Ge on Si SPADs for LiDAR & Quantum Technology Applications

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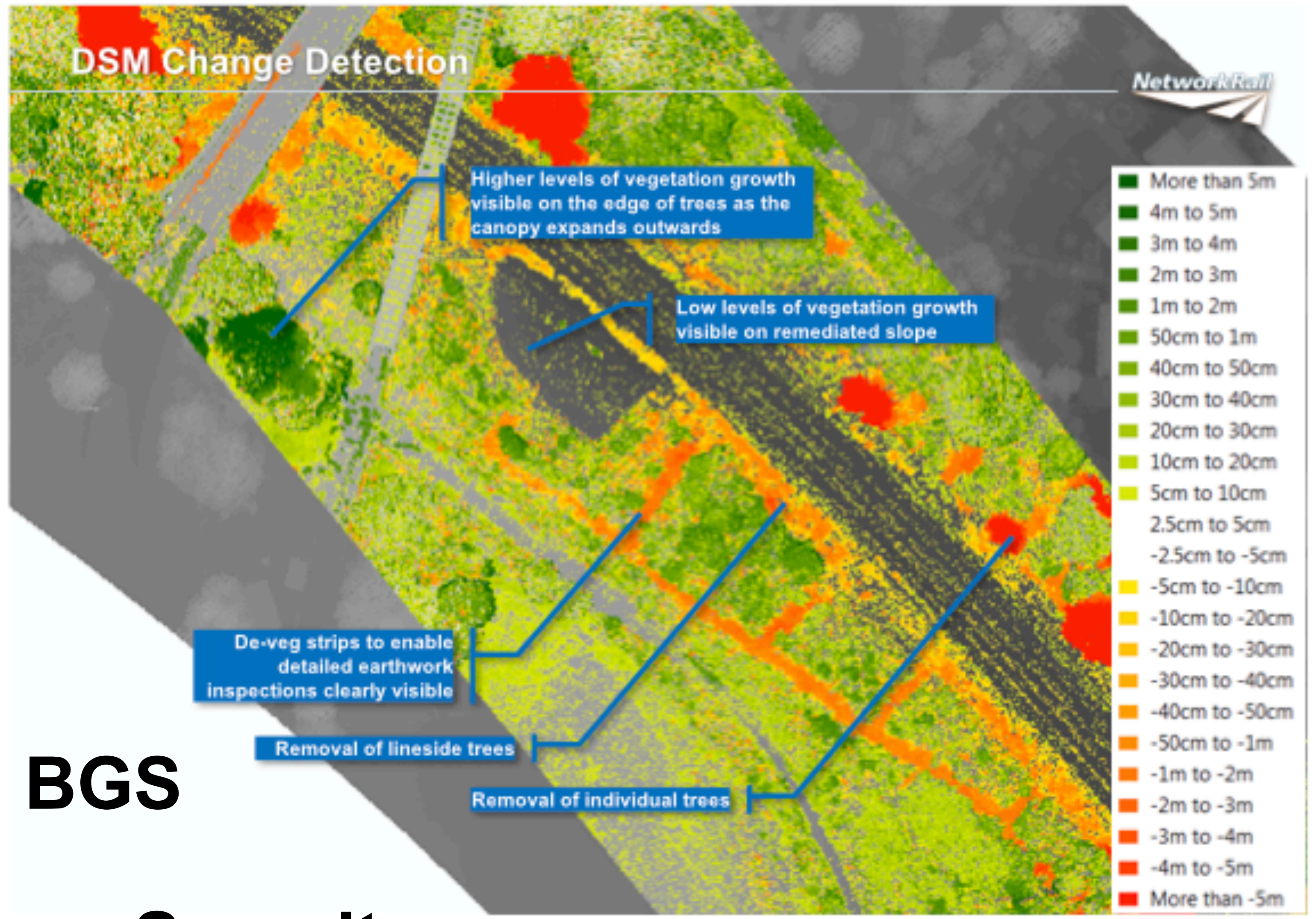
[1]James Watt School of Engineering, University of Glasgow, U.K
[2]Institute of Photonics and QT, Heriot-Watt University, U.K.

http://userweb.eng.gla.ac.uk/douglas.paul/

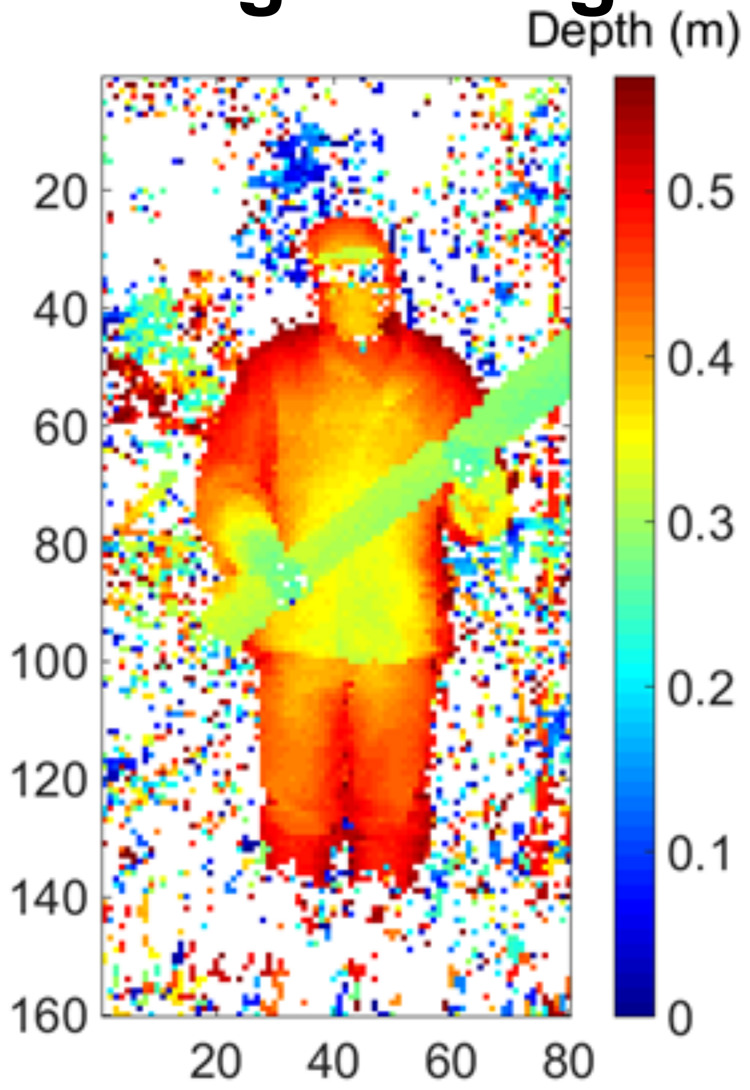
Single Photon Detector Applications

Erosion measurement



BGS

Security rangefinding



Automotive & autonomous vehicle lidar

Single Photon Detector Applications

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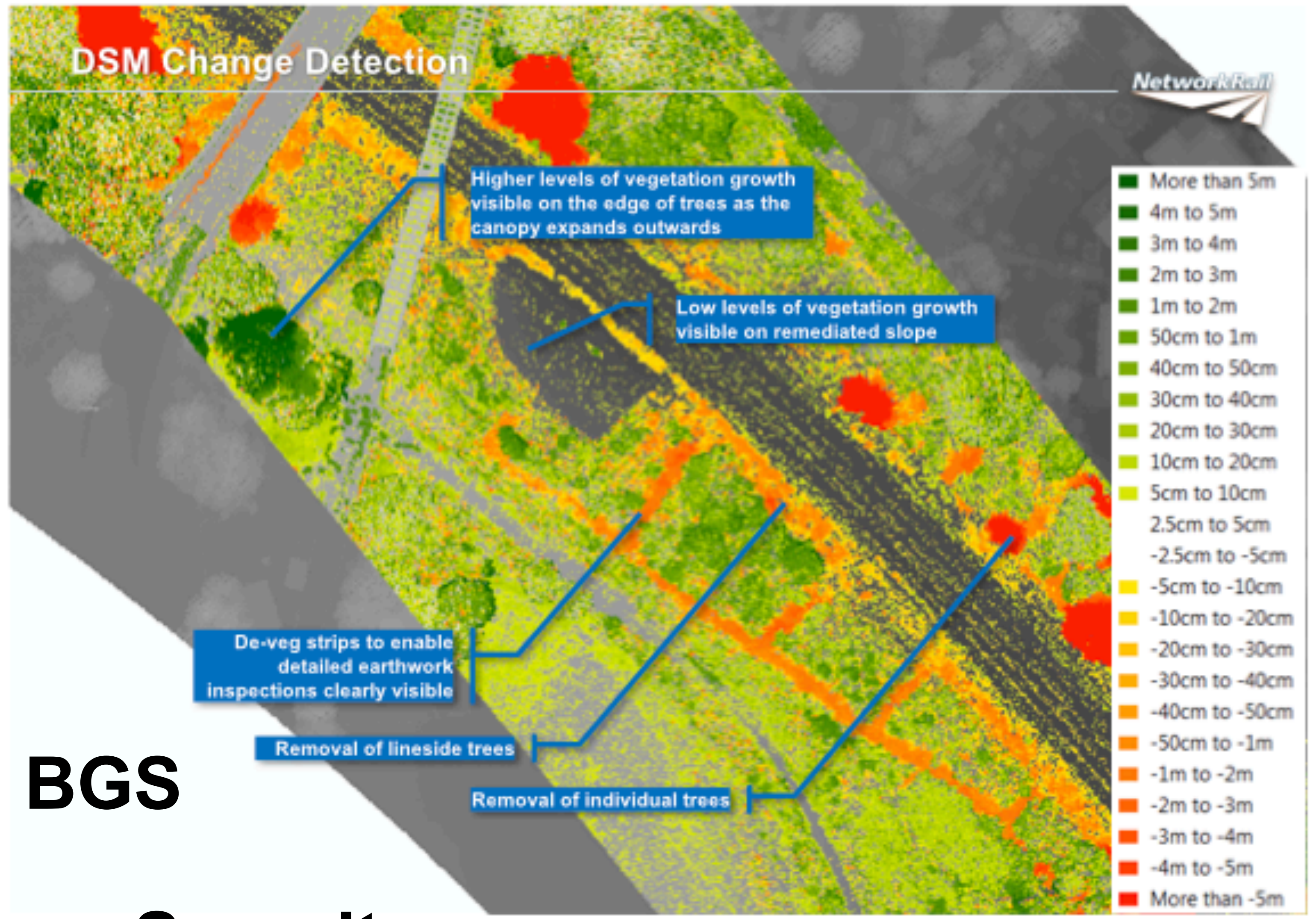
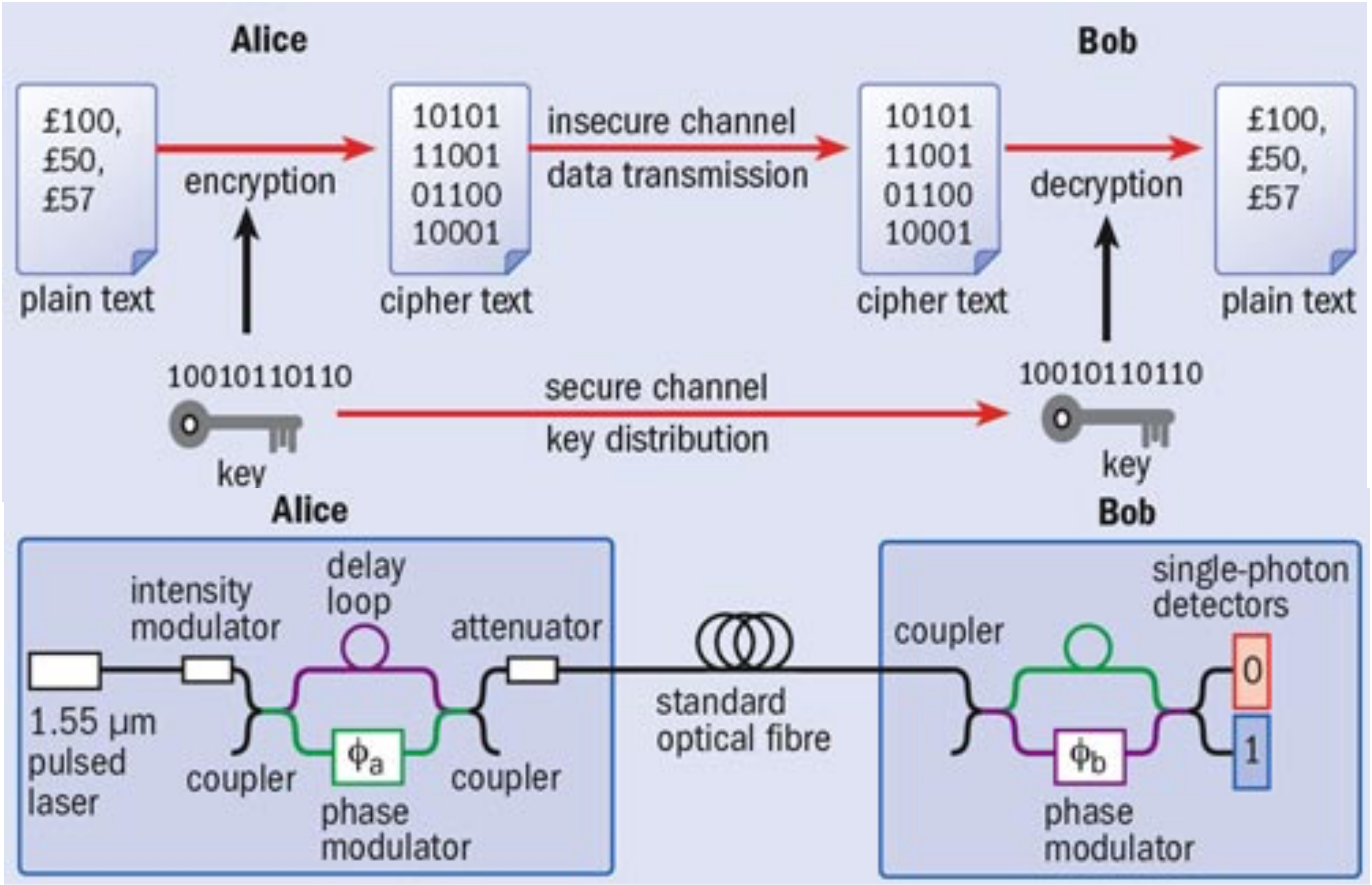


