Ge-Based Photoreceivers for SWIR Sensing and Imaging - Journey Toward Single-Photon Detection (*Invited*)

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***Abstract*—Ge-based photoreceivers, widely applied in Si photonics (SiPh) for high-speed optical communication, have recently adventured into the territory of shortwave infrared (SWIR) sensing and imaging. Here I review the history and key milestones including the recent demonstrations of lock-in detection with Ge-in-Si and single-photon detection with Ge-on-Si.**

Keywords—Ge, SiPh, SWIR sensing and imaging, lock-in detection, single-photon detection.

I. INTRODUCTION

The rise of SiPh in the past several decades have brought significant impacts over optical communication related industries. In particular, at the photoreceiver side, Ge has become the most popular material for high-speed photodetectors due to intrinsic properties such as complementary metal-oxide-semiconductor (CMOS) compatible, capability of being directly grown over Si, strong absorption at O-band and C-band wavelengths, and small effective electron mass, leading to crucial benefits such as low-cost, low dark current, high quantum efficiency, and large bandwidth, respectively.

Given all the benefits mentioned above, Ge has not be seriously considered as a suitable material for optical sensing and imaging for decades, primarily due to the "low" dark current for optical communication is simply not enough for optical sensing and imaging. In short, the sensitivity of a photoreceiver for optical communication is mainly limited by the high-speed transimpedance amplifier (TIA) input-referred noise, e.g., ~ 10 pA/sqrt(Hz) for 10 Gbps data rate, resulting into noise current ~ 1 µA at the very minimum. On the other hand, the sensitivity of a photoreceiver for optical sensing and imaging is strongly influenced by the shot noise associated with the dark current, rather than the common analog frontend (AFE) circuits used for optical sensing and imaging, e.g., low-speed TIA, passive pixel sensor (PPS) / active pixel sensor (APS) + analog-to-digital converter (ADC), or passive quenching circuit (PQC) / active quenching circuit (APS) + time-to-digital converter (TDC), meaning the material quality of Ge needs to approach that of InGaAs to compete in SWIR sensing and imaging. This is a daunting task considering the Ge used in SiPh are in fact Ge grown and patterned over Si, exhibiting threading dislocations in Ge due to the 4% lattice mismatch between Ge and Si, as well as surface defects on Ge due to the damages generated during fabrication processes.

Nevertheless, through a series of demonstrations starting in 2018 by Artilux [1-6], it is proven that, specifically for time-of-flight (TOF) applications, detectors made from Ge technology can feature performance comparable to, and in some cases better than [4,5], the corresponding detectors made from InGaAs technologies. In this paper, I shall review these Ge-based photoreceivers including their performance as well as their demonstrations of being used for indirect and direct TOF applications.

II. PERFORMANCE

A. Dark current density

The bulk and surface dark current densities of a GeSi photodiode (PD) fabricated by Artilux are extracted to be 4.12 µA/cm^2 and 0.742 nA/cm at -1V reverse bias, respectively, and are the lowest dark current densities among all Ge-based photodetectors to the best of our knowledge [7]. The effective dark current densities of a GeSi pixel can be even lower thanks to CMOS fabrication techniques in which the GeSi photodiode can be made smaller than the GeSi pixel, and the fill factor is compensated by a microlens fabricated over the GeSi pixel. In the next paragraph, these numbers will be used to calculate the performance of PD, avalanche photodiode (APD), lock-in PD (LIPD), and single-photon avalanche diode (SPAD).

B. Noise equivalent power

Here noise-equivalent power (NEP) is applied as the figure of merit to evaluate PD, APD, LIPD, or SPAD in a photoreceiver. Since NEP is related to what AFE is used under which applications, TOF application is assumed in the following. For the cases of 1) PD + TIA and 2) APD (i.e., APD in linear mode) + TIA [4], the NEP can be expressed as

$$NEP = \frac{\hbar\omega\sqrt{\left(2qI_d < G^2 > +\Delta I_c^2\right)\cdot BW}}{QE < G > q}. \quad (1)$$

I_d is the dark current, G is the avalanche gain, ΔI_c is the TIA noise current, BW is the measurement bandwidth, and QE is the quantum efficiency. For the cases of 1) LIPD + APS + ADC [3] and 2) SPAD (i.e., APD in Geiger mode) + AQC + TDC [6], the NEP can be expressed as

$$NEP = \frac{\hbar\omega\sqrt{2\left(\frac{I_d}{q} \text{ or } DCR\right)\cdot BW}}{\left(QE \text{ or } SPDE\right)}. \quad (2)$$

DCR is the dark count rate, and $SPDE$ is the single-photon detection efficiency. In Table 1, the summary of the demonstrated GeSi APD and GeSi SPAD performance is shown, and it can be observed for photoreceivers that can described by Eq. (2) such as using LIPD and SPAD, a better NEP can be obtained. In the next section, I shall review indirect and direct TOF applications based on photoreceivers using GeSi LIPD and GeSi SPAD for SWIR sensing and imaging.

