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# High Efficiency Planar Ge-on-Si Single-Photon Avalanche Diode Detectors

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**Abstract:** Planar Ge-on-Si single-photon avalanche diode detectors fabricated using CMOS-compatible processing demonstrate a 38% single photon detection efficiency at 125 K with 1310 nm wavelength illumination, exhibiting 310 ps jitter and $2\times10^{-16}$ WHz$^{-\frac{1}{2}}$ noise equivalent power. © 2019 The Author(s)

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Single-photon detectors are essential for a number of quantum optic and quantum information applications but also provide improved performance for range-finding and have emerged as potential candidates for long-range lidar and depth imaging applications [1]. Whilst superconducting devices demonstrate the highest performance for single-photon detection, most applications require room temperature or Peltier cooled detectors such as single-photon avalanche diode (SPAD) detectors. Below 1 $\mu$m wavelength, CMOS processed SPAD cameras are available with the latest research versions demonstrating 256×256 pixels, 40 ps time binning and frame rates of 100 kfps [2]. Range-finding and lidar applications in the short-wave infrared benefit from improved atmospheric transmission and increased laser safety thresholds compared to near-infrared, enabling ranging over10 km at mW average powers [3]. Similarly, fiber-based quantum communications also require 1310 nm or 1550 nm wavelength SPADs, currently requiring expensive InGaAs/InP SPAD technology [4].

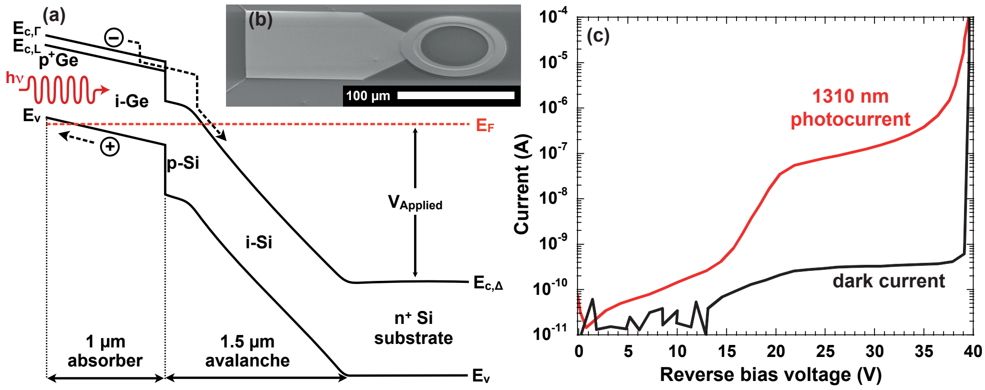

Fig. 1. (a) A schematic diagram of the band structure of the Ge-on-Si SPAD. (b) A SEM image of one device showing the bondpad and annular top contact. (c) The dark current and photocurrent at 1310 nm wavelength illumination at 78 K as a function of the applied reverse bias voltage.

Here we demonstrate 38% single-photon detection efficiency (SPDE) Ge-on-Si SPADs at the telecommunications wavelength of 1310 nm at 125 K from devices microfabricated using CMOS-compatible processing on 150 mm diameter Si wafers. The detectors use a separate absorber, charge and avalanche multiplication design (Fig. 1(a)). The incident photons are absorbed in the 1 $\mu$m thick Ge layer, and the photogenerated electron drifts into the high-field silicon avalanche region. When the device is biased above breakdown this primary electron instigates impact ionization events which lead to a self-sustaining avalanche current which is readily detectable.

The present results are for 100 $\mu$m diameter devices (Fig. 1(b)) with the dark current and photocurrent at 78 K presented in Fig. 1(c). The significant SPDE performance improvement (Fig. 2(a)) over previous Ge-on-Si SPADs [5–7] is mainly due to a significant decrease in the dark count rates (DCR) resulting from a novel planar design which ensures the high-field region is well away from the sidewall. At 100 K (78 K) with 26% SPDE the DCR per unit area in the present work is 18.3 (6.37) counts/s/$\mu$m$^2$ which is over 600 times (4000 times) below the

11,200 counts/s/$\mu$m$^2$ with 4% SPDE at 100 K for mesa geometry devices previously published [6] (and 31,400 counts/s/$\mu$m$^2$ with 5% SPDE at 80 K [7]). Although a vast improvement for Ge-on-Si SPADs the DCRs are still greater than optimised InGaAs/InP SPADs at 233 K and initial measurements of smaller 25 $\mu$m diameter devices already demonstrate further improvements with reduced area. The noise equivalent power (NEP) was $1.9\times10^{-16}$ ($7\times10^{-16}$) WHz$^{-\frac{1}{2}}$ at 78 K (125 K). The jitter as represented by the full-width-at-half maximum (FWHM) of the timing histogram is 310 ps which is dominated by the lateral spread of the avalanche current in the relatively large device area. Recent results on smaller area (26 $\mu$m diameter) have shown much lower jitter of 152 ps FWHM.

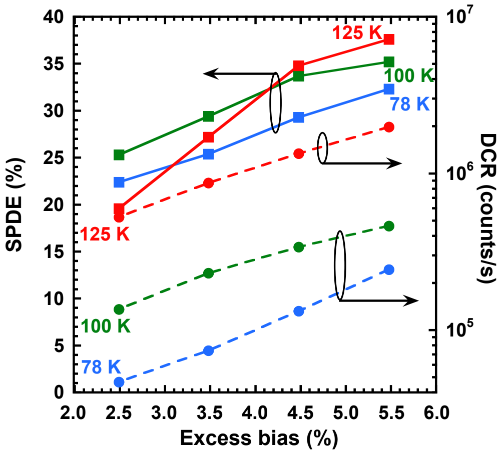

Fig. 2. The SPDE at 1310 nm wavelength and DCR for 3 temperatures as a function of excess bias.

Afterpulsing is an effect which results from carriers being trapped during the avalanche event, and being released later, triggering further avalanche events. The effect of afterpulsing is to increase the apparent background count level. This can be reduced by implementing long hold-off times after each detected event, but this limits the high repetition rates required for many applications, including range-finding, lidar and quantum communications. As afterpulsing decay times reduce at higher temperatures, we have measured afterpulsing using the time-correlated carrier counting method under nominally identical conditions for both the 100 $\mu$m diameter Ge-on-Si SPADs and a 26 $\mu$m diameter InGaAs/InP SPAD. These measurements were performed at 125 K, with overbias levels set to produce identical SPDE of 17% for each detector. Under these conditions the afterpulsing level of the Ge-on-Si SPAD was only 20% that of the InGaAs/InP SPAD.

Ge-on-Si SPADs with SPDE of 38% have been demonstrated operating at 1310 nm wavelength. Afterpulsing measurements under nominally identical conditions demonstrated 20% of the level of InGaAs SPADs. Further work is still required to reduce the DCR and to increase the operating temperatures to that consistent with Peltier cooled operation. Preliminary measurements on smaller area 26 $\mu$m diameter devices have already demonstrated significantly reduced DCRs and jitter. The thin 1 $\mu$m Ge absorber layer used is estimated to absorb only 50% of the incident photons, so further optimisation of the absorbing structure is likely to improve these results significantly.

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