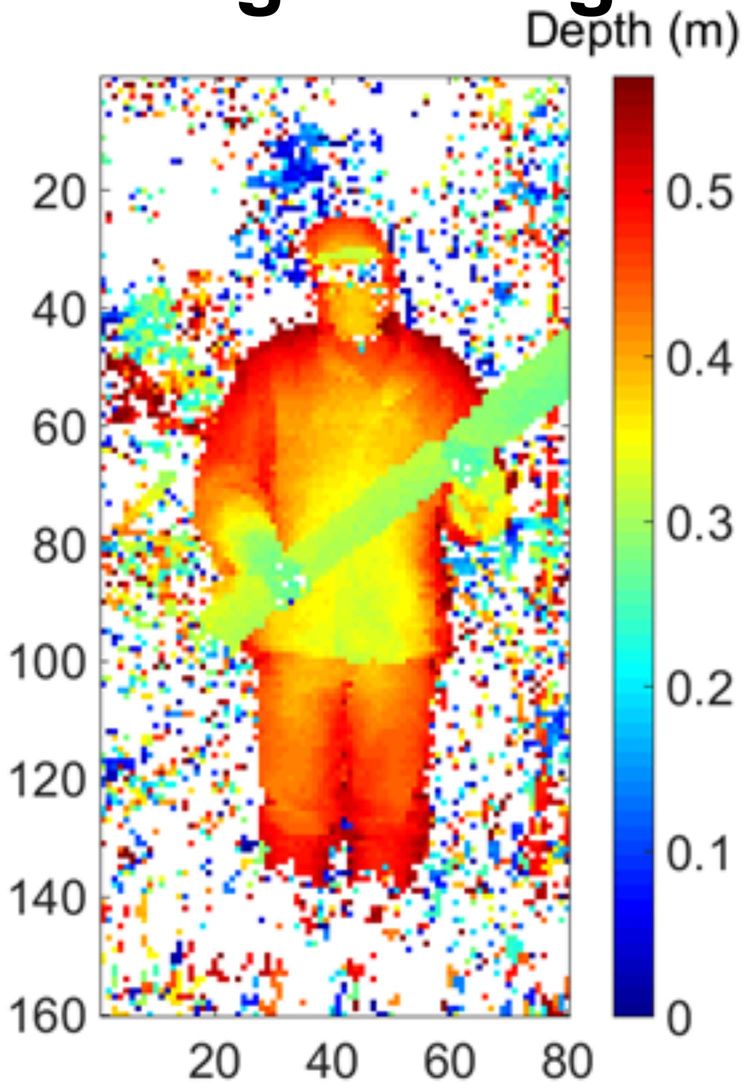
Automotive & autonomous vehicle lidar

Quantum key distribution

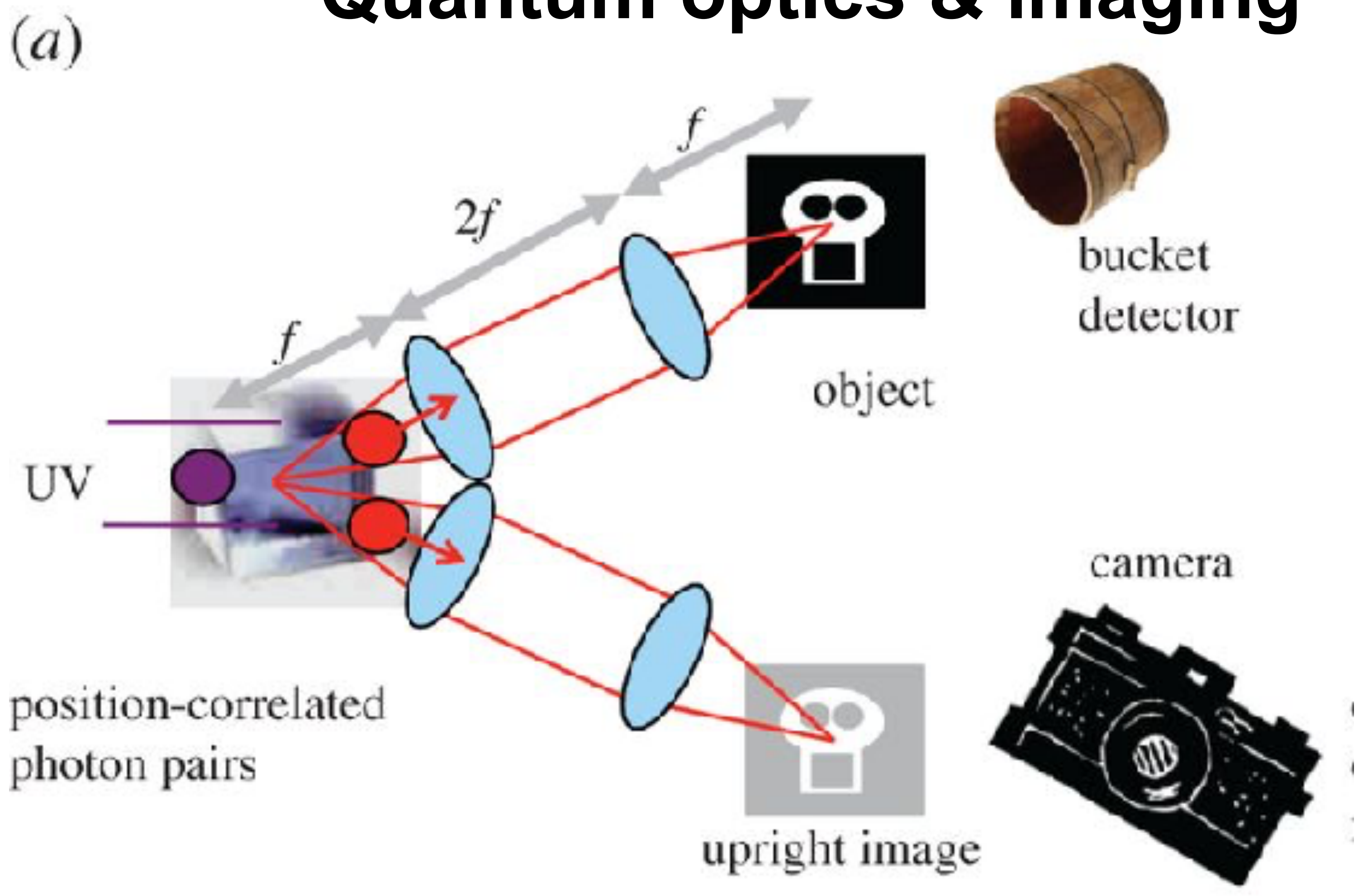


Andrew Shields, Phys. World (2007)

Security rangefinding

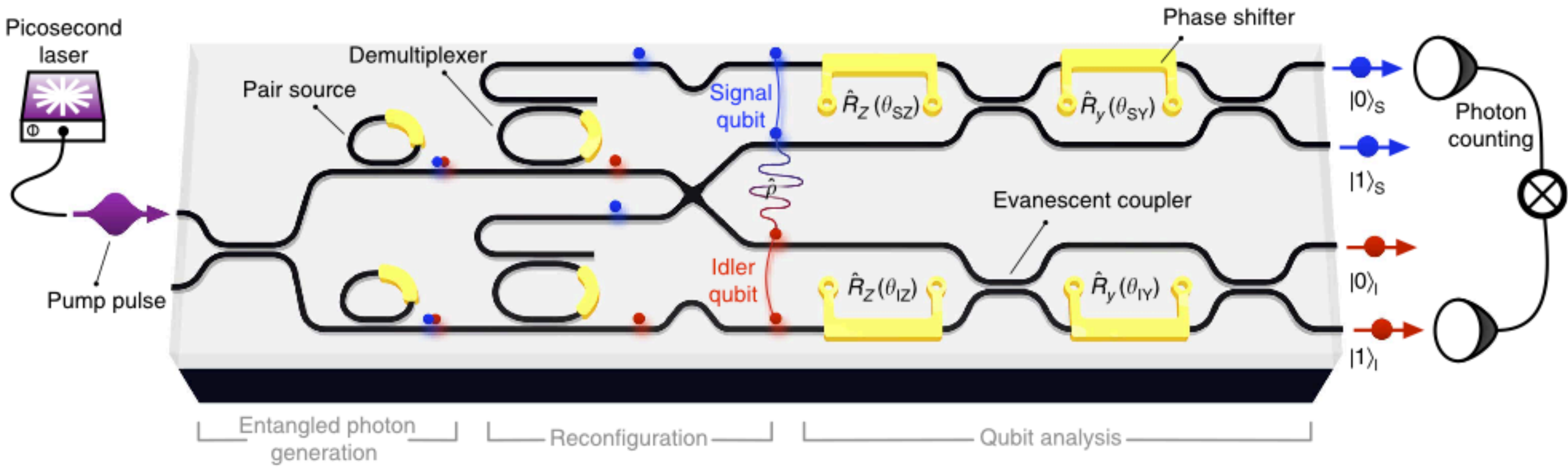


Quantum optics & imaging



Padgett & Boyd, Phil. Trans. Roy. Soc. A 375, 20160233 (2017)

Photonic quantum simulation / computing



J.W. Singleton et al. Nature Comms. 6, 7948 (2015)

Practical LIDAR: Imaging Through Obscurants

California

Practical LIDAR: Imaging Through Obscurants

California

Cambridge

https://youngcardriver.com/driving/driving-in-heavy-rain/

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Practical LIDAR: Imaging Through Obscurants

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- UK motorway or A-class road requirement: Level 4 autonomy requires identification of objects in 10 ms at 300 m

Practical LIDAR: Imaging Through Obscurants

California

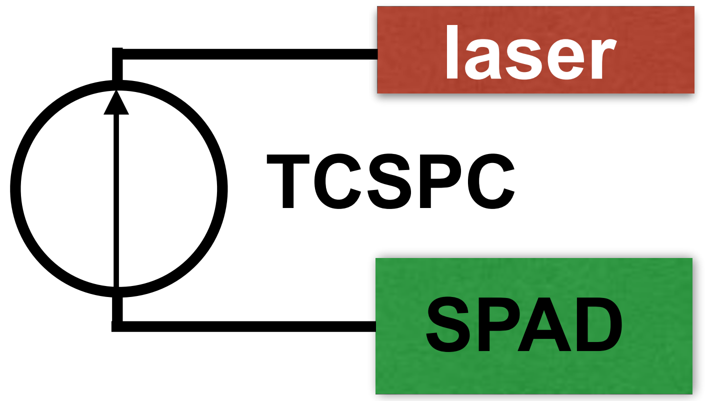
Cambridge

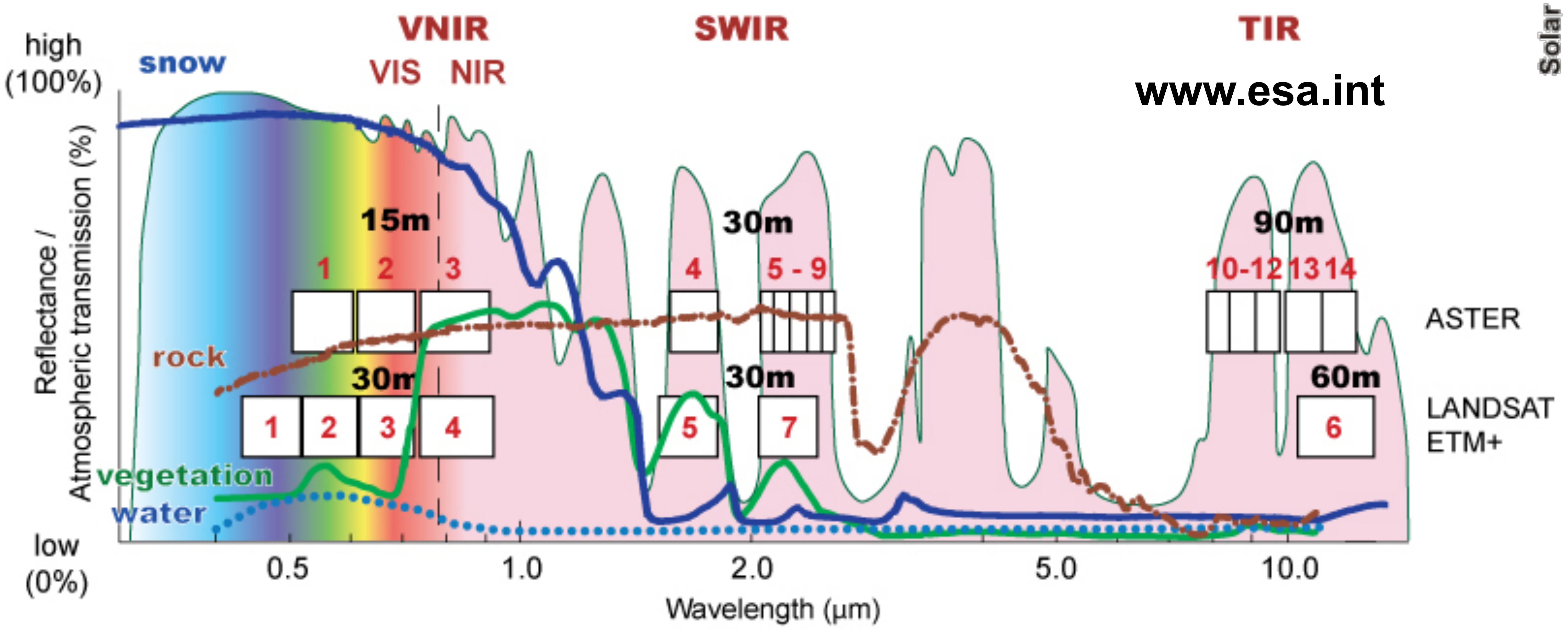
https://youngcardriver.com/driving/driving-in-heavy-rain/

- **UK motorway or A-class road requirement: Level 4 autonomy requires identification of objects in 10 ms at 300 m**
- **Military rangefinders & lidar $803.4M by 2023 with 6.29% CAGR (Reuters 2018)**
- **UK market for autonomous vehicle lidar, radar & GPS of £2.7Bn (£63Bn globally) by 2035 (UK Dept. Transport 2016)**

