Silicon nitride waveguide coupled 67+ GHz Ge photodiode for non-SOI PIC and ePIC platforms

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Abstract— A Ge photodiode, directly coupled to a silicon nitride waveguide, showing more than 67 GHz bandwidth is demonstrated for the first time, which paves the way for utterly new SiN waveguide platform based applications. By light feeding through SiN waveguides, the new photodiode can also be a key enabler for a bulk-Si based, monolithically integrated electronic-photonic integrated circuit platform. We show that the new devices, fabricated on bulk-Si, provide the same bandwidths as Si waveguide coupled SOI based reference Ge photodiodes. However, their O-band responsivity is 0.3 A/W, which is about three times lower compared to the SOI waveguide coupled devices. We attribute this effect to substrate losses and few specific layout features but see some potential for improvement by design and technological optimizations. We demonstrate that the diodes can be fabricated with high yield and low metrics tolerances.

I. Introduction

Silicon nitride (SiN) waveguides (WGs) outperform silicon-on-insulator (SOI) based waveguides in various aspects: they offer an enhanced optical bandwidth, allowing for low loss waveguides in the classic communication bands (C- and O-bands), widely addressed by SOI based photonics, as well as in the visible wavelength range, were Si WGs have already become opaque. Moreover, due to the absence of two-photon absorption in SiN, the optical power handling is superior compared to Si WGs [1–3]. Various platforms with outstanding optical loss performance have been demonstrated over the last years and are meanwhile offered for commercial purposes, as summarized in [1]. However, despite all these advantages, so far, commercially offered SiN based photonic integrated circuit (PIC) platforms neither provide monolithically integrated high speed modulators, nor fast SiN WG coupled detectors. In this work we focus on the detector side of a high-speed SiN PIC platform.

Communication applications for upcoming 400 Gbps standards require 56 Gbd symbol rates, which makes photodiodes (PDs) with more than 40 GHz opto-electrical (OE) bandwidth indispensable. Previous works with focus on Ge PDs in SiN platforms have either shown devices directly SiN WG fed or indirectly coupled via multi-layers (SiN on SOI WGs) where the Ge PDs are actually still located on SOI. However, the former ones showed only inferior bandwidth of less than 10 GHz [4] while the latter ones provide at least a bandwidth of about 30 GHz [5]. Here, we demonstrate for the first time a bulk-Si based, directly SiN WG coupled Ge PD with very high OE -3 dB bandwidth of more than 67 GHz which opens new perspectives for opto-electronic platform technologies:

(1) The combination of truly high-speed PDs with SiN WGs could be the start for a novel active SiN platform e.g. aiming at integrated coherent receivers at wavelengths far below the O-band.

(2) The demonstrated devices are in principle compatible for co-integration with IHP's photonic BiCMOS process [6], which opens various opportunities for novel sensing or spectroscopic applications as well.

(3) This work could pave the way towards a non-SOI based technology as an alternative to established SOI based PIC or electronic-photonic integrated circuit (ePIC) platforms, e.g. IHP's photonic BiCMOS technology. Circuit fabrication on pure bulk-Si wafers would significantly relieve process complexity, time and thus costs.

II. Bulk-Si photodiode fabrication

The fabrication of the bulk-Si based, SiN WG coupled Ge PD is to a large extend based on that of the SOI WG coupled reference PD whose fabrication details can be found in [7]. For this study, neither the actual PD layout was changed, nor were thicknesses of the Ge- or SiN-layers adjusted. All following images and measurement results stem from a 20 µm long Ge PD, the standard device in IHP's ePIC platform. One mandatory adjustment was the replacement of the SOI WG by a bulk-Si region. Both, the SOI based and the SiN WG coupled GePDs rely on selective Ge epitaxy on Si. In the bulk-Si case, shallow-trench isolation (STI) regions define the Si-stripe for selective Ge epitaxy, as shown in Fig. 1. For comparison, the SOI based device is shown in Fig. 2. The Ge PD discussed here has a lateral p-i-n structure where the SiN pedestal located on top of the Ge body supports the definition of the i-region by enabling self-alignment for the ion-implantations applied to form the p- and n-regions. To realize an in-plane waveguide in the non-SOI platform, the SiN pedestal was simply extended to the outside of the PD region. Hence, SiN WG fabrication does not require an extra photomask. Schematic sketches for the bulk-Si and SOI based layouts are presented in Fig. 3. Gratings were deployed for fiber-to-chip coupling. SEM cross-sections of a grating coupler and the extended SiN stripe used as WG are shown in Fig. 4. To minimize substrate losses, the SiN WG is positioned over STI regions. As a minor adjustment, we introduced a CMP step after the deposition of the SiN layer, in order to reduce the surface roughness. Considerable adjustments were done in the contact scheme below the first metal layer (Met1), to avoid abrasion of the SiN WGs during the interlayer dielectrics CMP. The difference can be seen in Figs. 1 and 2.

