GeSi SPAD for SWIR Sensing and Imaging

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We demonstrate a high-performing germanium-silicon (GeSi) single-photon avalanche diode (SPAD) operated at room and elevated temperatures, featuring a low breakdown voltage (BV) < 12 V. At room temperature, dark count rate (DCR) and single-photon detection probability (SPDP) are measured to be ~10 kHz/μm^2 and ~10 % from a device with active area of 15 μm diameter, at a low excess bias (EB) of only 0.5 V. As proof-of-concept, we operate such a GeSi SPAD in conjunction with active quenching circuit (AQC) and time-to-digital circuit (TDC), and successfully capture time-of-flight (TOF) histograms at the proximity of a few to tens of centimeters.

The capability of detecting single photons through solid-state sensors and imagers has greatly advanced research fields such as optical quantum information processing, bio-photonics, and light detection and ranging (LiDAR). While technologies such as Si photomultiplier (SiPM), Si SPAD, InGaAs SPAD, visible-light photon counter (VLPC), and superconducting nanowire single-photon detector (SNSPD) have been demonstrated, issues such as operation temperature and manufacture cost remain as major hurdles towards commercialization. Recently, Si SPAD for three-dimensional (3D) sensing and imaging at near-infrared (NIR) wavelength has attained consumer-level commercialization, and such a success can be attributed to factors such as 1) high crystalline quality allowing very low DCR at room temperature, and 2) compatibility with complementary metal-oxide-semiconductor (CMOS) fabrication making low-cost integration between devices and circuits possible.

However, there has been a growing demand in migrating the operation wavelength from NIR to short-wavelength infrared (SWIR), to achieve better laser eye-safety, lower solar ambient light, higher atmospheric transmission, and negligible interference with Si-based electronic devices and circuits. With SWIR operation wavelength, alternative solutions to Si SPAD are urgently needed because material-wise Si features poor optical absorption for wavelengths beyond 1 μm. Ge-on-Si SPAD using pure Ge as absorption material may be a suitable candidate for SWIR sensing and imaging, and has been investigated in the past decade by various works [1-5]. While it is CMOS compatible and so promises fabricating low-cost devices integrated with circuits, due to reasons including lattice mismatch between Si substrate and pure Ge as well as other issues, all reported Ge-on-Si SPADs in the literature feature very high DCRs and can only operate at low temperatures at least < 200 K.

In this paper, we report the demonstration of the first high-performing GeSi SPAD operating at room and elevated temperatures. A GeSi SPAD with active area of 15 μm diameter is designed, simulated, and fabricated, targeting a low breakdown voltage below 12 V for low-power operation. Fig. 1 shows the tilted-view scanning-electron-micrograph (SEM) image of the fabricated GeSi SPAD, in which two metal rings are used to bias the cathode and the anode of the device. From the measured IV characteristics, the BV is determined to be around 11 V, which matches the prediction from our numerical simulator very well.

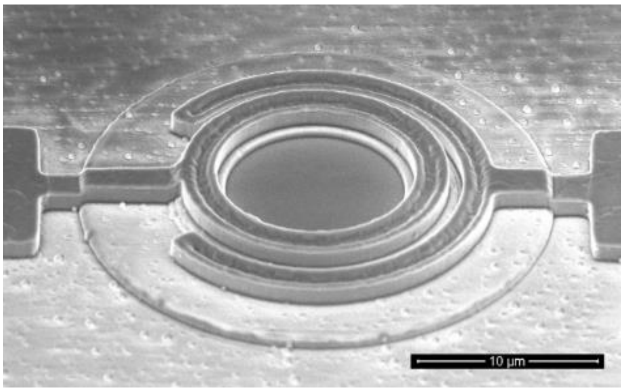


Fig. 1. A tilted-view SEM image of the fabricated GeSi SPAD with active area of 15 μm diameter.