University of Glasgow

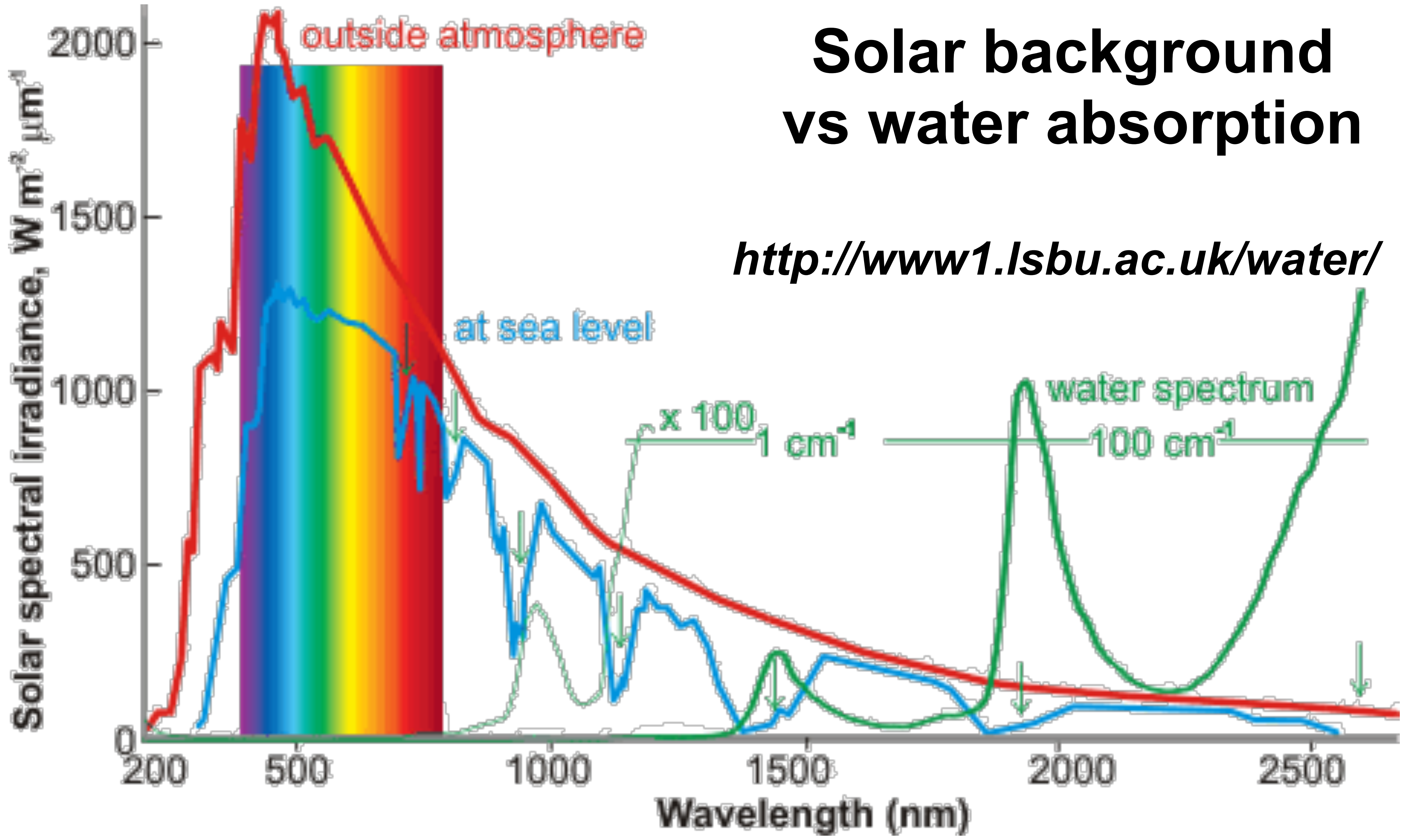
Longer Wavelengths

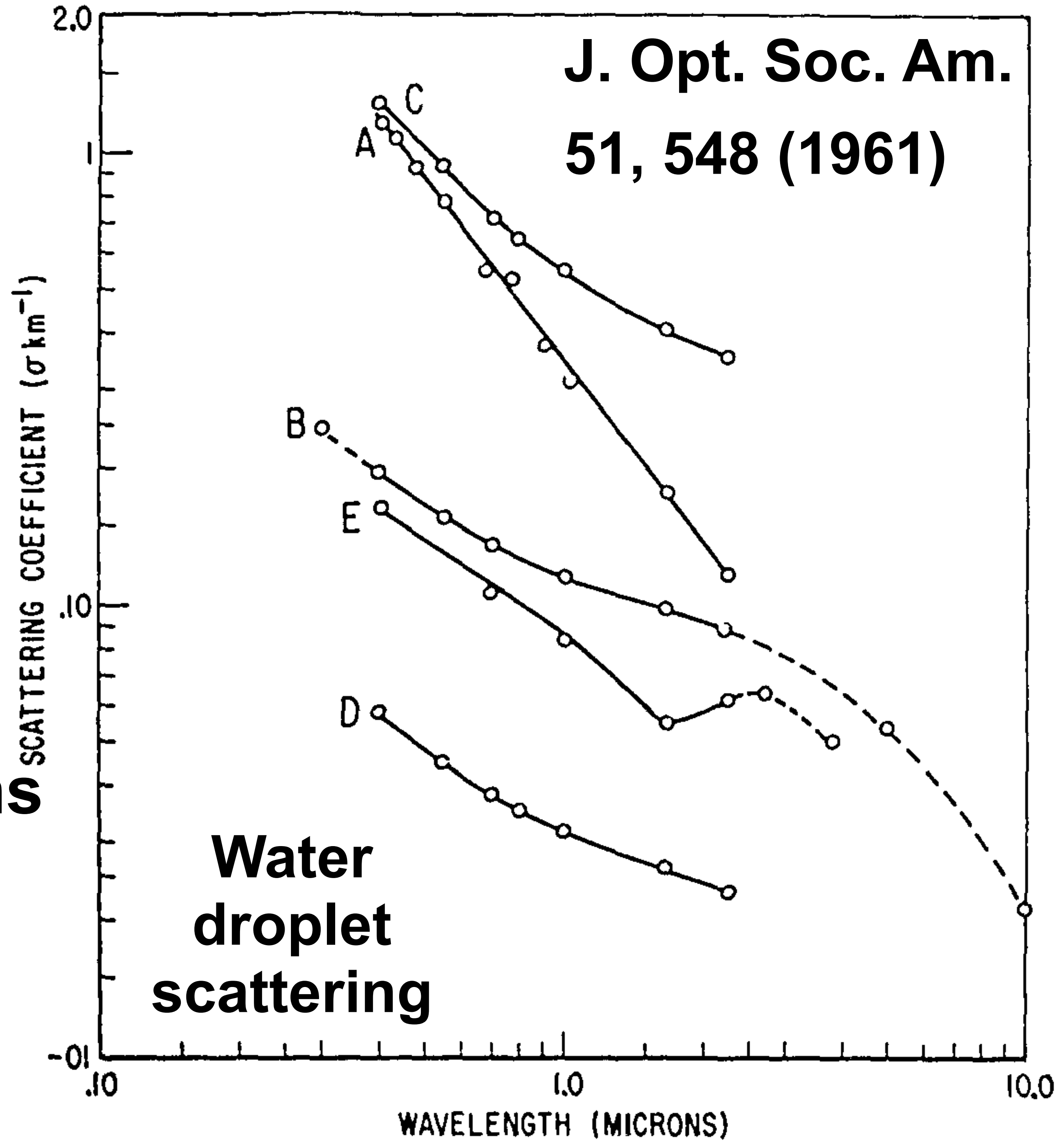




Solar background vs water absorption

http://www1.lsbu.ac.uk/water/





- Mie scattering from water droplets & solar background reduce at longer wavelengths
- IEC-60825-1 eye safe ~ 8 mW > 1400 nm wavelength – outside retina hazard region

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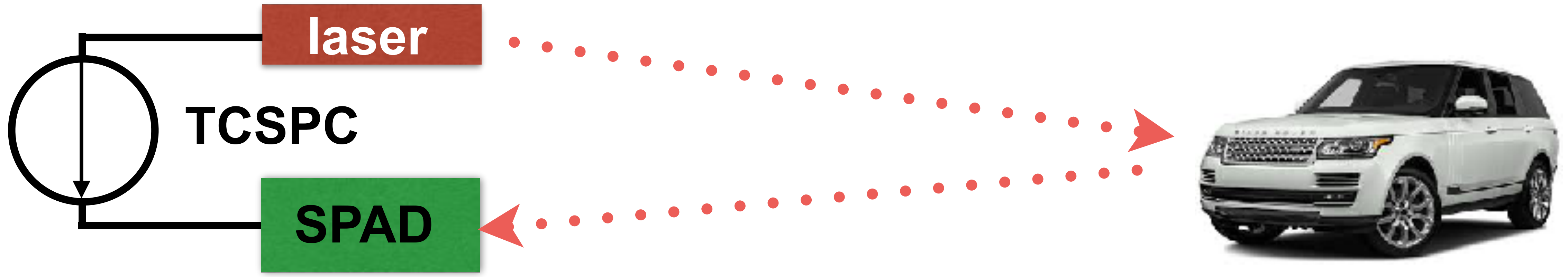

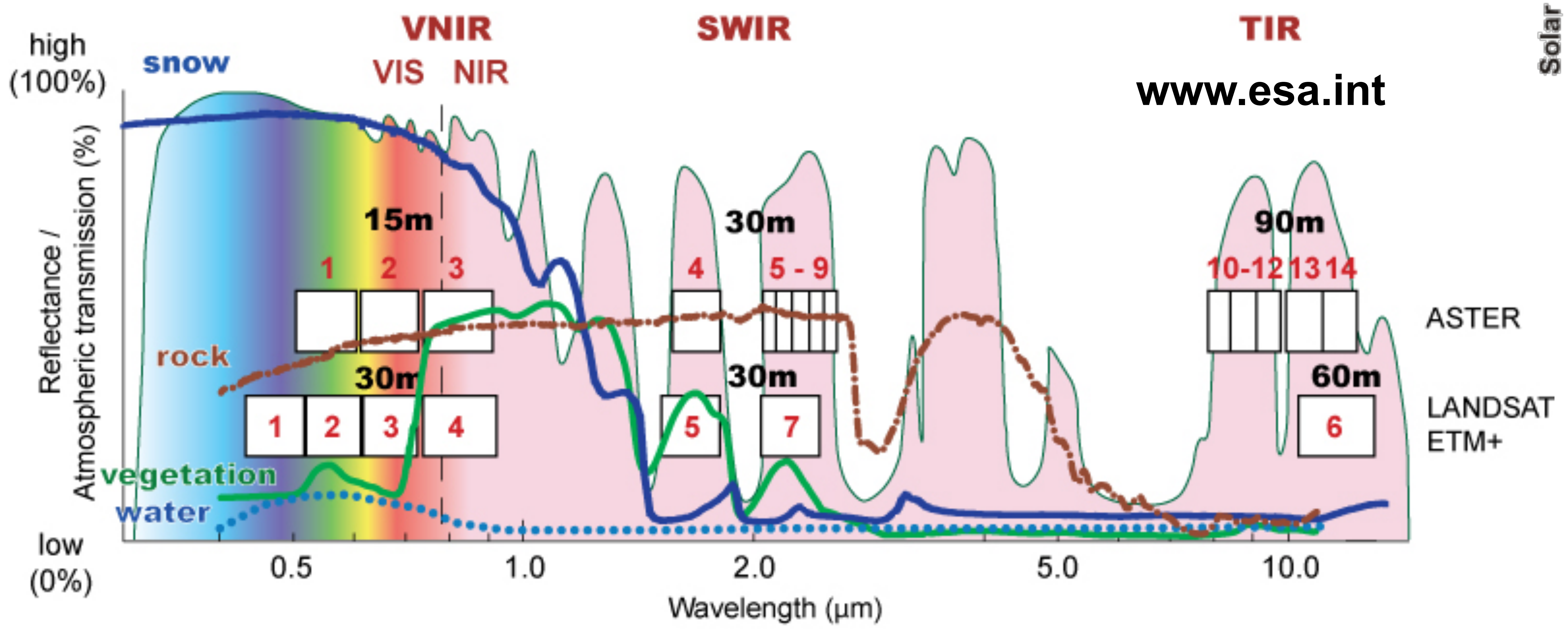

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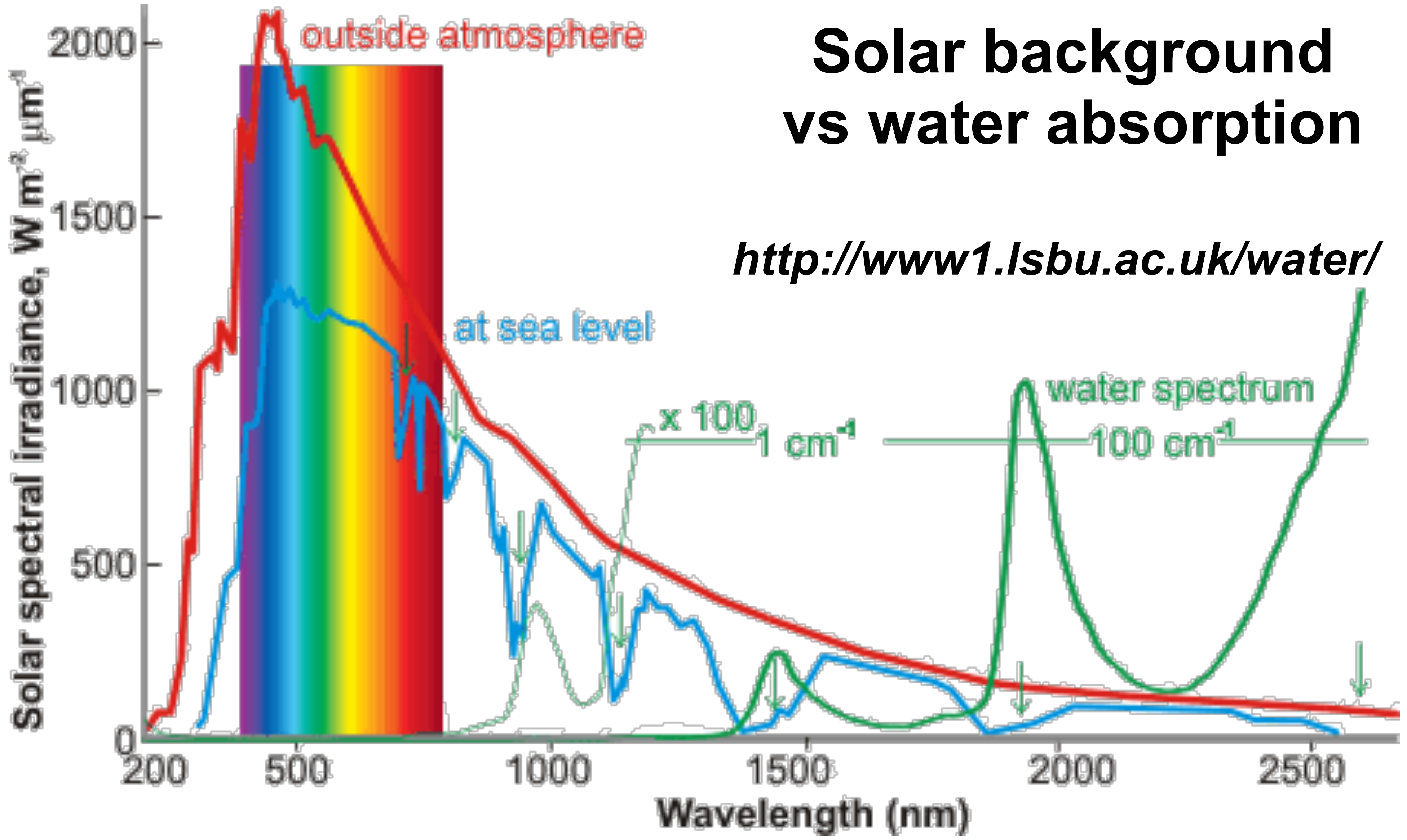