III. Measurement Results and Discussion

Normalized OE frequency response, measured with a 67 GHz LCA, of bulk-Si PDs is shown in Fig. 5. Obviously, the new devices exhibit very high -3 dB bandwidths of nearly 40 GHz at zero bias and more than 67 GHz under 2 V reverse bias. This performance is very close to that of the SOI based reference PD [7], despite slightly increased capacitances (Fig. 6), which are probably caused by the fringing field in the bulk-Si. Fig. 7 proves identical dark-current behavior of bulk-Si PDs and an SOI based reference device. The photo-currents for different optical input powers at fiber end (Fig. 8) allow for the estimation of the internal responsivity considering the normalized transmission spectra of two grating couplers (Fig. 9). Note that the maxima of the grating coupler spectra are slightly red shifted (maxima at about 1325 nm). With a loss per grating coupler of about 6.25 dB at 1310 nm, an internal responsivity of 0.29 A/W is determined. Compared to the responsivity of SOI based reference Ge PDs, this value is about three times lower.

We suspect three effects responsible for this responsivity reduction: (1) A certain fraction of the light is probably emitted into the Si substrate below the Ge body. (2) The SiN stripe above the Ge layer is supposed to shield ion-implantations. In case that this stripe functions as a WG, the exposure to that ion-bombardment might entail additional losses. (3) The propagation part of the SiN WG (1.3 µm wide) is tapered down to 600 nm, the width of SiN stripe above the Ge body, over the short distance of 30 µm, which might cause unwanted reflections. Investigations on these effects through simulations and experiments are still ongoing. We underline that all presented results originate from Ge PDs based on the reference device design which was optimized for an SOI environment. Therefore we see some potential to improve the responsivity of our new, SiN WG coupled PDs by technological and design optimizations, without compromising their bandwidth too much.

An overview of SiN platform integrated Ge PDs, compared to a state-of-the-art SOI based Ge PD, is given in Table 1. It makes obvious that our new devices clearly outperform other SiN coupled PDs in bandwidth and dark-current behavior, while there is still a deficit in responsivity.

Transmission spectra of 5 cm long SiN WGs are shown in Fig. 10. The propagation loss of the SiN WG realized only by the extension of the SiN stripe from the Ge PD yields to about 2.3 dB/cm at 1310 nm. We see improvement potential too, e.g. by geometry optimization or introduction of rib-WGs, which could be realized without extra effort using the grating coupler mask and etch.

That, despite all technological adjustments, the new, bulk-Si based Ge PDs can be fabricated with high yield and low metrics tolerances is demonstrated next. We focus on full-wafer measurements (@ 57 wafer sites) of arrays consisting of 500 Ge PDs contacted in parallel, i.e. 28k diodes are considered in total. Figs. 11 and 12 show the dark-current behavior of the arrays for reverse bias, while Fig. 13 shows that of the forward-currents. Corresponding cumulative plots are shown in Fig. 14. Only 3 of 57 arrays located at the wafer edge failed.

Results of a follow up lot with slightly deeper etched gratings to reduce the red-shift demonstrate loss mean values of about 5 dB per coupler at 1310 nm (Fig. 15). This clearly reflects also a homogeneous SiN WG and coupler fabrication.

The facts that the SiN coupled Ge PD fabrication scheme largely complies with that of the reference SOI based devices and that no additional thermal budget is applied for the SiN WG fabrication facilitate the implementation into IHP's photonic BiCMOS process. Together with substrate independent modulator approaches like recently demonstrated BTO based devices [8], the SiN coupled PD presented in this work could pave the way for utterly new high speed SiN based PIC or ePIC platforms with various opportunities for new applications.

IV. Conclusion

We have demonstrated for the first time a Ge photodiode, directly coupled to a SiN waveguide, with more than 67 GHz bandwidth, which can be fabricated with high yield and low metrics tolerances. This unique combination and the potential integration with high-speed electronics could pave the way for an utterly novel SiN platform potentially addressing applications in sensors, spectroscopy or even Tele- and Datacom. We see potential for improvement of the responsivity which is still lower compared to that of SOI based reference and other SiN coupled devices.