To characterize the DCR and the SPDP of the fabricated GeSi SPAD, gated-mode operation with gate pulse duration of a few ns and gate pulse repetition of a few hundreds of ns is applied, so that a wide range of DCR can be faithfully measured. In Fig. 2 (a), room-temperature DCR and SPDP are measured to be ~10 kHz/μm^2 and ~10 % at a low excess bias (EB) of only 0.5 V, i.e., 4.5% of the BV. The laser wavelength is chosen to be 1310 nm. To the best our knowledge, this is the first DCR and SPDP reported at room temperature from any Ge-based SPADs. DCR and SPDP can be further improved when translating such a technology into back-side illumination (BSI) pixel with smaller active area and thicker absorption layer. To benchmark the GeSi SPAD in this work with the Ge-on-Si SPADs in the literature, we adopt the metric of noise-equivalent power (NEP) using the formula $NEP = \hbar\omega\sqrt{2 \cdot DCR} / SPDP$, and calculate the adjusted temperature required to cool down the referenced devices so that their NEPs are equal to our NEP at 300 K. In Fig. 2 (b), the resultant adjusted temperatures are at least < 175 K, showcasing the unprecedented performance of our GeSi SPAD. Here we presume that DCR doubles for every 10 K increase in temperature for all devices in comparison, based on the measured value from our GeSi SPAD for temperatures between 20 ºC and 80 ºC.

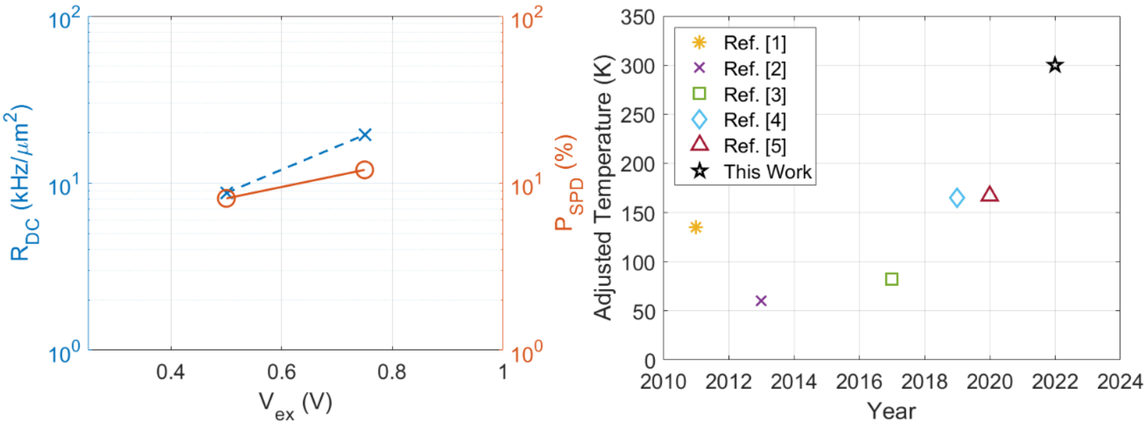
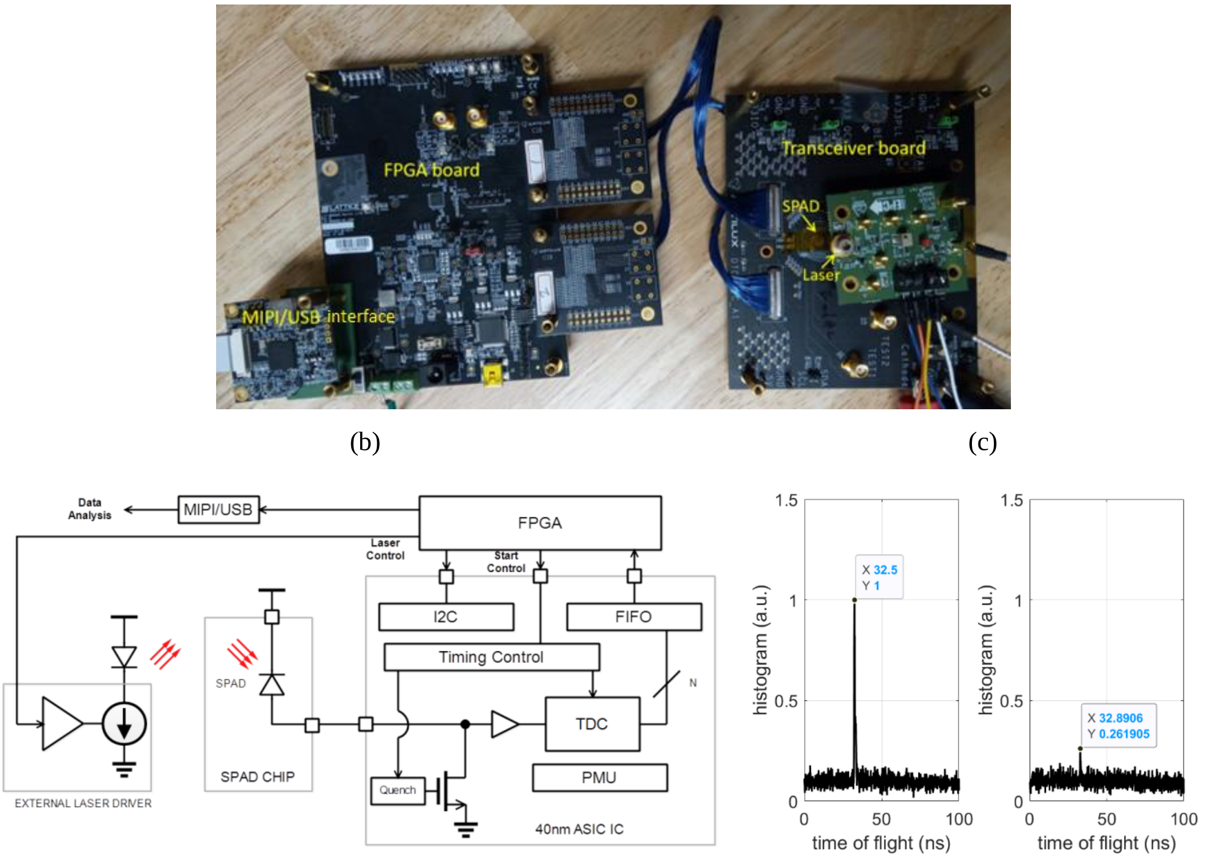

