# Geiger Mode Ge-on-Si Single-Photon Avalanche Diode Detectors

Jaroslaw Kirdoda*, Derek C.S. Dumas*, Kateryna Kuzmenko†, Peter Vines†, Zoë M. Greener†, Ross W. Millar*, Muhammad M. Mirza*, Gerald S. Buller† and Douglas J. Paul*
*School of Engineering, University of Glasgow, Rankine Building, Oakfield Avenue, Glasgow G12 8LT, U.K.
†Institute of Photonics and Quantum Sciences, School of Engineering and Physical Sciences,
Heriot-Watt University, Edinburgh EH14 4AS, U.K.

***Abstract*—Ge-on-Si single-photon avalanche diode (SPAD) detectors have demonstrated a high single-photon detection efficiency of 38% at a wavelength of 1310 nm when operated at a temperature of 125 K. These devices exhibit reduced afterpulsing compared to InGaAs/InP SPADs under nominally identical operating conditions.**

***Index Terms*—germanium on silicon, single-photon avalanche diode detector, Geiger mode, single-photon counting**

## I. INTRODUCTION

In recent years there has been an increased demand for high performance single-photon detectors operating at short-wave infrared (SWIR) wavelengths [1], [2]. Many quantum technology applications using squeezed, entangled or single-photons require SWIR photodetectors with single-photon measuring capabilities. Single-photon detectors in the SWIR region have also proved in emerging single-photon applications such as depth imaging, especially at long range and imaging through obscurants [3], [4]. Quantum communication in optical fibers require single-photon detectors at 1310 nm and 1550 nm wavelengths. For LIDAR applications, the reduced solar background at SWIR wavelengths compared to the near infrared, as well as the increased laser eye-safety threshold above 1400 nm wavelength, mean that significant improvements in signal-to-background can be achieved. Superconducting nanowire single-photon detectors [1] and InGaAs/InP SPADs [5] are commercially available for the SWIR region, however Ge-on-Si SPADs offer potential for near-room temperature, low afterpulsing, single-photon sensitive performance.

Ge-on-Si SPADs are fabricated using a separate absorption, charge and multiplication structure, using CMOS compatible processes. This structure was chosen in order to utilise Ge absorption for SWIR wavelengths and the ability to grow a high quality Si multiplication region with few trap states [6], [7]. The present devices have been fabricated in a novel planar geometry and demonstrate an order of magnitude higher single photon detection efficiency (SPDE), three orders of magnitude lower dark count rates (DCR) per unit area than previously reported Ge-on-Si SPAD devices [6], [7] and operate at temperatures up to 175 K.

## II. FABRICATION AND CHARACTERIZATION

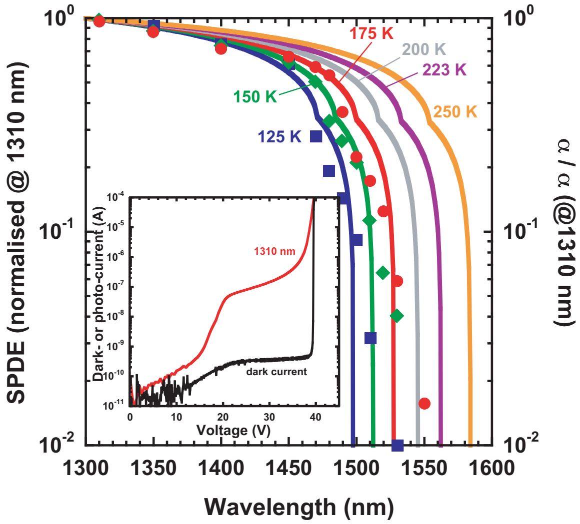

Fig. 1. The data points are experimental SPDE data normalized to 1310 nm wavelength performance and the solid lines are the estimated absorption for the Ge absorber. insert: the current-voltage characteristic of a 100 $\mu$m device operated at a temperature of 78 K under the dark conditions (black line) and illuminated with 1310 nm wavelength light (red line).

The device structure consisted of 1.5 $\mu$m of i-Si grown epitaxially on a 150 mm diameter $n^{++}$-Si (001) substrate using an ASM Epsilon 2000E reactor. A $p^{-}$-type sheet charge layer of Si was selectively implanted with boron before being activated, and then 1 $\mu$m of i-Ge was grown with a top cap of 50 nm $p^{++}$-Ge allowing the formation of Ohmic contacts. The devices were fabricated in a planar geometry with trench isolation laterally between devices [8].

The insert to Fig. 1 presents both dark current and photocurrent of a 100 $\mu$m diameter device operated at a temperature of 78 K. Before breakdown occurs, the leakage current of the device remains below 1 nA. In Fig. 1 insert, the red curve represents the I-V characteristics of the device illuminated with a 1310 nm wavelength light. The increased current at the reverse bias greater than 15 V indicates punch-through of the electric field into the Ge absorber, allowing photo-generated carriers to drift into the multiplication region. Measurements of the single-photon detection efficiency (SPDE), dark count rate (DCR) and jitter were performed in a cryostat with optical access. The optical power level at the device was attenuated to ensure that there is an average of less than 0.1 photons per optical pulse. This type of measurement follows the accepted procedure for single photon measurements, as described in [6], [8]. During both DCR and SPDE measurements, the devices were operated in Geiger mode. A fixed DC bias of just below the avalanche breakdown voltage was applied to the device and a short AC pulse was then applied to bring the device above breakdown. The timing of that gate was correlated to the time of an incident photon. The histograms were then recorded: one under dark conditions and the other when the SPAD was illuminated with 1310 nm wavelength light. The values of the DCR and the SPDE were then extracted from the histograms. A minimum FWHM timing jitter measured using these devices was 310 ps.

