# Waveguide-Coupled Ge Photodiodes with 3-dB Bandwidth ≥110 GHz

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***Abstract*— We present a photodiode construction in which germanium is sandwiched in between complementary in-situ doped silicon layers. With this new approach we demonstrate photodiodes with optoelectrical 3-dB bandwidth of 110 GHz and responsivity of 0.6 A/W at 1550 nm, obtained at reverse bias of 2 V.**

***Keywords—Germanium, photodiode, photodetector, silicon, photonics, PIC, ePIC***

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## I. 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]. 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.

Recently, we presented a novel Ge PD design in which we entirely omit ion-implantation [5]. Instead, complementary in-situ doped Si regions sandwich an intrinsic Ge region, such that a lateral p-i-n diode is realized. By this approach we aim 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 [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.

## II. Measurement Results and Discussion

Normalized frequency responses of PDs with nominal Ge widths of about 300 nm (referred to hereinafter as “Ge-300”) measured at chip level with a Keysight 110 GHz lightwave component analyzer (LCA) on four chips is shown in Fig. 1b. Clearly, the presented PDs achieve OE 3-dB bandwidths of 110 GHz and above. Fig. 1c 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. Internal responsivity at 1550 nm is estimated to about 0.64 A/W at 1550 nm and TE polarization.

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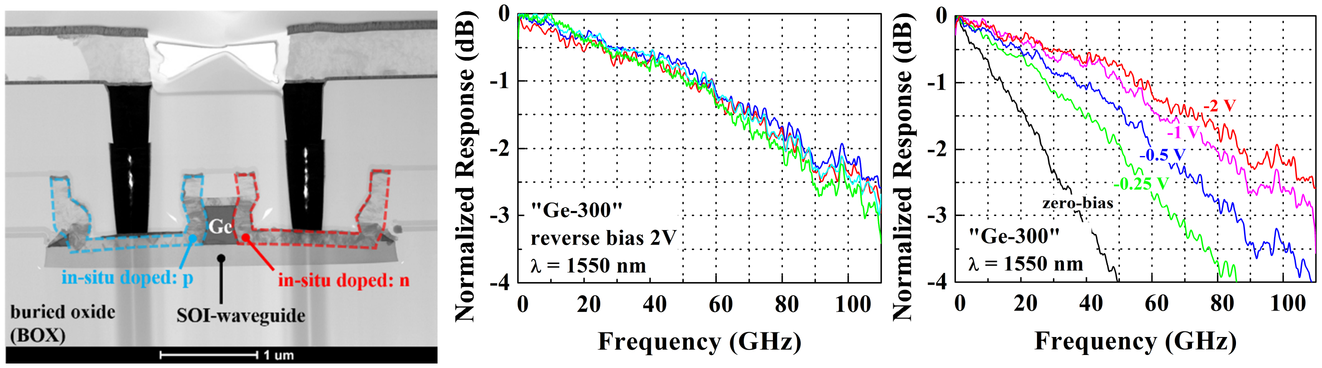


Fig. 1. (a) TEM image of the novel Ge PD with complementary in-situ doped silicon contact regions (indicated by different color). Image shows fabrication up to the first metal layer; cross-sections cut perpendicular to the light incidence direction, normalized frequency responses of Ge PDs from four chips at reverse bias of 2 V (b) as well as at different reverse bias conditions (c).

The optical power handling capability of PD "Ge-300" is demonstrated in Fig. 2a. 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 [6]. In Fig. 2b dark currents of "Ge-300" are compared to those of our prior PD generation [2], showing that in tendency the level and scattering is increased for our novel PDs. The inset, a box-plot, summarizes dark currents of "Ge-300" and a slightly broader diode named "Ge-350". 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. We therefore monitor the 1-dB bandwidths of a full wafer (Fig. 2c).

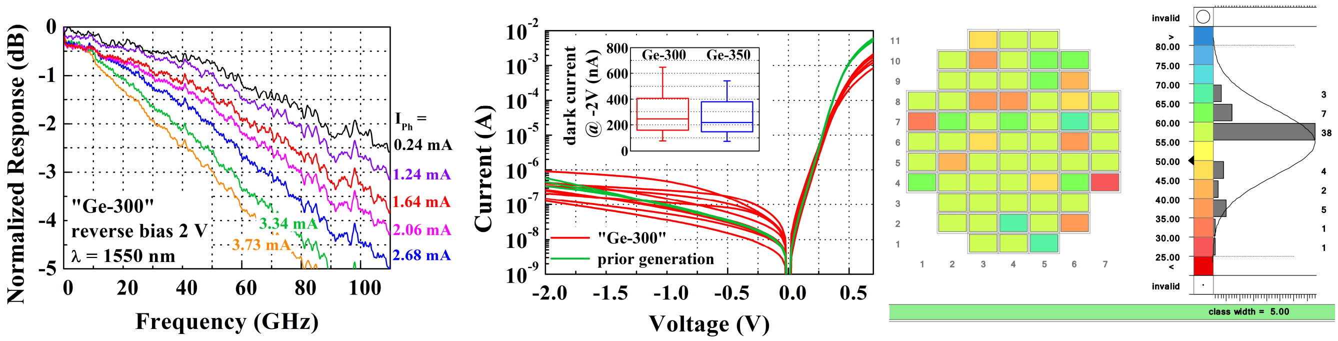


Fig. 2. (a) Normalized frequency responses of one "Ge-300" PD at varied optical input power to increase the photo currents; (b) Room temperature IV characteristics from 9 wafer sites compared to prior PDs (3 wfr. sites). Box-plots as inset show dark currents of "Ge-300" and "Ge-350" (each from on 61 wfr. sites). Lengths of all PDs are 20 µm. (c) Wafermap and histogram of 1-dB OE bandwidths at -2 V (in GHz), measured on 62 wafer sites.

## III. 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 complementary in-situ doped Si regions. By avoiding ion-implantation into the Ge minority carrier diffusion effects are suppressed. 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.

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