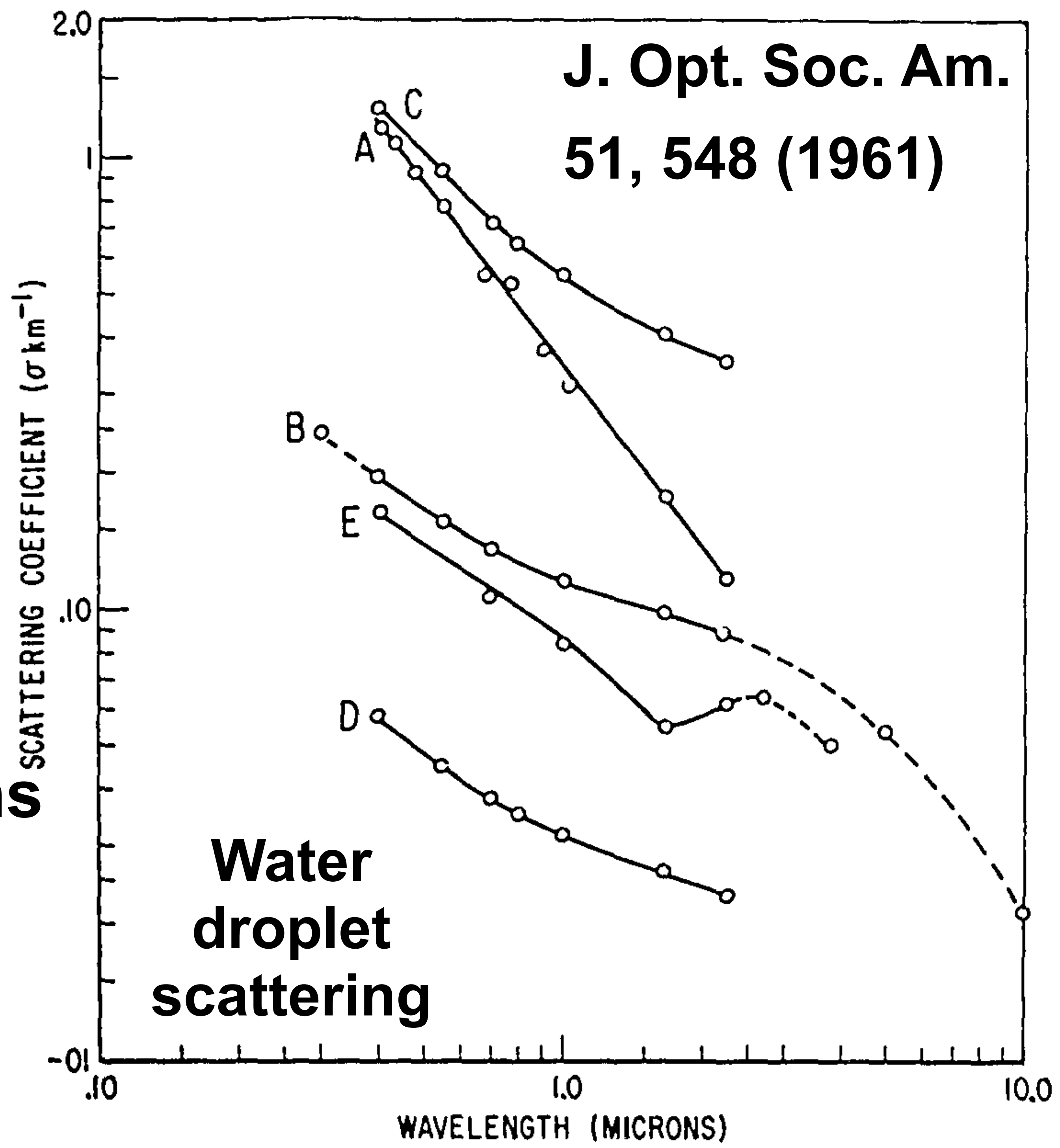

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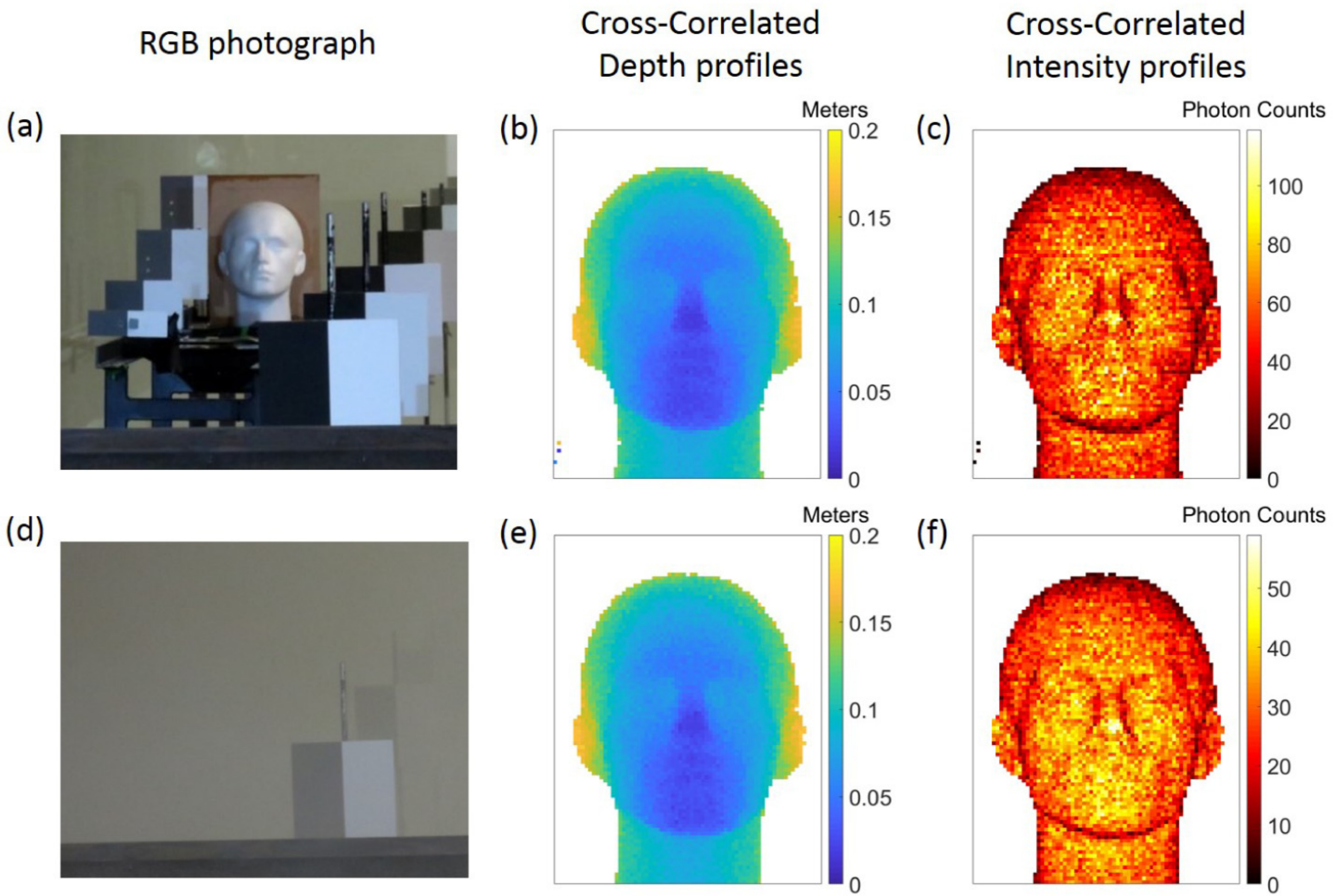
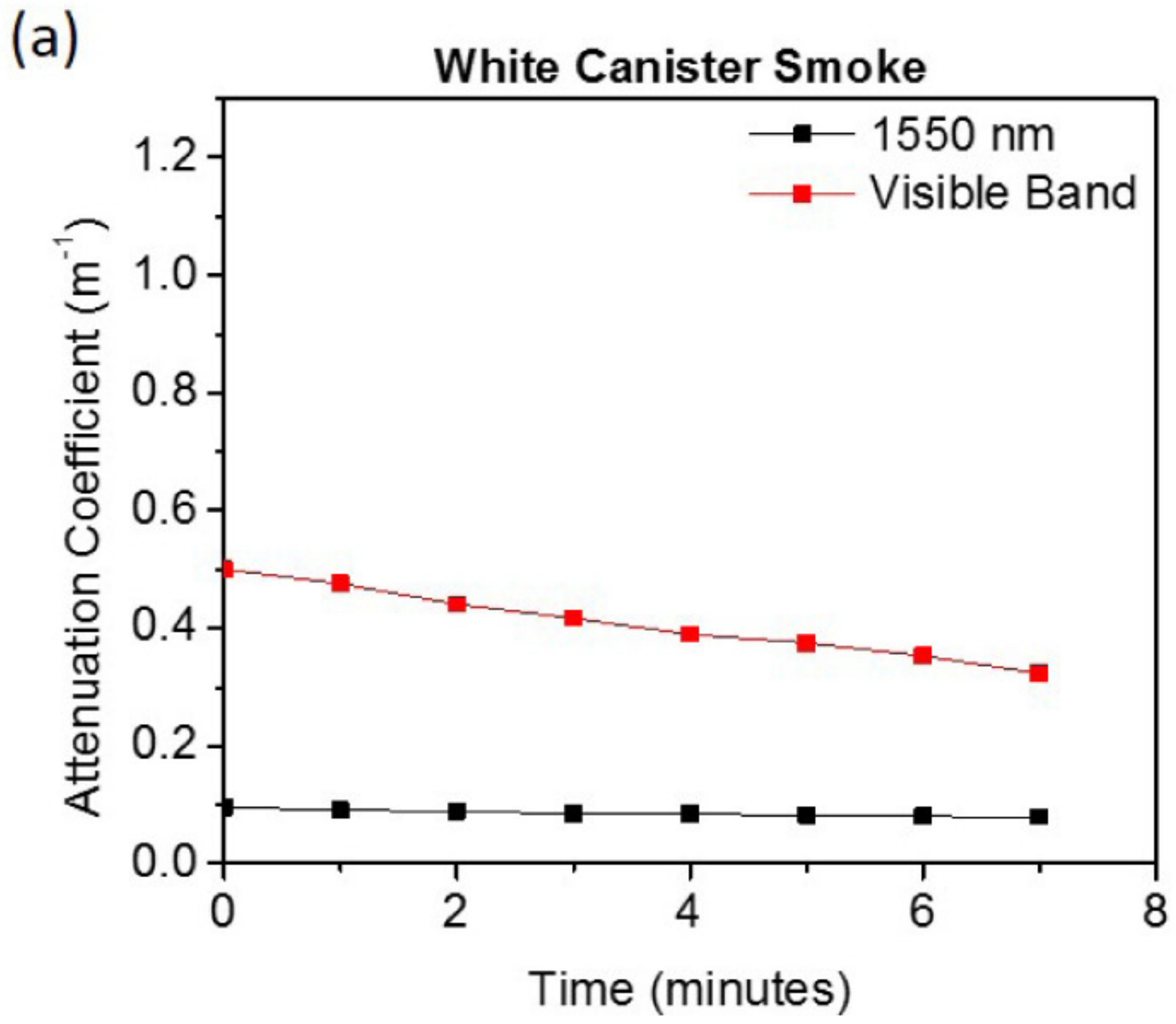
Imaging Through Obscurants



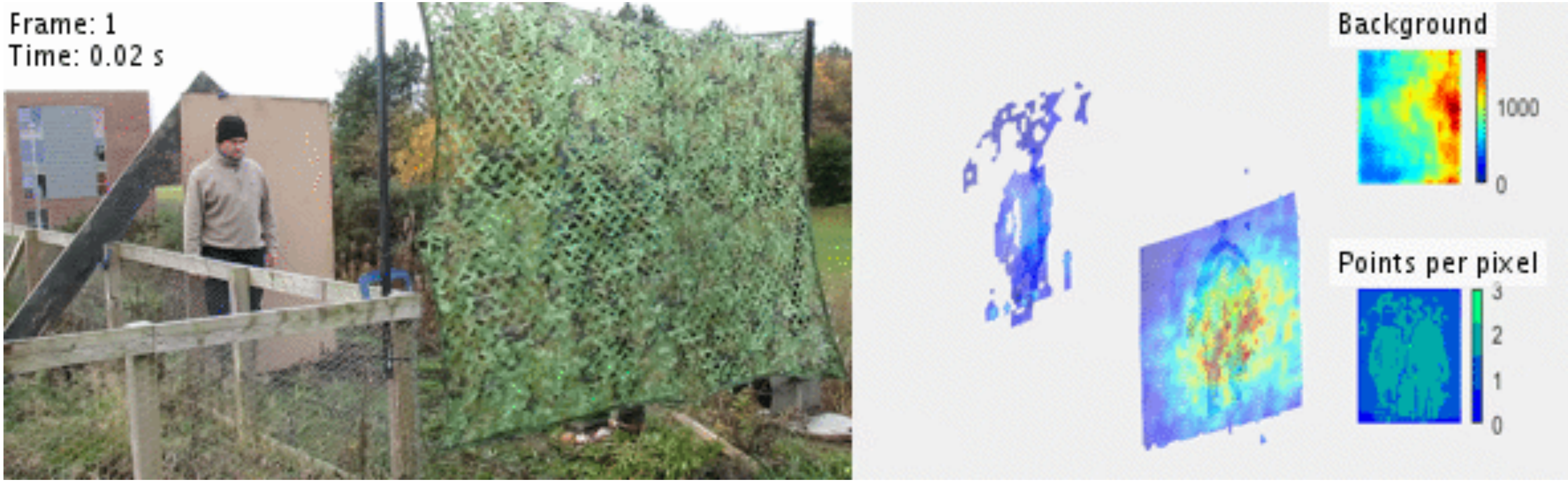
1550 nm 3D images at 24 m through smoke



- **1.5 mW laser at 1550 nm**
- **Princeton Lightwave SWIR SPAD camera at £150k**
- **f = 200 mm lens, 3 ms / pixel**
- **12 attenuation lengths in visible**
  2.4 attenuation lengths at 1550 nm