Acknowledgment

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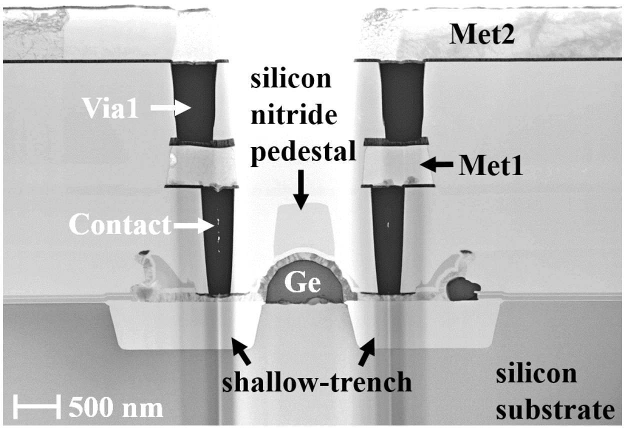

Fig.1. Cross-section (perpendicular to the light incidence direction) of Ge PD on bulk-Si. Selective Ge epitaxy is enabled by shallow-trench regions. The basic fabrication scheme of the SOI WG Ge PD is maintained.

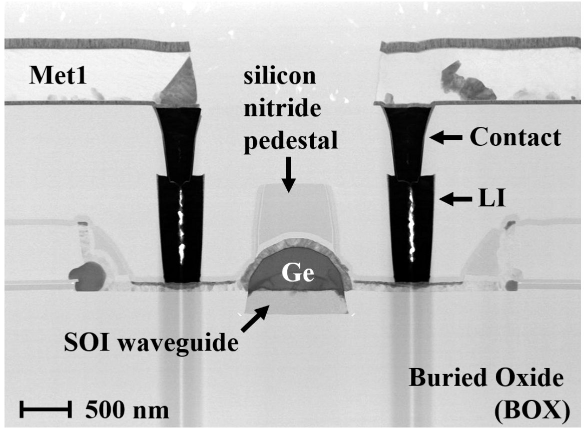

Fig. 2. Cross-section of reference Ge PD fabricated on SOI substrate. Selective Ge epitaxy is performed on a SOI WG. Note that for the sake of image details, the scale is slightly different compared to Fig1.

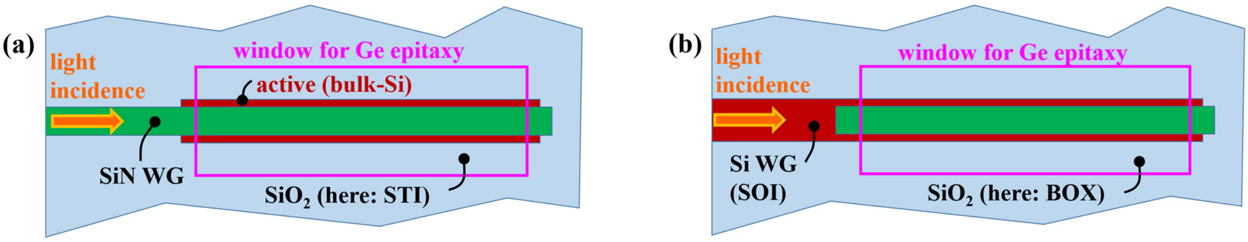

Fig. 3 Schematic layout top view of bulk-Si (a) and SOI based Ge PD (b). Main difference is the replacement of the waveguide layer by active and the extension of the SiN stripe from the diode region (defined by Ge epitaxy window) to the outside to form a SiN waveguide.

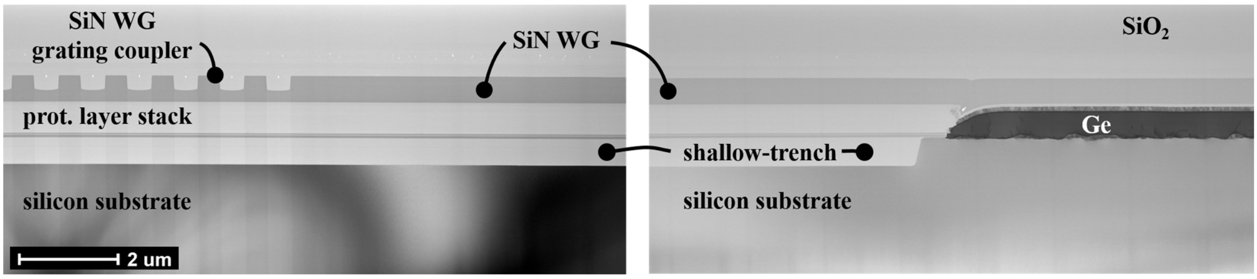

Fig. 4. Cross-section (longitudinal) of SiN WG grating coupler (left) and Ge photodiode (right). The SiN waveguide is positioned on top of the protection layer stack required for the photodiode fabrication. Beneath the protection layer, there is shallow-trench region.

