Micro-Transfer-Printed Photodiodes on Silicon Nitride for High-Speed Communications

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Silicon photonics is a key technology for high-speed interconnects. Its small footprint, integrated nature, and CMOS-compatible manufacturing make it a technological platform that is rapidly being embraced by industry. Silicon Nitride (SiN) flavored platforms have some extra benefits, including low-loss waveguides, allowing high-Q filters, and no two-photon absorption (TPA), greatly improving its power handling. However, the functionality of this passive platform needs to be extended to feature active components, and as such relies on heterogenous integration techniques for detectors and light sources.

To this end, we have transfer-printed uni-travelling-carrier photodiodes (UTC PDs) on a SiN photonic integrated circuit (PIC). These evanescently coupled photodiodes have a waveguide-referenced responsivity of 0.3 A/W, a dark current of 10 nA at -1 V bias and a 3-dB bandwidth of 155 GHz and 135 GHz at -1 V and zero bias, respectively.

In this paper, we show that such a high-bandwidth heterogeneously integrated photodetector can be used for direct photomixing at sub-mmWave (sub-THz) frequencies, enabling data rates beyond 100 Gbit/s.

1. Introduction

Optical technologies have since long been important in communication systems. The internet is unimaginable without high-speed fiber interconnects. However, the optical subsystem in these interconnects has only in recent years been growing beyond the optical fiber and necessary peripheral components. Silicon Photonics (SiPh) accelerates this change: complex and cost-effective photonic circuits are possible thanks to the CMOS-compatible manufacturing and the small footprint of these chips.

Silicon-Photonic technologies not only enable more sophisticated, more efficient, and faster transceivers for fixed datacom and telecom. It also finds its way to wireless communication systems, e.g. next-generation wireless networks (6G). The field of microwave photonics leverages the fact that high-bandwidth radio signals are relatively narrowband in the optical domain. Compared to their electronic counterparts, this allows for easy filtering and manipulation of millimeter wave (mmWave) signals and even terahertz (THz) signals.

Silicon Nitride (SiN) is one particular flavor of Silicon Photonics that is increasingly gaining popularity thanks to its noticeable benefits. SiN waveguides are very low loss, allowing high-Q filters, and the absence of two-photon absorption (TPA) greatly improves the linearity at high optical powers. On the other hand, many SiN platforms only excel for their passive components (waveguides, filters...) and require hybrid or heterogeneous integration of active components (lasers, modulators, photodetectors...).

In this paper, we show that a low-loss passive SiN platform can be extended with very high-bandwidth photodetectors using the micro-transfer-printing technology. We further demonstrate that this device can be used in future THz systems by setting up a link at 300 GHz with a bit rate beyond 100 Gbit/s. The remainder of this paper is divided in two sections: Section 2 describes the integration of the high-bandwidth photodetectors on SiN, and in Section 3 we demonstrate a THz data link leveraging this device.

2. High-bandwidth photodetectors on SiN

Multiple technologies have been developed to bring high-speed detectors to SiN platforms. Oftentimes these approaches start from a high-speed photodetector developed on a III-V platform, e.g. based on InP and InGaAs. One particular type of photodetector, the uni-travelling-carrier photodiode (UTC PD), is a great choice for high-speed high-power applications. By limiting the carrier transport to high-mobility electrons, the transit-time-limited bandwidth is greatly increased, making the RC-time limit dominant. Furthermore, the UTC PD only shows carrier-screening effects at much higher powers – compared to traditional PIN photodiodes – making it a perfect suitor for a SiN platform.

Yu et al. [1] have shown that waveguide-coupled UTC PDs can be integrated on a SiN platform by means of wafer-bonding. Their approach yielded a high responsivity of 0.8 A/W and a respectable 3-dB opto-electric bandwidth of 20 GHz.