R. Tobin, Opt. Exp. 27, 4590 (2019)

Real Time Reconstruction of Multi-Surface Moving Scenes using Single-Photon Detection at 330 Meters Range



- **Multiple surfaces resolved – more than one surface per pixel, on average**
- **50 grayscale frames per second of 32 x 32 pixels at 1550 nm**
- **Real-time processing**
- **Eye-safe illumination in presence of solar background**

J. Tachella, et al.“Real-time 3D reconstruction of complex scenes using single-photon lidar: when image processing meets computer graphics” Nature Comms. 10, 4984 (2019)

Real Time Reconstruction of Multi-Surface Moving Scenes using Single-Photon Detection at 330 Meters Range

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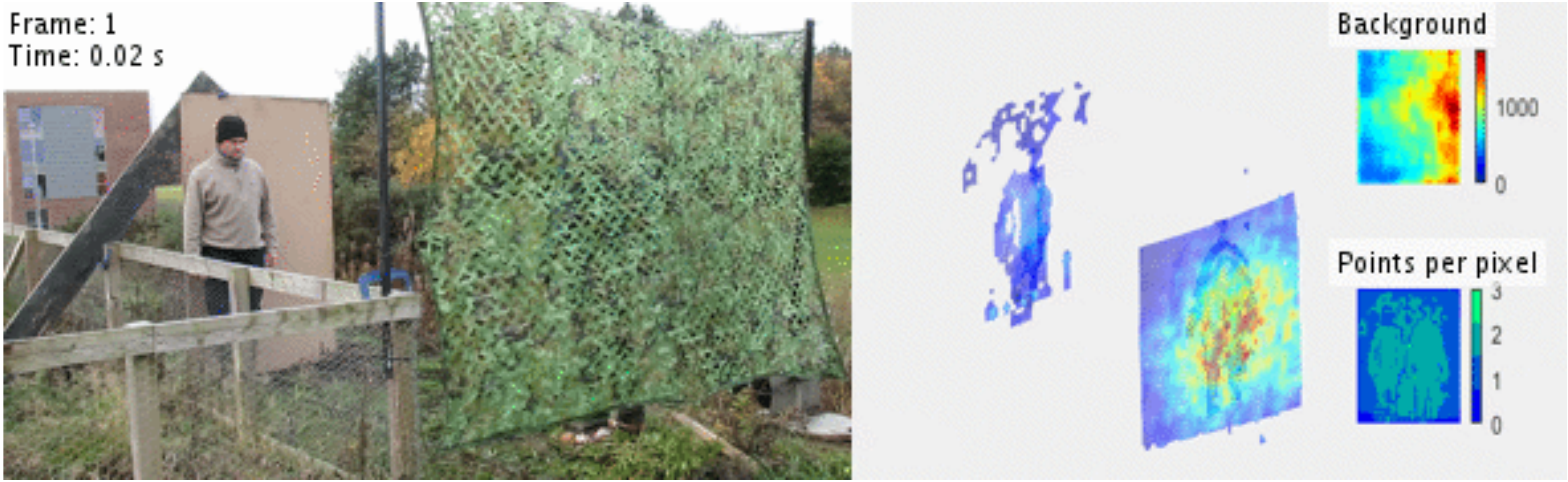

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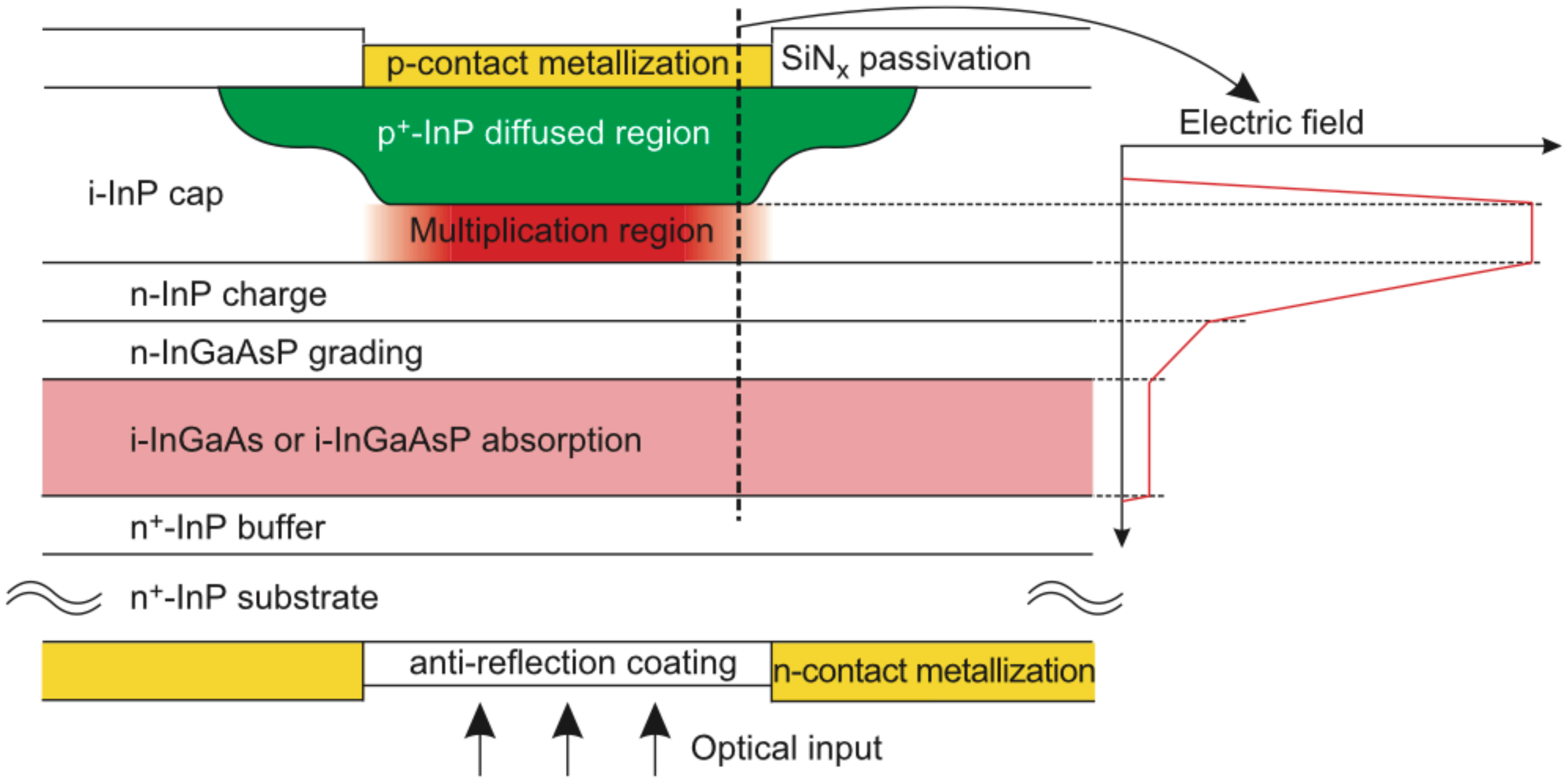
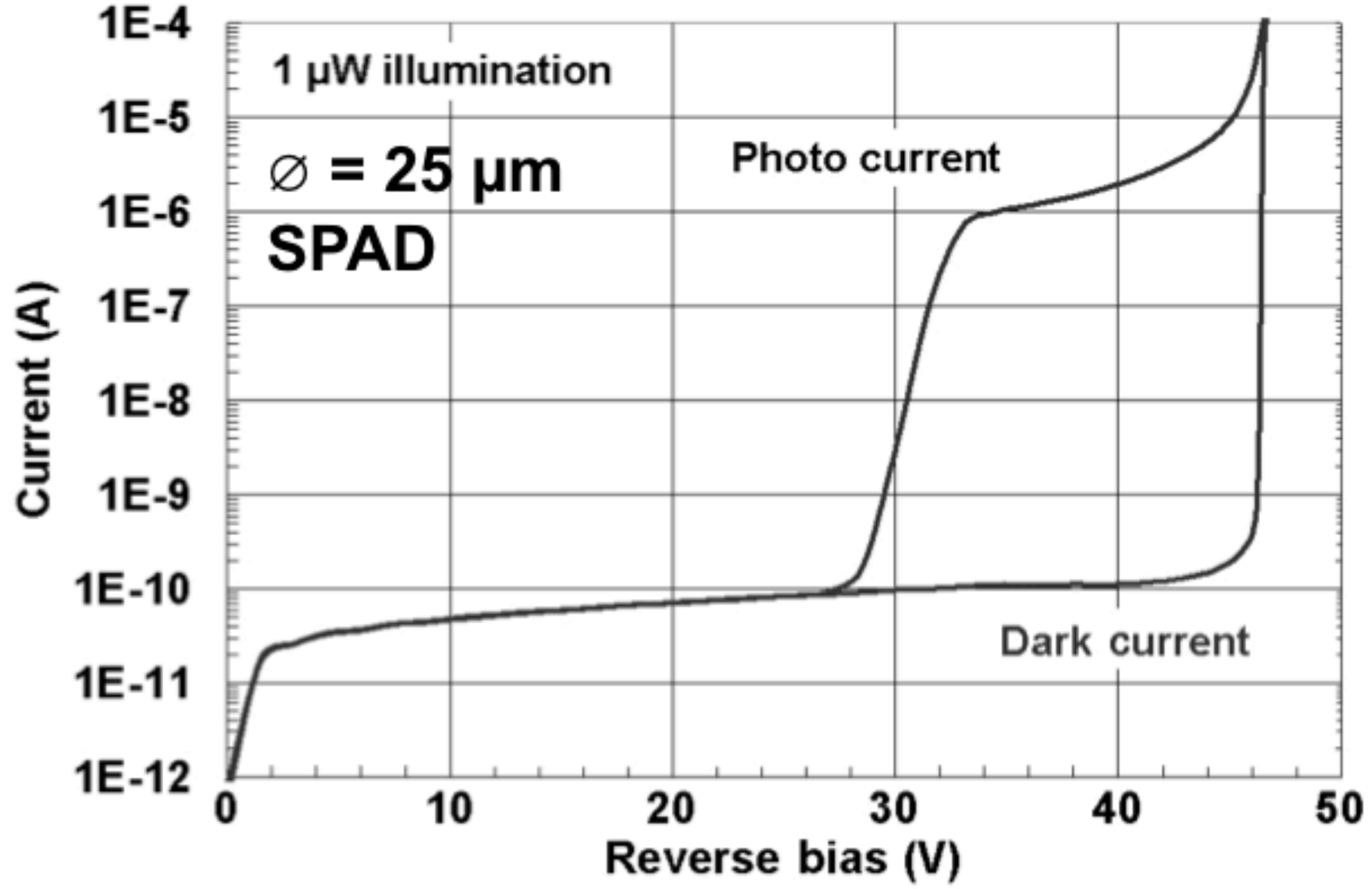
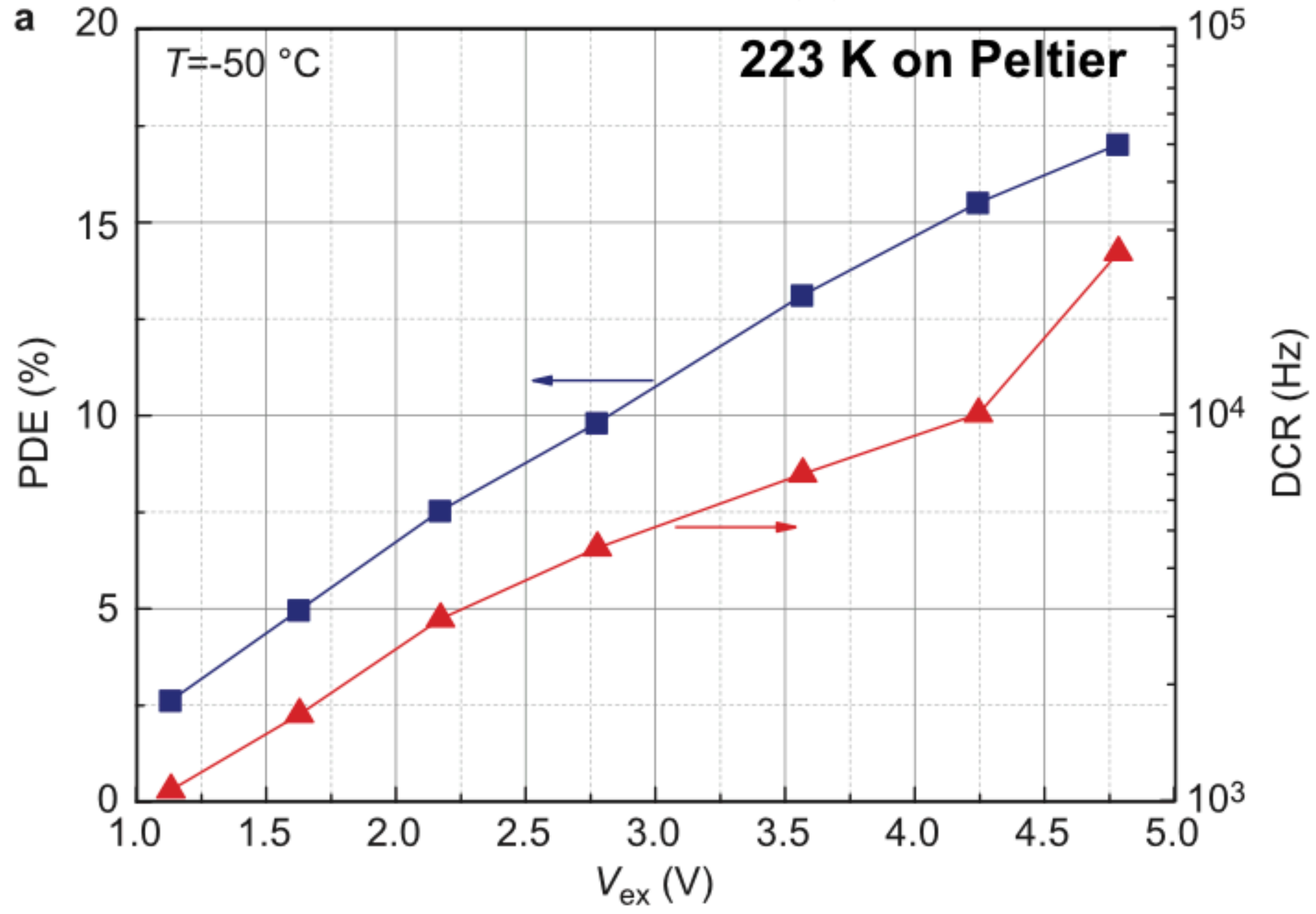
InGaAs SPADs