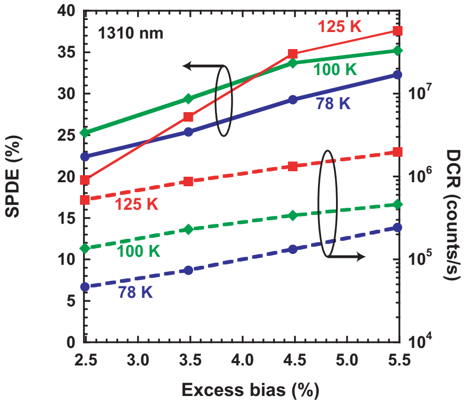

Fig. 2. The SPDE and the DCR as a function of excess bias while operated at a temperature of 78 K (blue lines), 100 K (green lines) and 125 K (red lines).

The wavelength dependence of the SPDE is presented in Fig. 1 for temperatures of 125 K, 150 K and 175 K. The cut-off is related to the direct bandgap edge and the solid lines in Fig. 1 are simulations for the absorption in Ge at temperatures between 125 K and 250 K. The simulations suggest that the direct bandgap absorption required for high SPDEs at 1550 nm wavelength would be achieved at a temperature of 245 K, compatible with the Peltier cooling. The SPDE at the detection wavelength of 1310 nm and DCR as a function of temperature are presented in Fig. 2. The maximum SPDE is an order of magnitude higher than the values of previously reported Ge-on-Si SPADs [6], [7] and the DCR per unit area is reduced by three orders of magnitude. A noise equivalent power (NEP) of $3 \times 10^{-16}$ W/Hz$^{\frac{1}{2}}$ was measured at 100 K and 1310 nm.

Afterpulsing occurs when carriers are trapped during an avalanche event and are subsequently released, triggering a further avalanche event. Afterpulsing can be reduced by increasing the hold-off time after an event, at the expense of reducing the overall count rate, increasing measurement acquisition time. A comparison of this Ge-on-Si SPAD compared to a commercial InGaAs/InP SPAD under nominally identical conditions is presented in Fig. 3. The afterpulsing in the Ge-on-Si SPAD was only 20% that of the InGaAs/InP SPAD which shows potential for high count rate applications.

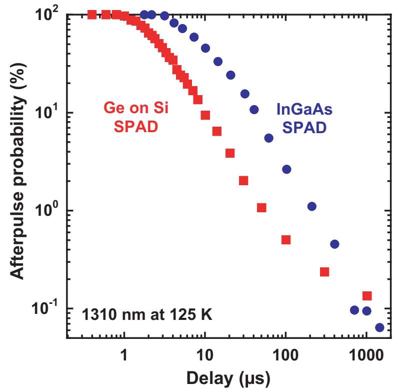

Fig. 3. The afterpulsing for a 100 $\mu$m diameter Ge-on-Si SPAD compared to a 26 $\mu$m diameter InGaAs/InP SPAD under nominally identical conditions (T = 125 K and 17% SPDE at 1310 nm).

## III. CONCLUSIONS

100 $\mu$m diameter Ge-on-Si SPADs with a maximum SPDE of 38% operated at 125 K have been demonstrated with single-photon sensitivity at temperatures up to 175 K. Measurements of afterpulsing under nominally identical conditions demonstrate a factor five reduction in afterpulsing compared to InGaAs/InP SPADs. Preliminary measurements of 26 $\mu$m diameter Ge-on-Si SPADs have already demonstrated significant reductions in jitter and DCR as well as an increased operating temperature. As the present 1 $\mu$m thick Ge absorber absorbs less than 50% of the incident light, there is significant potential for optimised devices to achieve improved performance.

## ACKNOWLEDGMENT

The work was supported by DSTLX-1000092774 and UK EPSRC projects EP/N003446/1, EP/K015338/1, EP/L024020/1, EP/M01326X/1 and EPN003225/1.

## REFERENCES

[1] R.H. Hadfield, "Single-photon detectors for optical quantum information applications" Nat. Photon. vol. 3, pp. 696–705, 2009.
[2] G.S. Buller and R.J. Collins, "Single-photon generation and detection" Meas. Sci. Technol. vol. 21, 012002, 2010.
[3] R. Tobin et al., "Three-dimensional single-photon imaging through obscurants" Opt. Express, vol. 27 , pp. 4590-4611, 2019.
[4] A.M. Pawlikowska, A. Halimi, R.A. Lamb and G.S. Buller, "Single-photon 3D imaging at up to 10 km range" Opt. Exp. vol. 25, pp. 11919–11931, 2017.
[5] J. Zhang, M.A. Itzler, H. Zbinden and J.-W. Pan, "Advances in InGaAs/InP single-photon detector systems for quantum communication" Light Sci. Appl. vol. 4, e286, 2015.
[6] R. E. Warburton et al., "Ge-on-Si single-photon avalanche diode detectors: design, modeling, fabrication, and characterization at wavelengths 1310 and 1550 nm", IEEE Trans. Electron Dev., vol. 60, no. 11, pp. 3807-3813, 2013.
[7] A.Y. Loudon et al., "Enhancement of the infrared Detection Efficiency in Si Photon Counting Avalanche Photodiode using SiGe Absorbing Layers" Optics Letters vol. 27, pp. 219-221, 2002.
[8] N.J.D. Martinez et al., "Single photon detection in a waveguide-coupled Ge-on-Si lateral avalanche photodiode" Opt. Exp. vol. 25, pp. 16130-16139, 2017.
[9] P. Vines et al., "High performance planar Ge-on-Si single-photon avalanche diode detectors" Nature Comms. vol. 10, 1086, 2019.