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Ge Photodiode with -3 dB OE Bandwidth of 110 GHz for PIC and ePIC Platforms

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***Abstract*—We present an SOI-waveguide coupled germanium photodiode with very high OE -3 dB bandwidth of ≥110 GHz at reverse bias of 2 V. This performance is achieved by a novel construction in that the germanium is sandwiched in between two in-situ doped silicon regions. This fabrication approach allows for avoiding ion-implantation into the germanium, which is certainly beneficial for the bandwidth as minority carrier diffusion effects are strongly suppressed. A responsivity of >0.6 A/W at 1550 nm (-2 V) is achieved, while the dark current of this device yields to about 300 nA (-2 V). To our knowledge, this is the most advanced germanium photo detector in terms of bandwidth combined with state-of-the-art responsivity as well as moderate dark currents. We demonstrate that the novel photodiodes can be fabricated with high yield.**

I. INTRODUCTION AND MOTIVATION

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 opto-electrical (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]. However, further Ge PD improvement has been impeded since and 67 GHz OE bandwidth remained the benchmark until now. In this article, we demonstrate for the first time realization of PIC/EPIC compatible Ge PDs with OE bandwidths exceeding 110 GHz, which show responsivity values >0.6 A/W, approaching the performance of state-of-the-art III-V photodiodes [2, 3].

In [1, 4] 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 cannot be diminished easily.

Here, we demonstrate for the first time a Ge PD with in-situ doped Si regions that sandwich an intrinsic Ge region and thus circumvent ion-implantation into Ge. A lateral p-i-n diode is realized, aiming on avoiding photo carrier generation in doped Ge (Fig. 1a). In contrast to vertical drift field PDs, the Si WG below the Ge remains un-doped in our approach, which shall be beneficial for the responsivity. Similar to the prior PD (Fig. 2), 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. A TEM image at a larger magnification (Fig. 1b) makes the vertical alignment of the Si offshoots along the Ge, which ensures very homogenous electrical field distribution, more obvious.

II. FABRICATION

The fabrication of this novel PD is schematically sketched in Fig. 3: similar to our prior PD generations, we start with selective Ge epitaxy that is conducted on an exposed SOI WG (a). Encapsulation of the Ge by a thin Si layer helps to protect the Ge from abrasive chemicals. By anisotropic dry etching a prior deposited SiO_2 layer and the Ge body is patterned, such that a trench is formed (b). Subsequently, an in-situ doped Si layer is deposited, e.g. by non-selective epitaxy (c). SiO_2 deposition is carried out to fill the trench and by chemical mechanical polishing (CMP) the topography of the trench is planarized. The Si layer outside of the trench is then removed by CMP as well (d). Anisotropic dry etch of the hard-mask layer and the Ge on the opposite side is performed (e), followed by deposition of an in-situ doped Si layer with the inverse doping species, with respect to the first Si layer. The relative position of the first and second hard-mask patterning and Ge dry etchings define the actual width of the Ge region. Similar to the prior process, subsequent steps are conducted for filling, planarization and removal of the protruding Si (f). Finally, both in-situ doped Si offshoots are exposed, enabling $CoSi_2$ formation and fabrication of the back-end-of-line process.

III. MEASUREMENT RESULTS AND DISCUSSION

Normalized frequency response of a PD with a 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) is shown in Fig. 4. Clearly, the presented PDs achieve OE -3 dB bandwidths of 110 GHz and above. Fig. 5 depicts normalized frequency response of one PD measured at different bias conditions and proves a large bandwidth of 70 GHz already at -0.25 V. The large difference between zero-bias and -0.25 V bandwidths indicates that some undepleted regions remain where minority carrier diffusion contributes. However, at low reverse bias, those regions seem to be widely depleted. In Fig. 6 dark currents of "Ge-300" are compared to those of our prior PD generation [1], showing that in tendency the level and scattering is increased for our novel PDs. The inserted box-plot summarizes dark current of "Ge-300" and a bit broader diode named "Ge-350". A comparison of the capacitance vs. voltage characteristics to our prior PDs (Fig. 7) points out, that the PD "Ge-300" seems to have a wider depletion region although the prior PD features a wider i-region (~ 600 nm) by means of the drawn layout (length and height of the PDs are similar). This strengthens our assumption, that there is significant dopant diffusion in the prior PDs which is now strongly suppressed.