- **Princeton Lightwave (now Argo AI): significant funding over decades & commercial leader in InGaAs SPADs on InP**





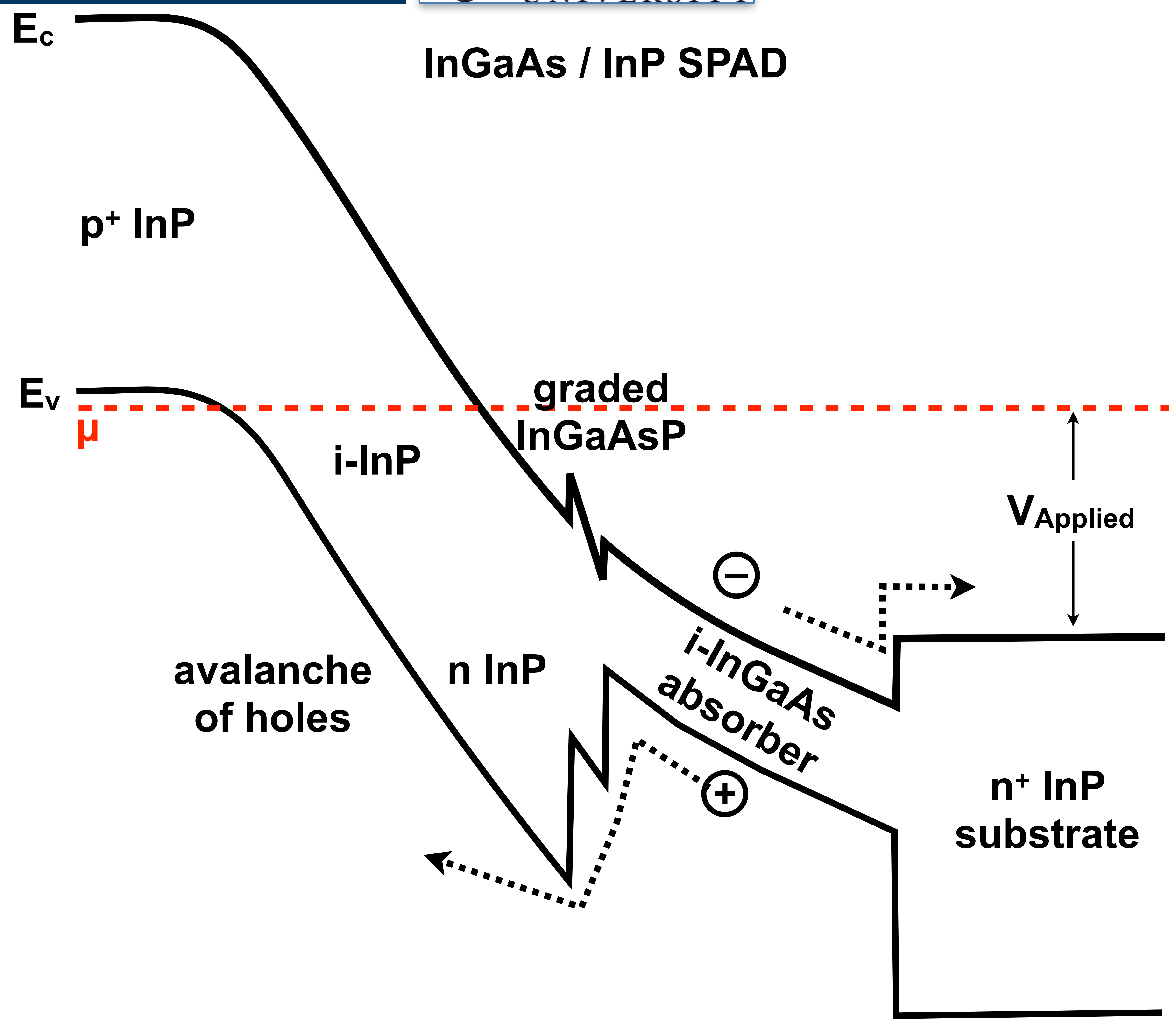
area = 4.91 x 10^{-10} m^{-2}
= x16 smaller than Ge on Si



J. Zhang et al., Light Sci. App. 4, e286 (2015)

$20k single pixel, $150k for 32 x 32 camera

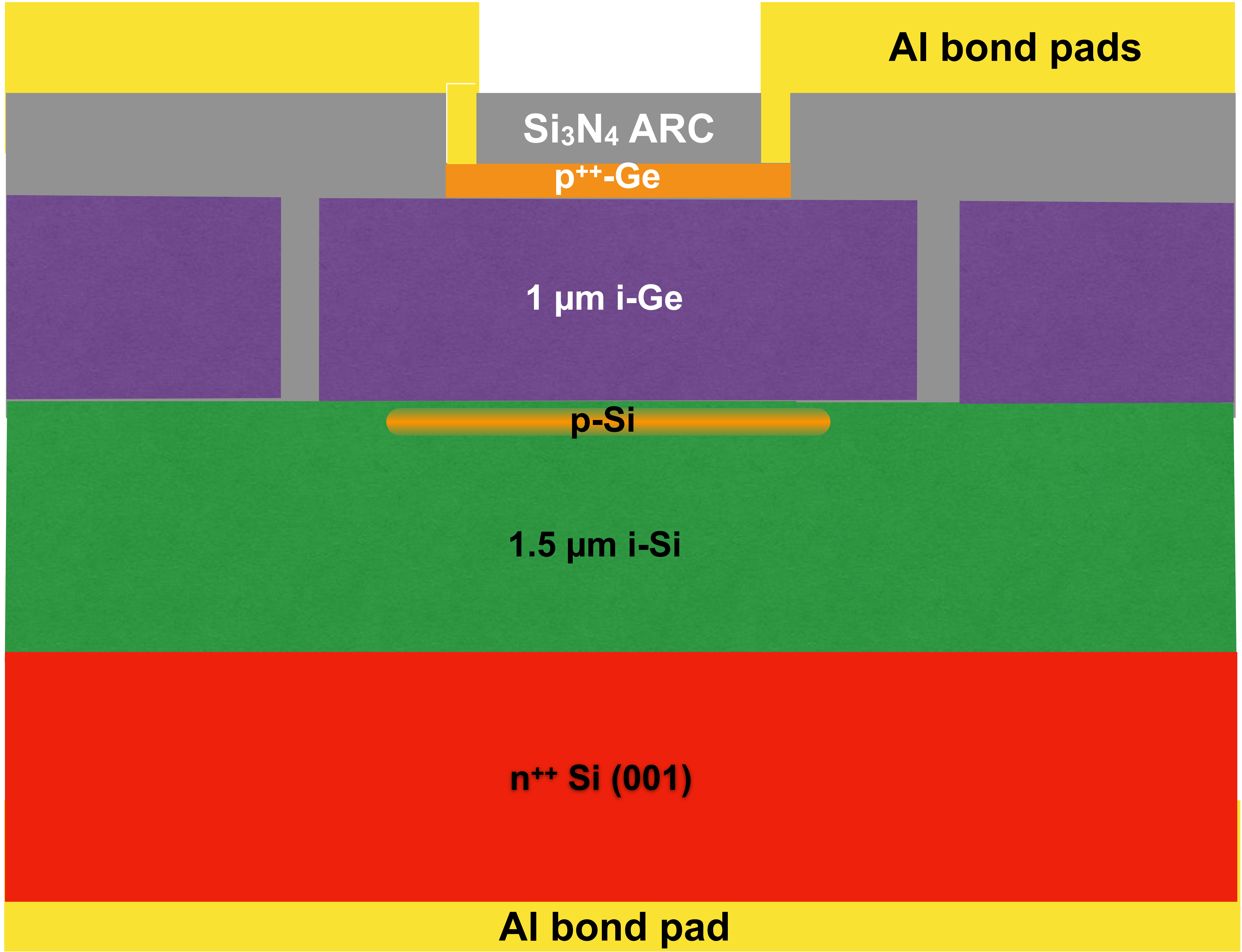
Band Structure



Band Structure

Si has the best impact ionisation coefficients for any material

Epitaxial & Device Process

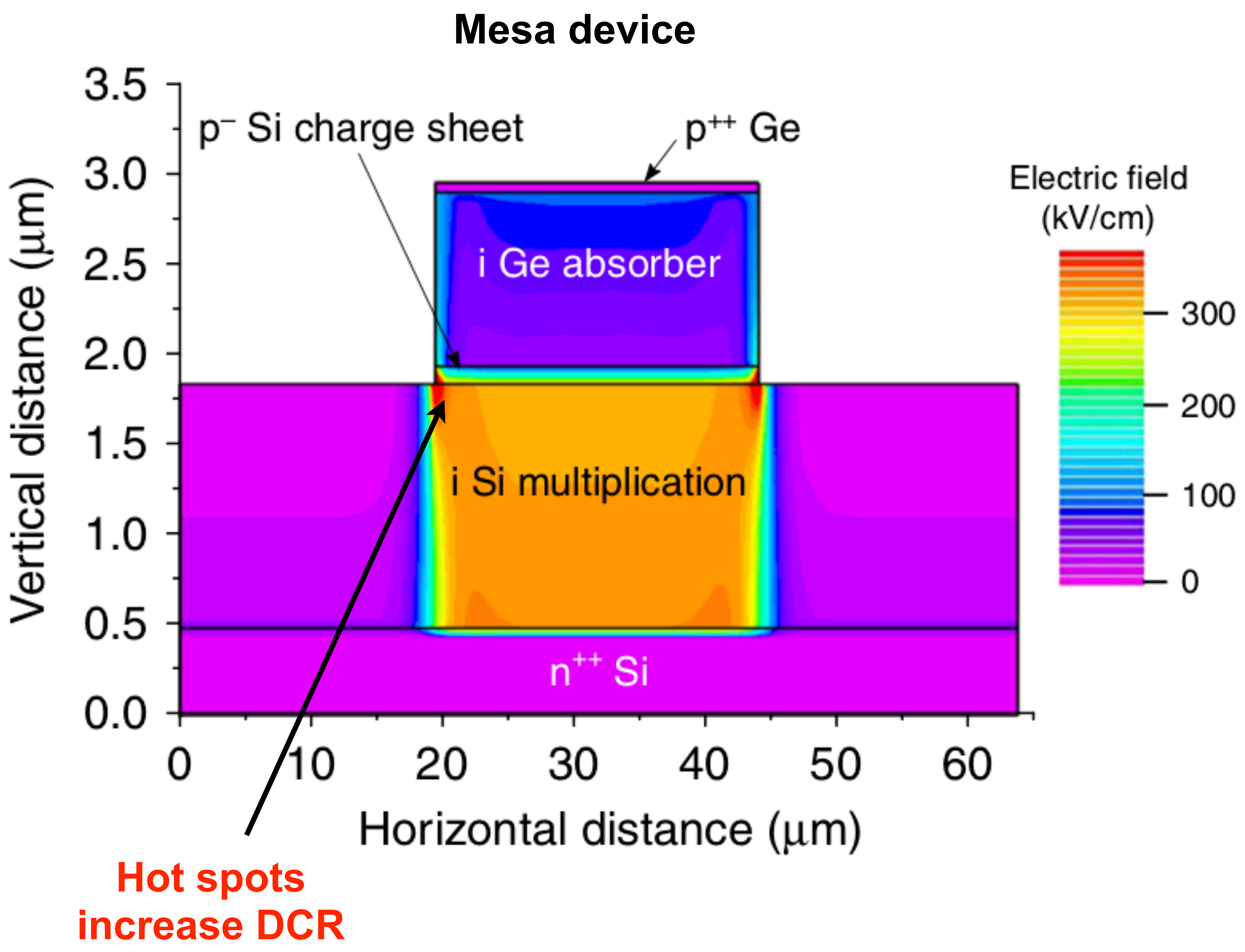


- ASM Epsilon 2000E LPCVD with 150 mm Si (001) wafers
- 1.5 µm i-Si epi for avalanche on n^{++} Si
- Implant p^{-} sheet charge layer
- 1 µm i-Ge absorber with 50 nm p^{++}-Ge contact
- All silicon foundry compatible processing