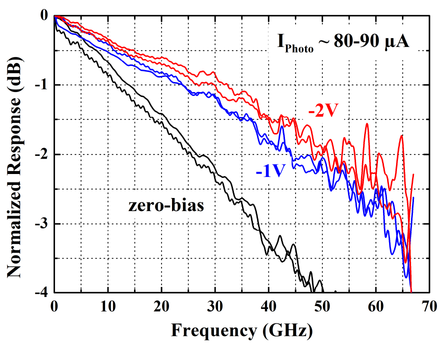

Fig. 5. Normalized frequency response of two bulk-Si, SiN WG coupled Ge PD measured with a 67 GHz lightwave component analyzer (LCA).

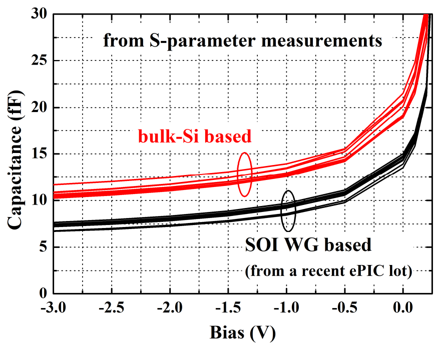

Fig. 6. Capacitance vs. voltage characteristics of bulk-Si Ge PDs and SOI based devices, each of both measured on 9 sites of one respective wafer.

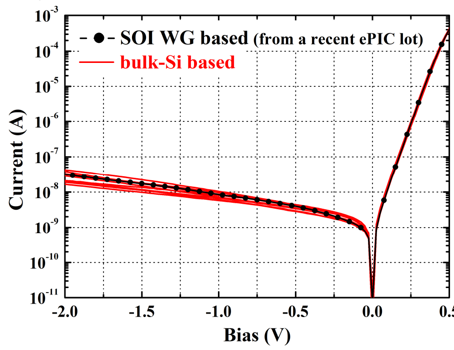

Fig. 7. Room temperature dark-current characteristics of bulk-Si Ge PDs, measured on 9 sites of one wafer, and one SOI based reference device.

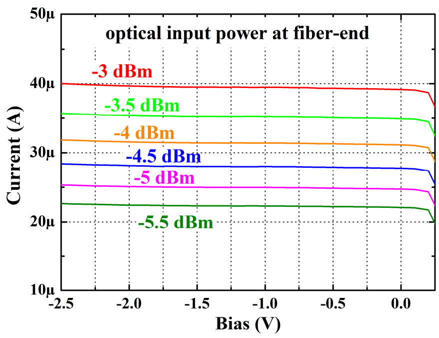

Fig. 8. Photo-currents of a SiN WG coupled Ge PD at 1310 nm wavelength for different optical input powers. Considering -6.25 dB grating coupler losses, the internal responsivity is about 0.29 A/W.

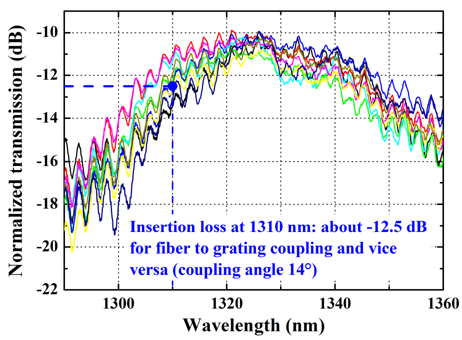

Fig. 9. Grating coupler transmission spectra (fiber to grating and vice versa) for 9 sites on one wafer. Insertion loss of one grating coupler is about -6 to -6.5 dB at 1310 nm wavelength. The maxima are slightly red-shifted.