Bias dependent photo currents measured at varied optical input power are shown in Fig. 8 (including also one dark current curve). From the photo current sweep the external and internal responsivities are estimated, summarized in Fig. 9. Compared to PD "Ge-300" and probably owed to the wider i-region, PD "Ge-350" achieves a bit less OE bandwidth of about 100 GHz (-2 V). The corresponding normalized frequency response is shown in Fig. 10. Internal responsivity at 1550 nm is estimated to about 0.64 A/W and 0.74 A/W for "Ge-300" and "Ge-350", respectively (here, we only present results at 1550 nm and TE polarization, due to equipment limitations and the use of 1D grating couplers; however, we expect similar behavior as demonstrated for the prior PD).

As seen in Fig. 1(b), $CoSi_2$ is partially formed at the vertically aligned Si-offshoots. The impact of this nearby metal layer on the responsivity is still under investigation and could be easily controlled by the introduction of spacers. Referring to the thoroughly high electrical RC bandwidth (>400 GHz) we do not foresee much negative impact on the overall frequency response even if spacers would slightly increase the resistance.

The optical power handling capability of the PD "Ge-300" is demonstrated in Fig. 11. By varying the laser input power the frequency response is measured at increased photo currents. Up to a photo current of about 1.2 mA, the PD achieves high bandwidth ≥100 GHz. Further increase of the optical power causes a degradation of the bandwidths such that at 3 mA the OE bandwidth drops to about 60 GHz. Compared to our prior PD, this is an improvement of a factor 1.5 [5].

Measurements with the 110 GHz LCA were performed at chip level, investigations on a full wafer could therefore not be performed. Instead, a 67 GHz LCA was available for wafer level characterization, however, this LCA does not allow for the estimation of the -3 dB bandwidths. As both LCA measurements match quite well in direct comparison (Fig. 12) we monitor the -1 dB bandwidths of a full wafer (Fig. 13).

Wafermap and the histogram of the dark current at -2 V for PD "Ge-300" are shown in Fig. 14. Obviously only one PD at the very edge of the wafer fails while few chips show increased dark currents (values above 600 nA). We find it remarkable that on the very same chips also PD "Ge-350" shows increased dark current (marked by dotted frames in Figs. 14 and 15). We attribute this effect to weaknesses at the early maturity level of the fabrication process. Despite that, the full wafer characterizations prove high yield and underline the potential for adaptation of this novel PD into IHP's photonic BiCMOS or PIC processes. A comparison to state-of-the-art PDs in table 1 emphasizes that our novel PD is approaching to the performance of III-V detectors and outperforms other detector approaches that aim for the integration in silicon photonic platforms.

IV. CONCLUSION

We presented an SOI-waveguide coupled Ge PD with very high OE -3 dB bandwidth of >110 GHz at reverse bias of 2 V. This performance gain was achieved by a novel construction in that Ge is sandwiched in between two in-situ doped Si regions. By avoiding ion-implantation into the Ge minority carrier diffusion effects are supressed. A responsivity of >0.6 A/W at 1550 nm is achieved, while the dark current of this device yields to about 300 nA (both at -2 V). Compared to our prior PD, the new diodes show improved optical power handling capability as well. 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. We demonstrated that the new PDs can be fabricated with high yield.

ACKNOWLEDGMENT

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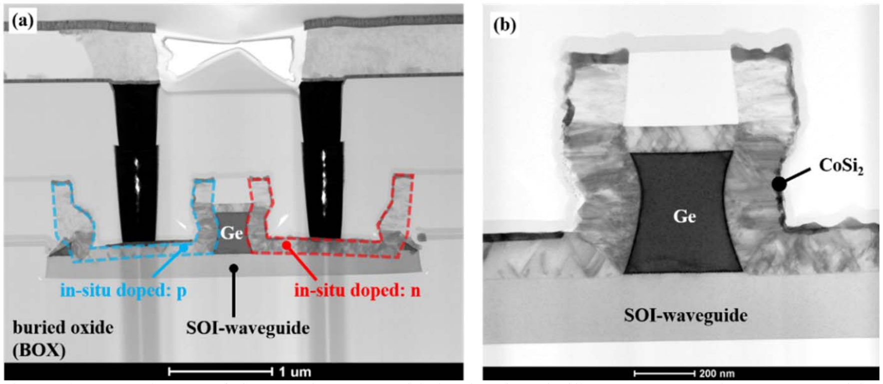

Fig. 1: (a) TEM image of the novel Ge PD with in-situ doped silicon contact regions (separated by different color). Image shows fabrication up to the first metal layer; (b) TEM image of the same structure at a larger magnification; both cross-sections cut perpendicular to the light-incidence direction.