P. Vines et al., Nature Comms. 10, 1086 (2019)

Electric Field Profiles

Silvaco Athena TCAD

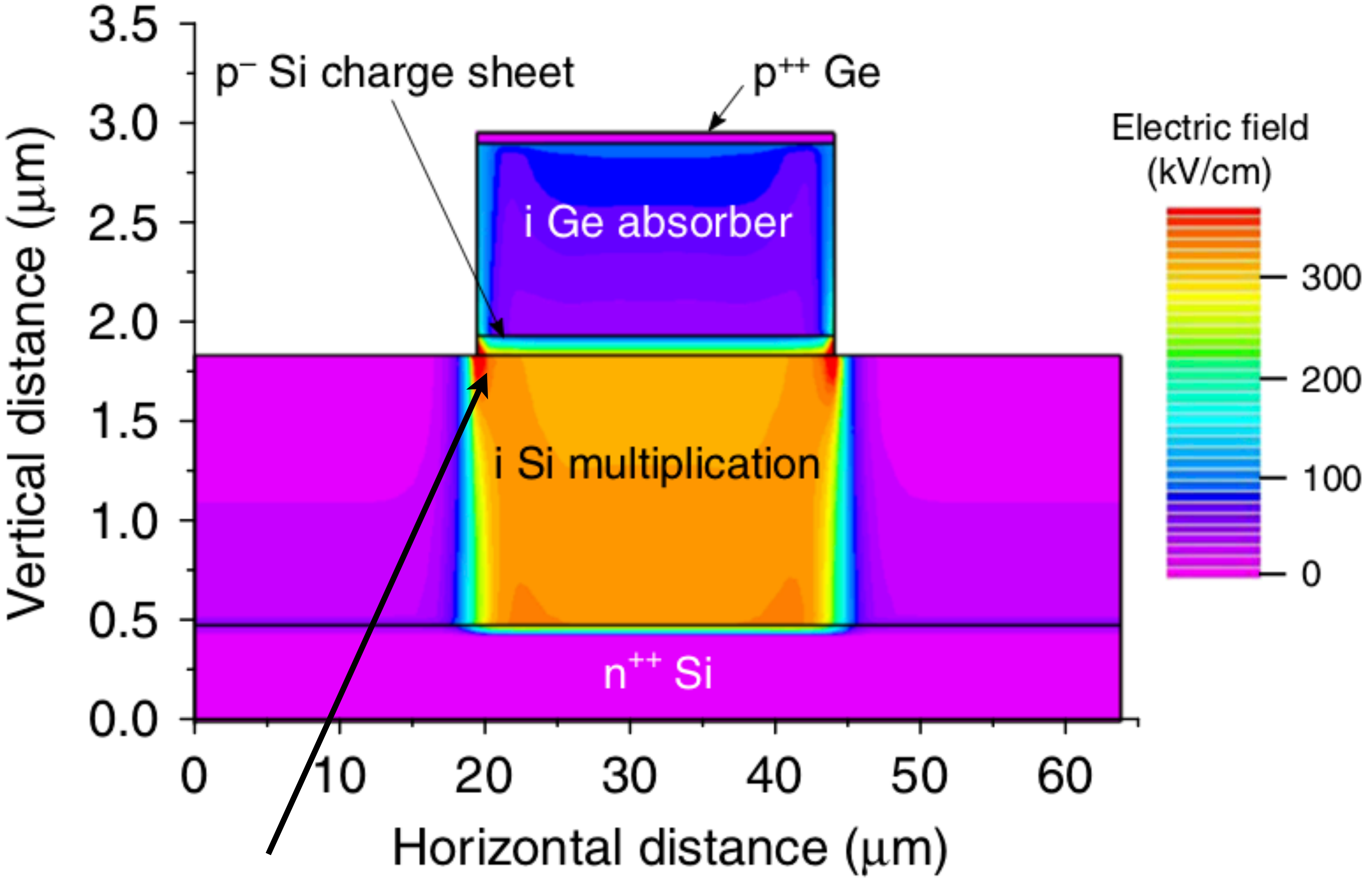


R.E. Warburton et al., IEEE Trans. Elec. Dev. 60, 3807 (2013)

Electric Field Profiles

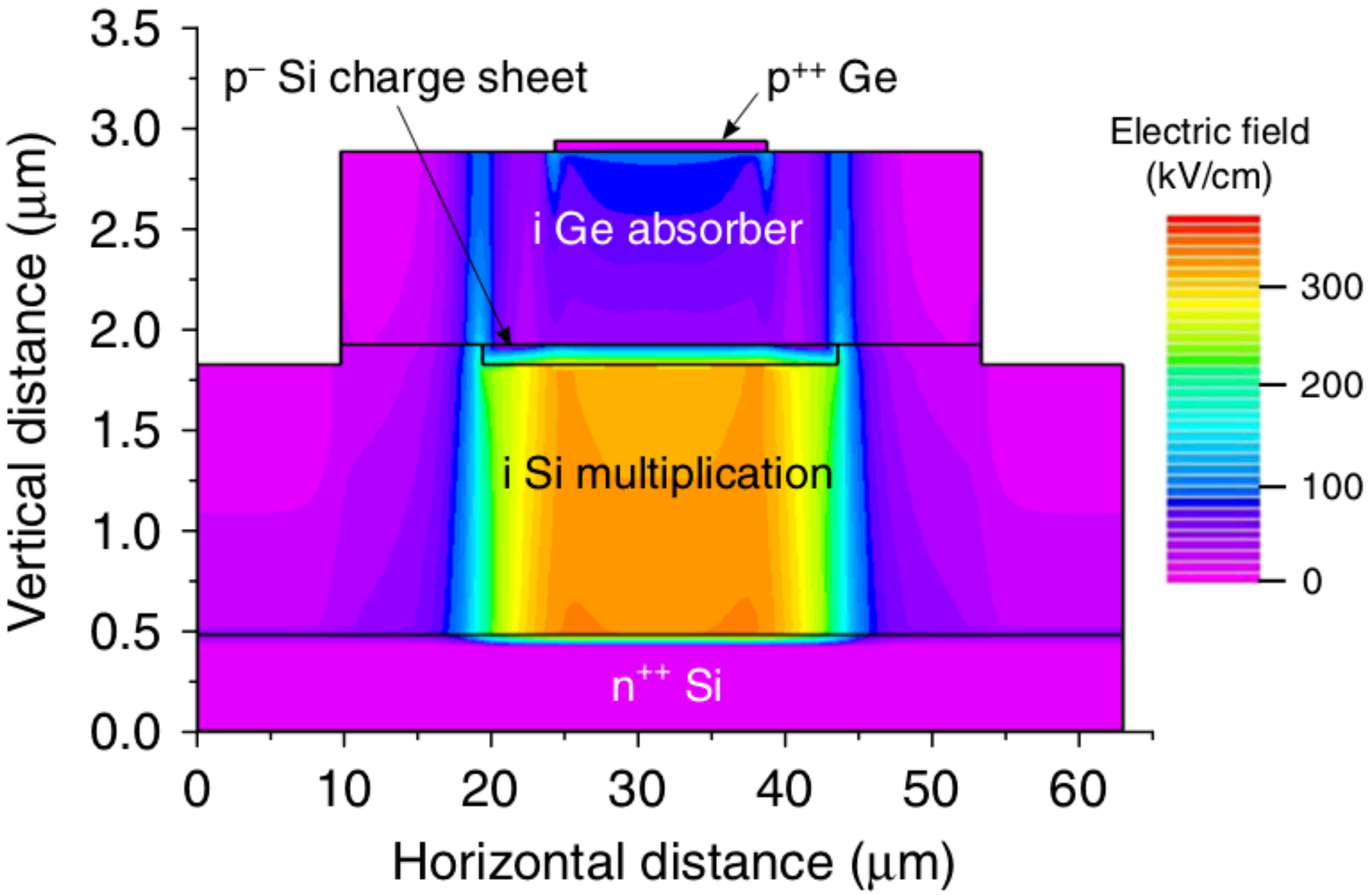
Silvaco Athena TCAD

Mesa device



Hot spots increase DCR

Planar device



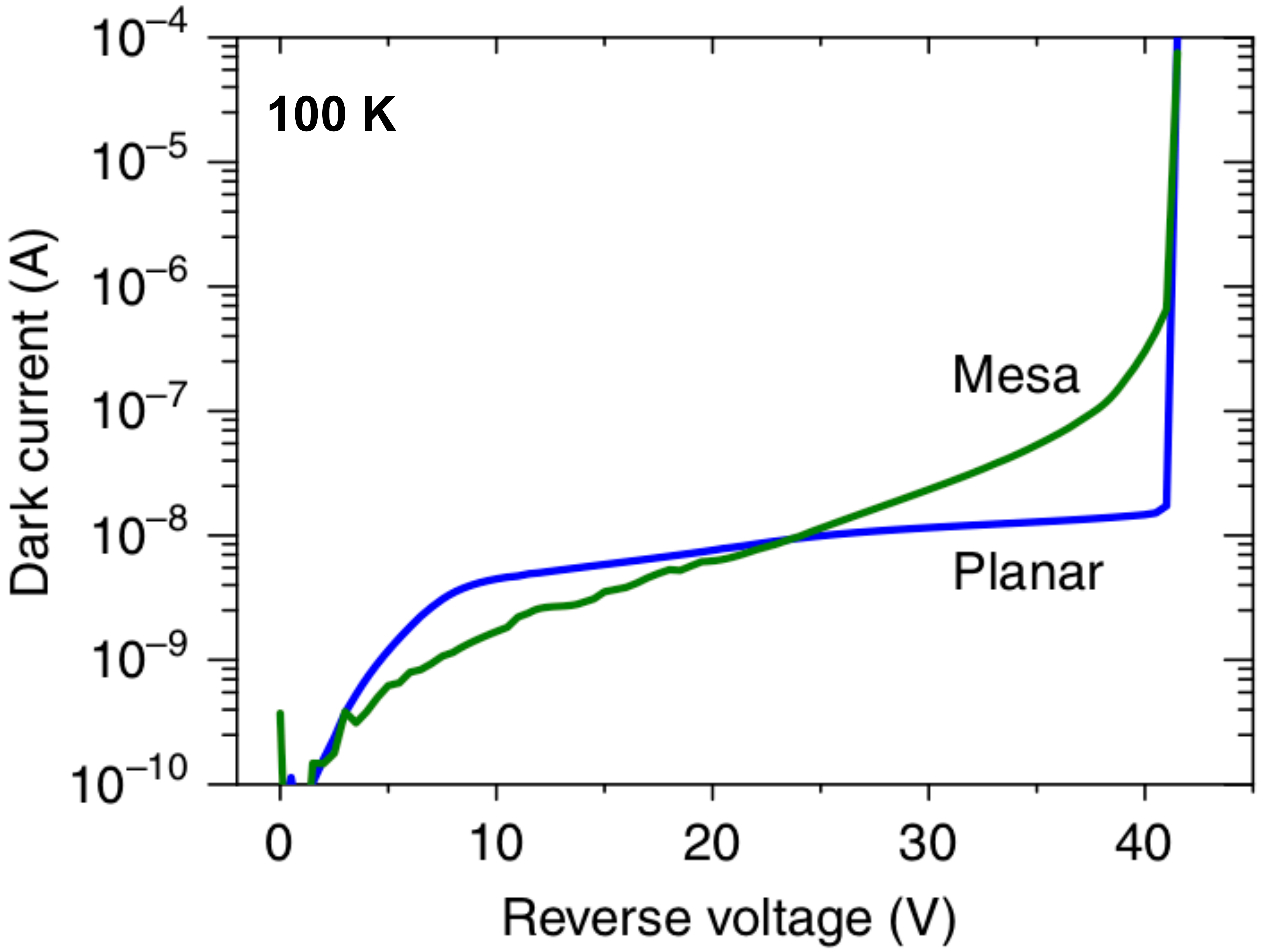
GB Patent application no. 1814688.6 (10th September 2018)

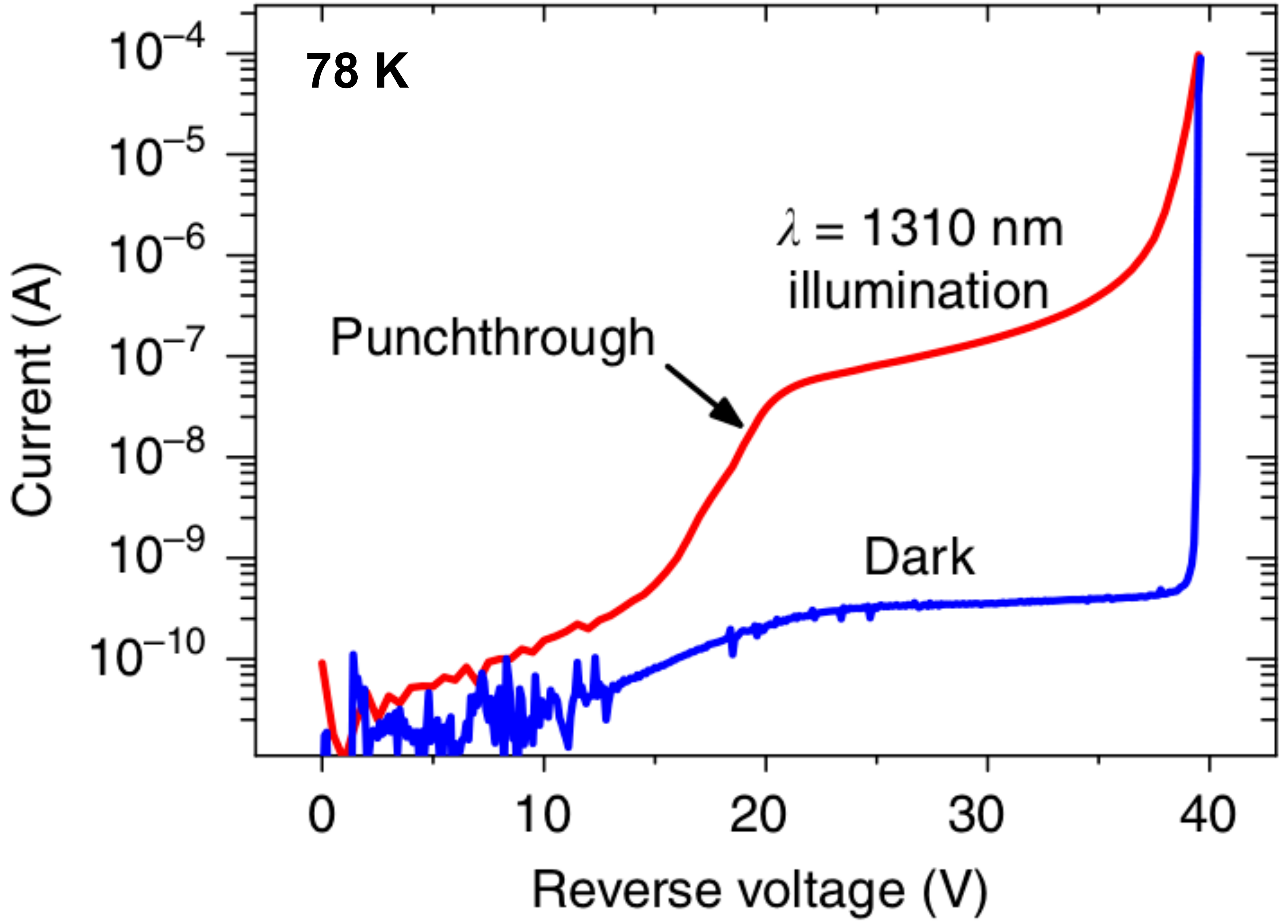
R.E. Warburton et al., IEEE Trans. Elec. Dev. 60, 3807 (2013)

