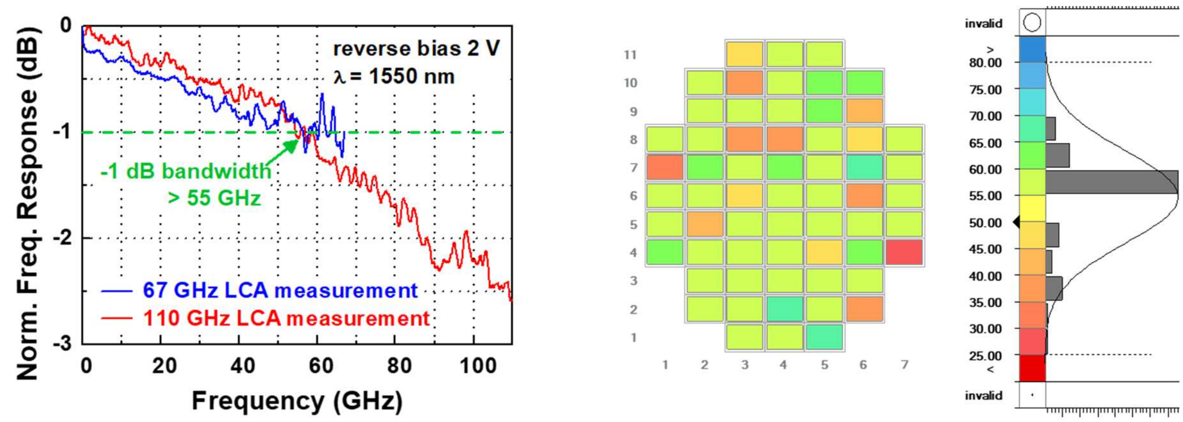

Fig. 4.: Normalized frequency responses (left, [2]) of one chip (diode "Ge-300") measured with Keysight 67 GHz LCA and 110 GHz LCA, all at 1550 nm. Wafermap and histogram (right, [2]) of 1-dB OE bandwidths of "Ge-300" PD at -2 V (in GHz), measured on 62 wafer sites, 1550 nm wavelength.

from the slope of linear fits of photo-current vs. optical power plots, Fig. 3 (right). At 1310 nm wavelength, internal and external responsivities are about 0.39 A/W and 0.8 A/W for PD "Ge-300", respectively (here, we only present results at TE polarization, due to the use of uniform 1D grating couplers; however, we expect similar behaviour as for the prior PD).

Measurements with the 110 GHz LCA were performed at chip level, investigations on a full wafer could not be performed. Instead, with the 67 GHz LCA wafer level characterization is available, however, this LCA does not allow for the estimation of the 3-dB bandwidths. As both LCA measurements match quite well (Fig. 4, left) we monitor the 1-dB bandwidths of a full wafer (Fig. 4, right). This demonstrates that the new PDs can be fabricated with high yield.

A comparison to state-of-the-art PDs [3, 4, 6, 7] proofs that our novel PDs are approaching to the performance of WG-coupled InP-based PDs and outperform other approaches that aim for the integration in silicon photonic platforms.

Conclusion

We presented an SOI-waveguide coupled Ge PD with very high OE 3-dB bandwidth of >110 GHz at -2 V and, for the first time, measurement results at 1310 nm. The significant performance gain with respect to our prior Ge PD and other state-of-the-art Ge PDs was achieved by a novel construction in that Ge is sandwiched in between two compementary in-situ doped Si regions. By avoiding ion-implantation into the Ge minority carrier diffusion effects are supressed. Internal responsivity of >0.6 A/W [2] at 1550 nm and ~0.8 A/W at 1310 nm are achieved, which makes our novel devices very well suited for use in data center applications. To our knowledge, this is the most advanced germanium photo detector in terms of very high bandwidth combined with state-of-the-art responsivity as well as moderate dark currents.

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