In our work, we use micro transfer-printing (μTP) as heterogenous integration technology. In this technology, first a fully operational photodiode is created on the III-V wafer (the *source* wafer). Next, the photodiode is encapsulated in a passivation layer and under-etched to create a suspended chiplet, i.e. a *coupon*. This coupon can then be picked up using a polymer stamp and is printed on top of the desired photonic structure. In our design it is printed on top of a SiN waveguide on the SiPh wafer (the *target* wafer). Compared to wafer bonding this offers some additional benefits: the chiplet can be fully made on the source wafer without alteration of the original process flow, multiple chiplets of difference source wafers can be printed close to each other on the target wafer allowing for multi-material integration, and this process is more efficient by requiring less source wafer material [2].

In our previous work [3] we reported a UTC PD on SiN with a 3-dB bandwidth beyond 100 GHz, a responsivity of 0.45 A/W at 1550 nm and a dark current of 10 nA. The smooth roll-off at high frequencies makes this device a great component for sub-mmWave (sub-THz) signal generation.

3. On-chip photomixing for THz generation

Generating continuous-wave radiation at frequencies beyond 100 GHz is not easy for electronic ICs, especially in CMOS. Monolithic microwave integrated circuits (MMICs) are fabricated in advanced technological nodes and mostly rely on high-electron-mobility transistors (HEMTs) made using GaAs and AlGaAs. In microwave photonics, an alternative approach called photomixing is used to generate high-frequency microwave signals. By beating two optical tones on a photomixer, i.e. a photodetector with a high electrical bandwidth, an electrical signal at the beat note of the two optical frequencies is generated. As such, if two tunable lasers are used, the only limit on the maximum frequency that can be generated is the efficiency of the photomixer at this frequency.

This approach is not limited to continuous wave (CW) signals, but also data can easily be upconverted to (sub-)THz frequencies this way. One of the two optical lines is modulated and the resulting data signal is then heterodyne-mixed to the desired THz carrier by choosing the appropriate wavelength for the second laser. We demonstrated that this approach for high data-rate THz communication is possible with a SiN photonic integrated circuit (PIC) featuring our high-speed UTC PD (Fig. 1).

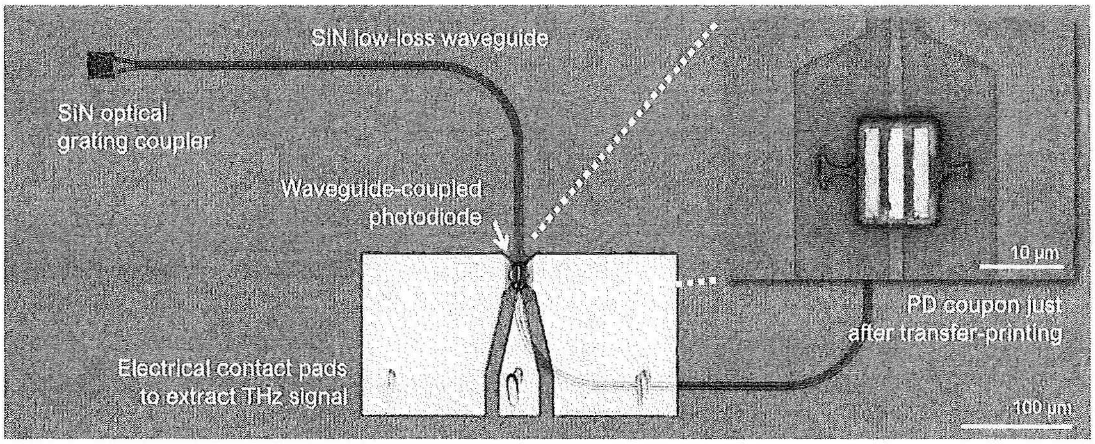


Figure 1. The SiN PIC consists of an optical grating coupler, SiN waveguide and electrical contact pads to probe the waveguide-coupled UTC PD.