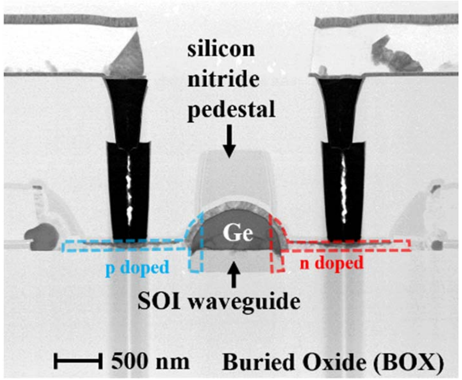

Fig. 2: TEM image of the prior photo detector generation [1]. The silicon nitride pedestal serves, amongst others, for alignment of the ion-implantation that is carried out for the formation of p- and n-doped regions.

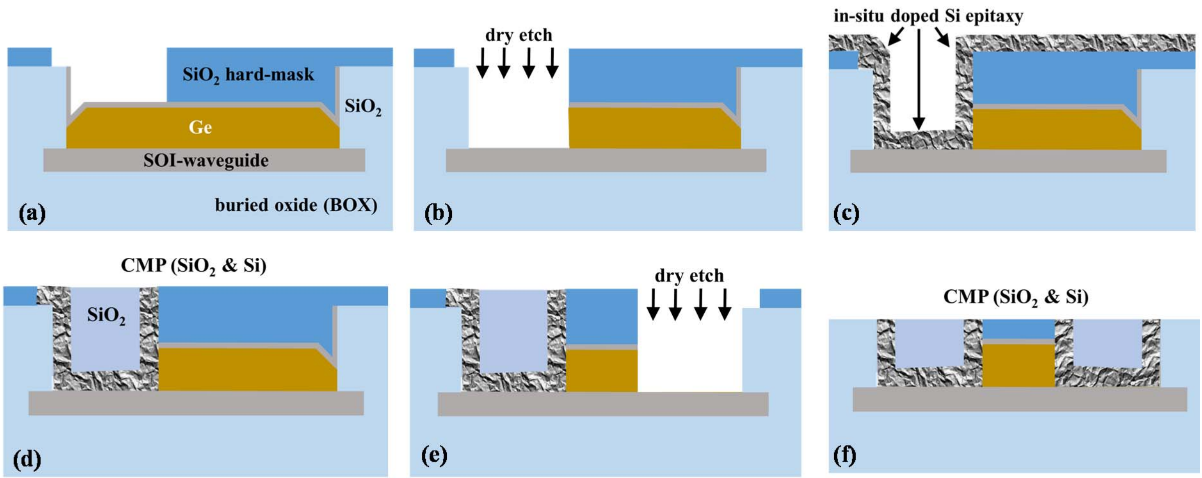

Fig. 3: Schematic fabrication flow of the novel Ge PD: starting with a wide Ge body, several hard-masks, dry etch- and CMP- processes are conducted. Epitaxially grown in-situ doped silicon layers finally sandwich the intrinsic Ge region in between them, such that a lateral Si-Ge-Si p-i-n diode is formed. The actual width of the Ge region is eventually defined by lithography and etch.

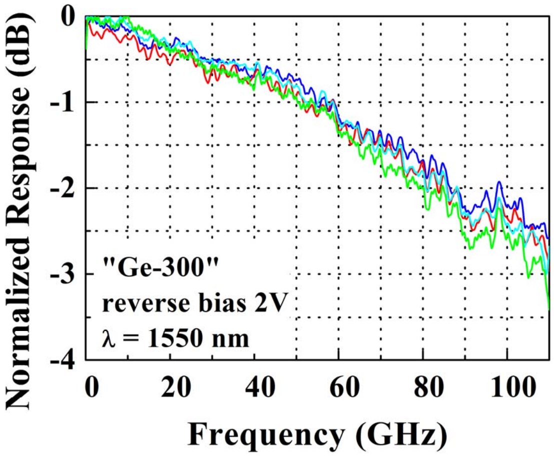

Fig. 4: Normalized frequency response of Ge PDs from four chips at reverse bias of 2 V. Measurements were performed at chip level with a Keysight 110 GHz lightwave component analyzer (LCA).