(a) (b)

Fig. 2. (a) The measured DCR and SPDP plotted as a function of EB. (b) The adjusted temperatures of the Ge-on-Si SPADs in the literature and the GeSi SPAD in this work shown in chronological order (note the highest operation temperatures of Ref. [1-5] are 200 K, 100 K, 80 K, 125 K, 175 K).

To demonstrate the applicability of our GeSi SPAD for SWIR sensing and imaging, a proof-of-concept ranging demo is carried out and shown in Fig. 3 (a). It consists of a transceiver board, a field-programmable gate array (FPGA) board, and a laptop to display TOF histograms in real-time. On the transceiver board, the transmitter is a 1550 nm laser diode driven by a pulse driver, and the receiver is the GeSi SPAD wired bonded to an application specific integrated circuit (ASIC). The transmitter is positioned closely to the receiver, and no optics, e.g., Tx lens for laser beam collimation and Rx lens for backscattered light collection, are installed. During the experiment, the laser is operated to transmit 200 ps pulses at repetition frequency of 500 kHz and peak power of 20 mW. The TDC and the FPGA are configured to generate each histogram with accumulation duration of 131 ms and bin width of 156 ps. A piece of Kodak gray card, of which the white side is held toward the transceiver board, is used as the target. The collected data are sent for further analyses through a MIPI-to-USB bridge IC. The block diagram of the ranging system is shown in Fig. 3 (b). The ASIC IC is fabricated in a commercial 40 nm CMOS process and interfaces with the SPAD IC 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 phase-locked loop (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 FPGA. Finally, the exemplary TOF histograms captured by the ranging system are shown in Fig. 3 (c).

(a)



(b)

(c)

Fig. 3. (a) The ranging system including laser, SPAD, transceiver board, FPGA board, and MIPI/USB interface. (b) Schematic diagram of the ranging system including the 40 nm ASIC. (c) TOF histograms captured when the target is ~3 cm (left) or ~9 cm (right) away from the test board.

To summarize, we have successfully demonstrated the world-first high-performing GeSi SPAD at room and elevated temperatures, and performed a proximity ranging demo. We believe this work will open new possibilities for SWIR sensors and imagers to be applied to the landscape of consumer applications in the near future.

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