Fig 2. shows the setup we used for this photomixing experiment. Two optical lines are generated using tunable C-band lasers at a wavelength of 1547.9 nm and 1550.1 nm (193.68 GHz and 193.40 GHz respectively). A Mach-Zehnder Modulator (MZM) is used to modulate the data generated by the Arbitrary Waveform Generator (AWG) on the optical carrier. To overcome the optical losses of coupling into the PIC using a grating coupler, an optical Erbium-Doped Fiber Amplifier (EDFA) was used to increase the power. After photomixing, the sub-THz (sub-mmWave) signal with a center frequency of 280 GHz is fed over a waveguide channel (WR3) before being mixed down at the receiver side. The signal is mixed down again to an intermediate frequency (IF) that is within the bandwidth of the real-time oscilloscope.

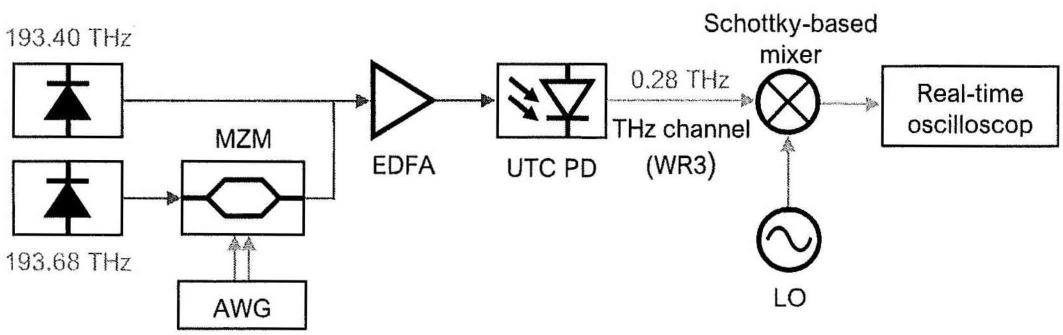
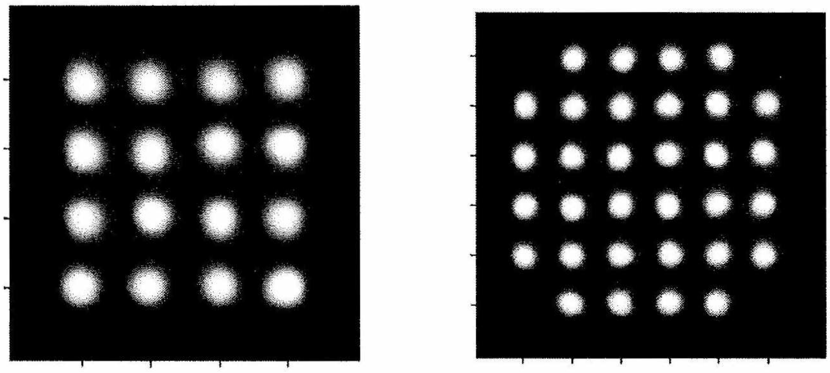


Figure 2. The photomixing experiment consists centrally of the optically and electrically probed PIC containing the UTC PD.

With this setup, we were able to transmit data back-to-back at a rate up to 140 Gbit/s. A 16-point quadrature amplitude modulation (16-QAM) scheme was deployed at symbol rate of 35 GBaud. This resulted in a low error vector magnitude (EVM) of 11%, below the 12.5% EVM forward-error-correction (FEC) limit. Also higher order modulation (32-QAM) yielded high bit rate transmission (125 Gbit/s at 25 GBaud) with low EVM (7%). Fig. 3 shows the constellation diagrams.



(a) 16-QAM at 35 GBd: 140 GBit/s **(b) 32-QAM at 25 GBd: 125 Gbit/s**

Figure 3. Constellation diagrams for both configurations show a low EVM.

4. Conclusion

Silicon photonics offers many technological benefits for future fixed and wireless networks. We have demonstrated that low-loss passive SiN platforms can be extended with state-of-the-art photodetectors by heterogeneous integration of a UTC PD using the micro-transfer-printing technology. We further demonstrate that these devices on a SiN PIC are ready to be used in a sub-THz communication link at 280 GHz. For this a back-to-back link with a data rate up to 140 Gbit/s was set up.

References

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