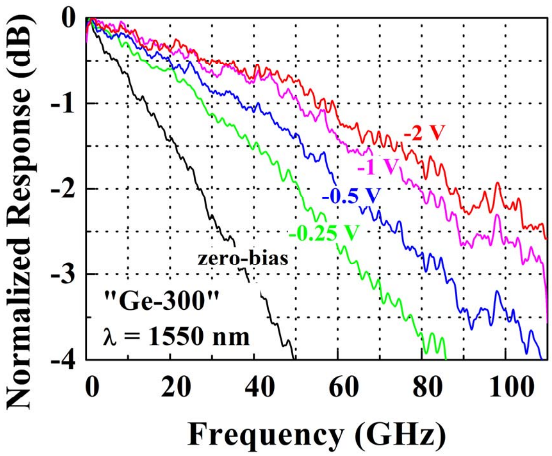

Fig. 5: Normalized frequency response of one Ge PD at different biases, Measurements were performed at chip level with a Keysight 110 GHz LCA.

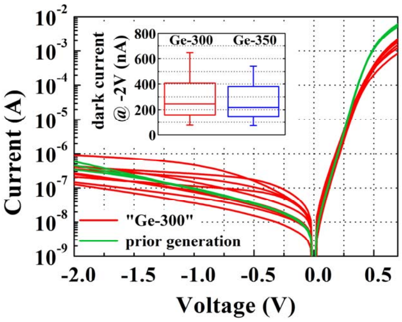

Fig. 6: Room temperature IV characteristics of PD "Ge-300" (from 9 wafer sites) compared to prior PDs (3 wfr. sites). Box-plots show dark currents of "Ge-300" and "Ge-350" (each from on 61 wfr. sites). Lengths of all PDs are 20 µm.

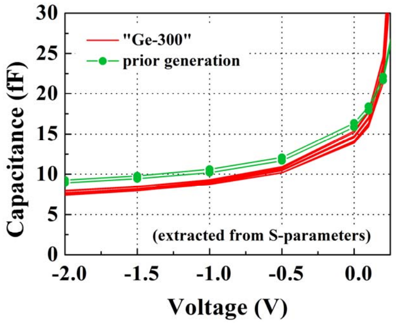

Fig. 7: Capacitance vs. voltage characteristics of "Ge-300" measured on 9 wafer sites compared to those of prior generation (2 wafer sites). Lengths of all PDs are 20 µm.

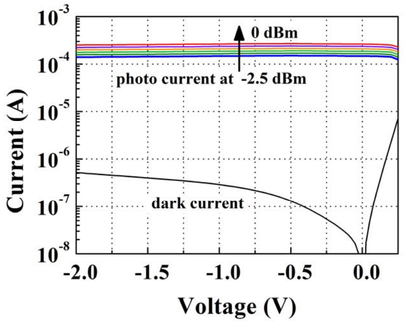

Fig. 8: Dark and photo currents at different optical input power at fiber end for "Ge-300" measured on one wafer site.

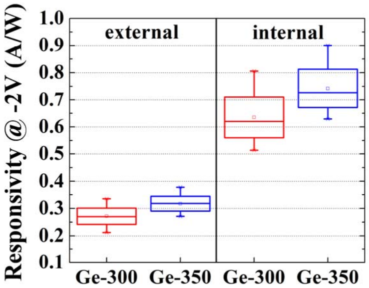

Fig. 9: Box-plot of internal and external responsivities for PDs "Ge-300" and "Ge-350", each measured on 62 wafer sites. Grating coupler loss mean value of 3.7 dB (σ = ±0.18 dB) is considered for estimation of internal responsivity.

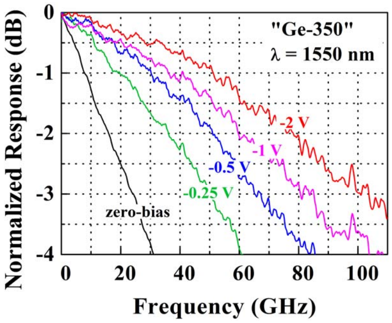

Fig. 10: Normalized frequency response of one PD "Ge-350" at different reverse biases, measured with a Keysight 110 GHz LCA.