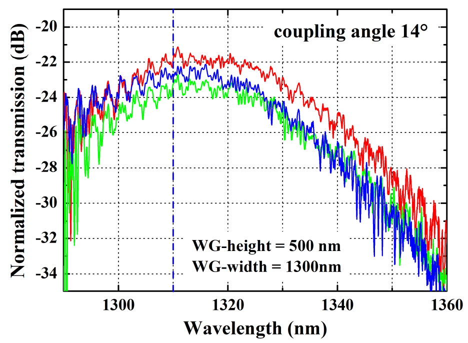

Fig. 10. Transmission spectra of 5 cm long SiN WG measured on 3 sites of one wafer. Subtraction of two grating couplers (in and out coupling loss of ~12.5 dB) yields in propagation loss of about 2.3 dB/cm.

Parameter \ Platform	SOI WGs [7]	SiN on SOI WGs [5]	Bulk-Si with SiN WG [4]	Bulk-Si with SiN WG [this work]
-3 dB bandwidth	> 67 GHz (-2 V)	29 GHz (-2 V)	7.2 GHz (-1 V)	> 67 GHz (-2 V)
internal resp. in O-band	> 0.8 A/W (-2 V)	0.85 A/W (-2 V)	*n/a*	0.3 A/W (-2 V)
internal resp. in C-band	> 0.8 A/W (-2 V)	*n/a*	> 1 A/W (-1 V)	*n/a*
dark-current	< 400 nA (-2 V)	2 µA (-2 V)	~ 1 µA (-1 V)	< 400 nA (-2 V)

Table 1: Overview of Ge photodiodes available in SiN WG platforms. Compared are the -3 dB bandwidths, the internal responsivities in O- and C-bands, if applicable, and the diode dark currents. Values in brackets indicate the respective bias conditions. (n/a = values not available in original publication)

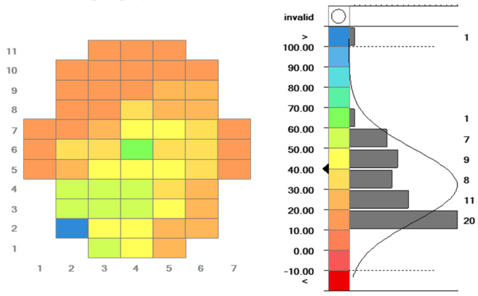

Fig. 11. Wafermap and histogram of dark-currents at -1 V (nA per single diode) of Ge PD arrays consisting of 500 diodes in parallel, measured on 57 wafer sites.

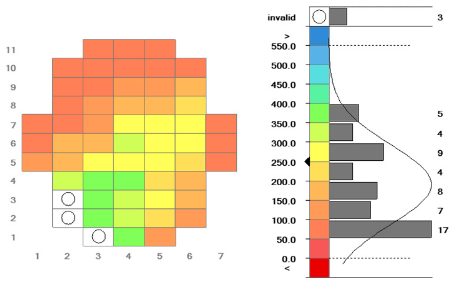

Fig. 12. Wafermap and histogram of dark-currents at -2 V (nA per single diode) of Ge PD arrays consisting of 500 diodes in parallel, measured on 57 wafer sites.

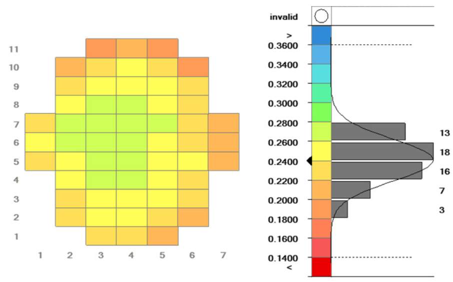

Fig. 13. Wafermap and histogram of forward-currents at +0.2 V (nA per single diode) of Ge PD arrays consisting of 500 diodes in parallel, measured on 57 wafer sites.

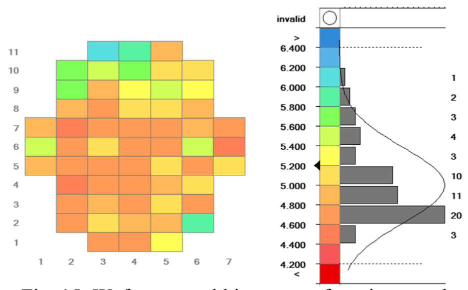

Fig. 15. Wafermap and histogram of grating coupler insertion losses at 1310 nm (in dB, coupling angle 14°), determined for 57 sites of a follow up wafer with compensated red shift, compared to Fig. 10.

Fig. 14. Cumulative plots of Ge PD array currents measured at reverse biases of 1 V [a] and 2 V [b], resp., and forward bias of 0.2 V [c].
Arrays consist of 500 single Ge PDs connected in parallel. Currents were measured on 57 sites of one wafer. For plotting, measured array currents were divided by 500.