TABLE I. PERFORMANCE SUMMARY

	Device Type	***Device Diameter***	***NEP @ Room Temperature***
Ref. [4]	APD	50 µm	75 fW/sqrt(Hz), using Eq. (1)
Ref. [5,6]	SPAD	15 µm	3 fW/sqrt(Hz), using Eq. (2)

III. APPLICATION

Indirect and direct TOF techniques refer to the acquisition of depth information through optical phase delay and optical time delay, typically using LIPD [3] and SPAD [6], respectively. It should be noted that while their NEP are both described by Eq. (2), the inverse of the deadtime in free-running mode or the gating window time in gated-mode sets up an upper limit of DCR that a SPAD can operate. Beyond this limit, saturation occurs and the SPAD becomes "blind", a major issue for Ge-based SPAD to be operated at room temperature. For this reason, Artilux starts with the indirect TOF application through demonstrating the world-first GeSi LIPD [1,2] based on selective Ge-in-Si growth, and with the improved material growth and passivation methods over the years, later works on the direct TOF application through demonstrating the world-first GeSi SPAD operated at room and elevated temperatures [5,6] based on blanket Ge-on-Si growth.

A. Indirect Time-of-Flight

In Fig. 1, a 240×180 indirect TOF image sensor is implemented. Four-phase system clocks are generated from a conventional Integer-N phase-locked loop (PLL) for modulation and demodulation. Before sending to the pixel array and external illumination driver, these clocks are gated and conditioned by the timing generator for a preset integration time and different operation modes. A readout circuit bridges the image sensor array to column ADCs, and the ADC outputs are further processed and integrated in the digital domain before reaching the output interface. The output interface is mainly composed of a 2-lane, 1.2Gbps D-PHY MIPI transmitter. Two voltage domains VDDH receiving a voltage > 2.7V and VDDL receiving a voltage of 1.8V are implemented. A temperature sensor is also implemented for the possible use of depth calibration and power control. All the blocks can be accessed through the I^{2}C interface.

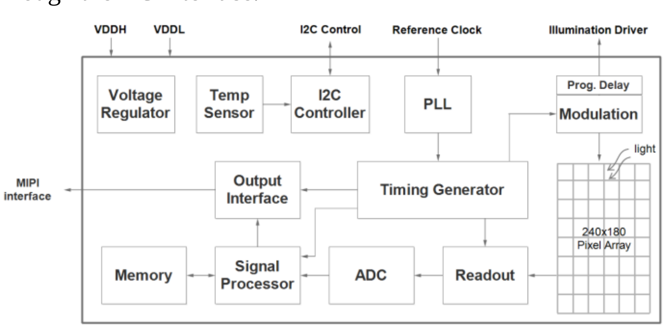

Fig. 1. Block diagram of the photoreceiver based on GeSi LIPD to implement a 240×180 indirect TOF image sensor [3].

B. Direct Time-of-Flight

In Fig. 2, a single-pixel proximity sensor is implemented. The application specific integrated circuit (ASIC) is fabricated in a commercial 40 nm CMOS process and interfaces the SPAD through an AQC and a 13-bit TDC designed for baseline resolution of ~1 cm and typical range of ~100 m. Finer resolutions and closer ranges can be obtained by adjusting the PLL clock frequency. A high-speed first-in-first-out (FIFO) port serves as the data buffer to handle the operating speed difference between the TDC and the field-programmable gate array (FPGA).

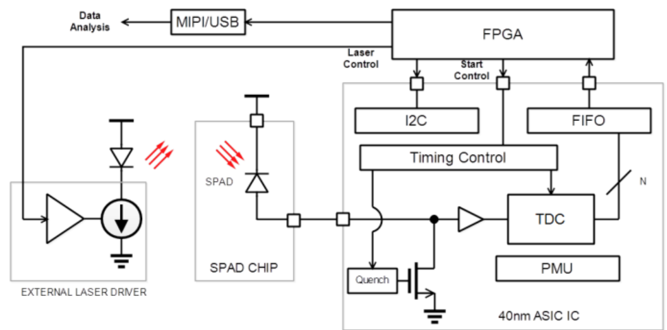

Fig. 2. Block diagram of the photoreceiver based on GeSi SPAD to implement a single-pixel proximity sensor [6].

IV. CONCLUSION AND OUTLOOK

With drastically reducing the dark current densities, Artilux shows that high-performing Ge-based photoreceivers for indirect and direct TOF applications can be achieved, and are competitive against InGaAs-based photoreceivers not to mention the additional low-cost benefit. For applications beyond optical communication as well as SWIR sensing and imaging, photonic quantum computing in SiPh is predicted to benefit from GeSi SPAD for cryogenics-free operation [7].

REFERENCES

[1] N. Na et al., "Proposal and demonstration of germanium-on-silicon lock-in pixels for indirect time-of-flight based three-dimensional sensing," https://arxiv.org/abs/1806.07972.

[2] N. Na et al., "High-performance germanium-on-silicon lock-in pixels for indirect time-of-flight applications," International Electron Devices Meeting (IEDM), pp. 32.4.1-32.4.4 (2018).

[3] C. L. Chen et al., "An Up-to-1400nm 500MHz Demodulated Time-of-Flight Image Sensor on a Ge-on-Si Platform," International Solid-State Circuit Conference (ISSCC), pp. 98-100 (2020).

[4] N. Na et al., "GeSi APD with Ultralow Dark Currents for LiDAR," Silicon Photonics Conference (SiPhotonics), (2023).

[5] N. Na et al., "Room temperature operation of germanium–silicon single-photon avalanche diode," Nature **627**, 295-300(2024).

[6] N. Na et al., "GeSi SPAD for SWIR Sensing and Imaging," International Image Sensor Workshop (IISW), pp. 1-2 (2023).

[7] N. Na, C.-Y. Hsu, E. Chen, and R. Soref, "Room-temperature photonic quantum computing in integrated silicon photonics with germanium-silicon single-photon avalanche diodes," (submitted)