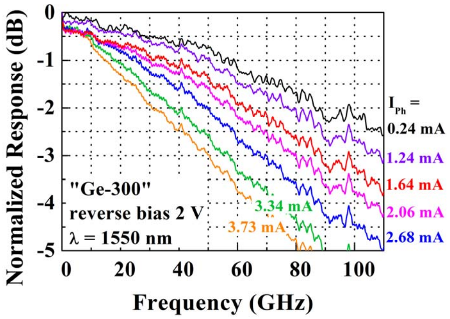

Fig. 11: Normalized frequency response of one "Ge-300" PD at varied optical input power to increase the photo currents; measured with a Keysight 110 GHz LCA.

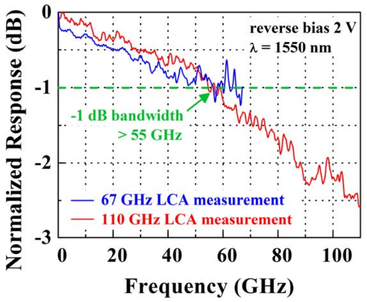

Fig. 12: Normalized frequency response of one chip (diode "Ge-300") measured with Keysight 67 GHz and 110 GHz LCAs.

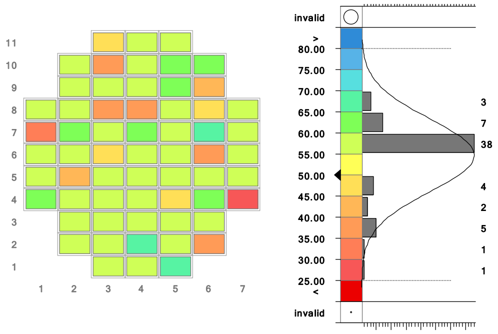

Fig. 13: Wafermap and histogram of -1 dB OE bandwidths of "Ge-300" PD at -2 V (in GHz), measured on 62 wafer sites.

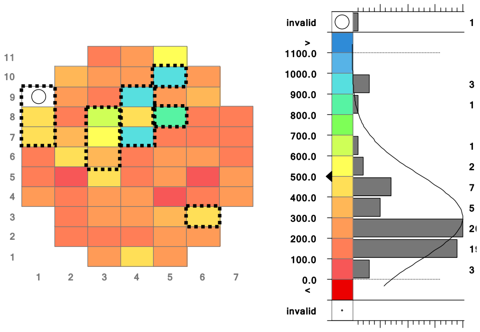

Fig. 14: Wafermap and histogram of dark currents of "Ge-300" at -2 V (nA per diode; valid-range 10 nA-1 µA), measured on 62 wafer sites.

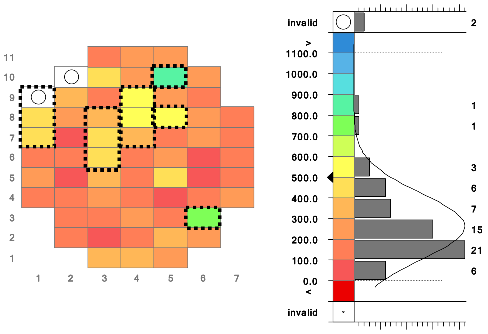

Fig. 15: Wafermap and histogram of dark currents of "Ge-350" at -2 V (nA per diode; valid-range 10 nA-1 µA), measured on 62 wafer sites.

Reference / Parameter	[2]	[3]	[6]	[7]	[this work] (-2 V) "Ge-350"	[this work] (-2 V) "Ge-300"
Material	InP	InP	Graphene	Ge	Ge	
-3 dB OE bandwidth	110 GHz	130 GHz	≥ 110 GHz (-1 V)	67 GHz (-1 V)	≥ 100 GHz	≥ 110 GHz
external resp. in C-band	0.5 A/W	0.45 A/W	0.5 A/W (-0.4 V)	n/a	0.32 A/W	0.27 A/W
internal resp. in C-band*	n/a	n/a	n/a	*(1 A/W)**	0.74 A/W	0.64 A/W
dark current	5 nA	2 nA (-5 V)	4 mA (-0.4 V)	20 nA (-1 V)	260 nA	300 nA

Table 1: Overview of state-of-the-art photo detectors. Compared are the -3 dB bandwidths, internal and external responsivities (C-band*) and dark currents. Values in brackets indicate the respective bias conditions (n/a = values not available in original publication). Results from [8] are not considered because the OE bandwidth was only estimated. *…Responsivity in [7] available for O-band only.