P. Vines et al., Nature Comms. 10, 1086 (2019)

Ge SPADs Planar vs Mesa

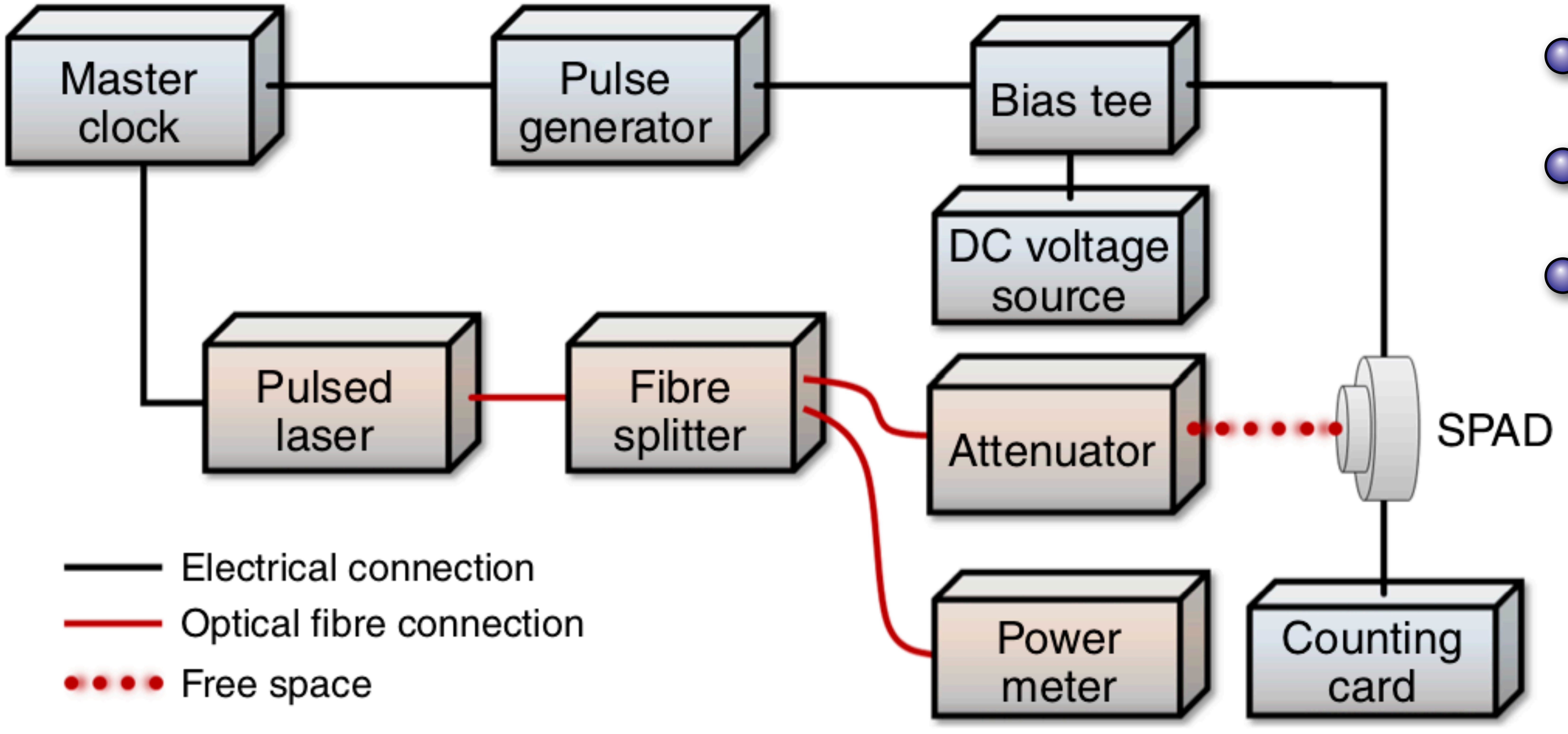
100 µm diameter Ge on Si SPAD



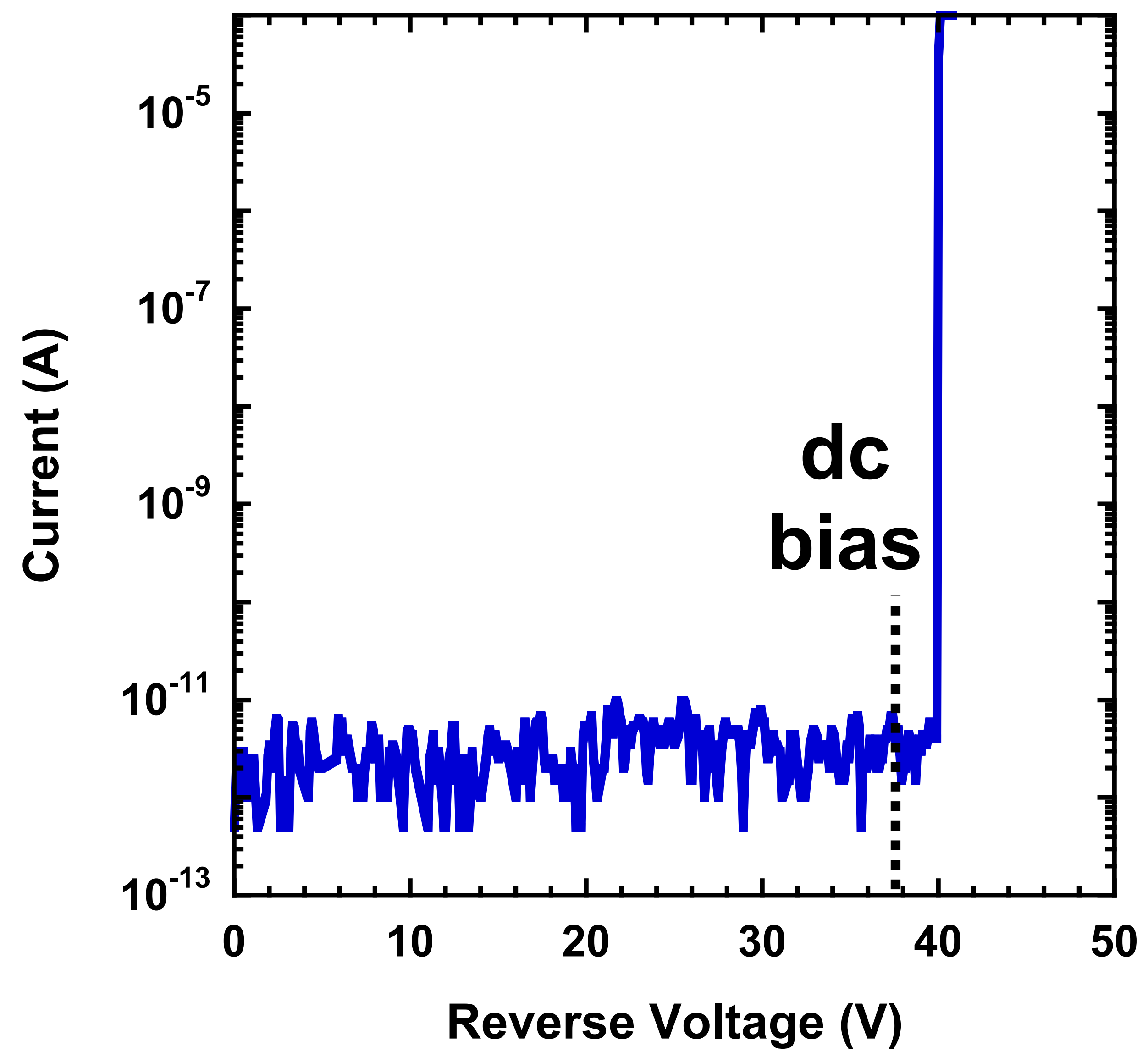


P. Vines et al., Nature Comms. 10, 1086 (2019)

Geiger Mode Measurements



- 50 ns detector gate at 1 kHz rep. rate
- Picoquant ps pulsed 1310 nm laser
- NKT ps supercontinuum laser
- Photon flux <0.1 photons / pulse
- 19.5 ps timing bin for jitter measurements



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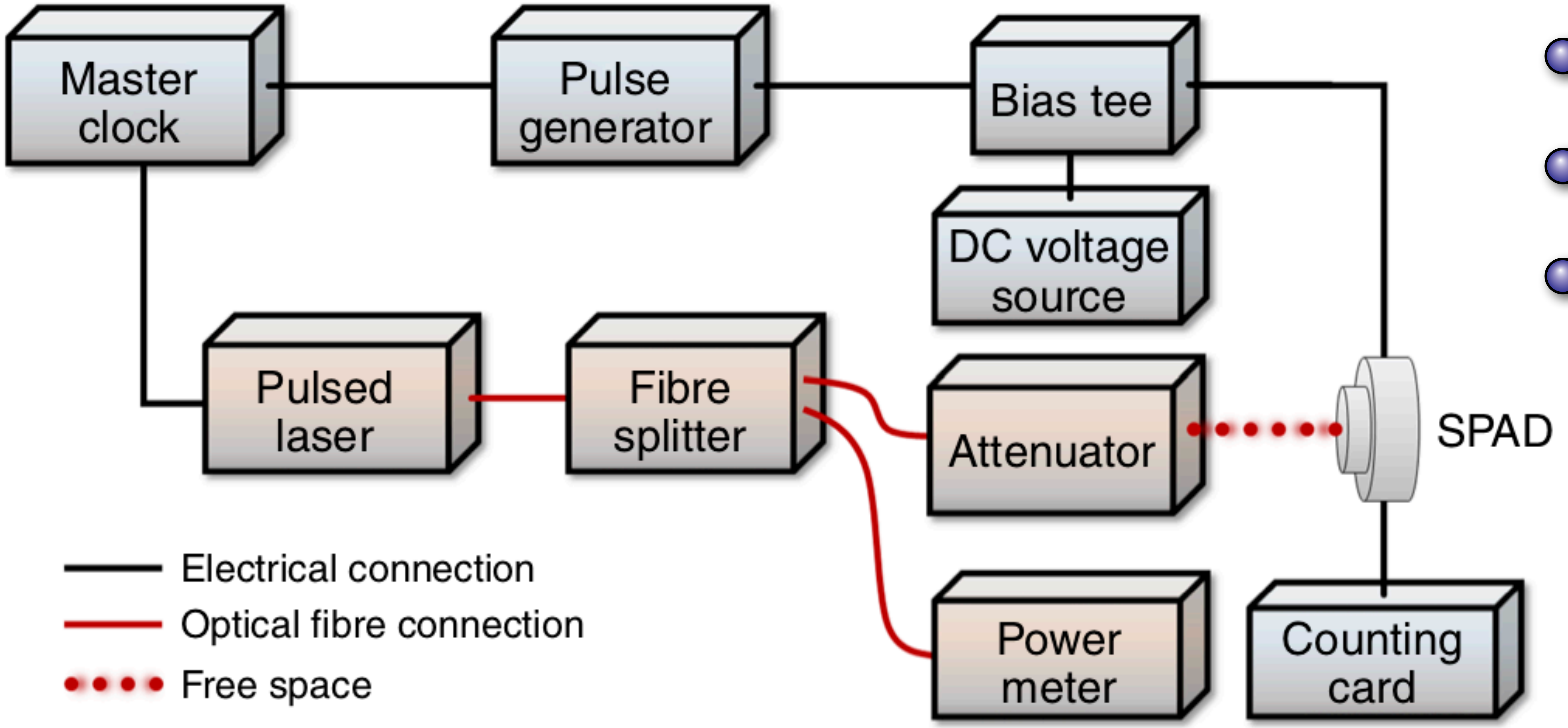
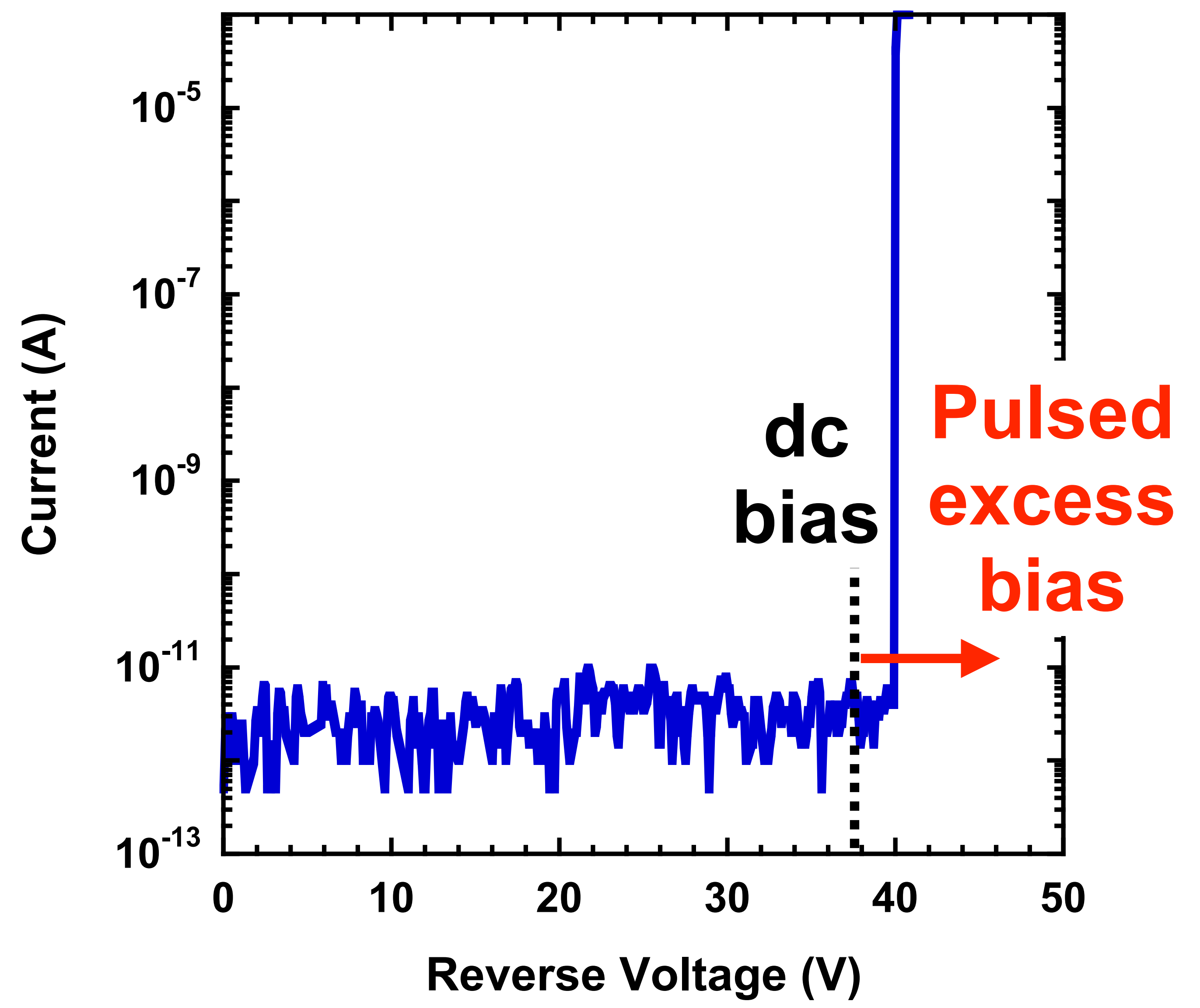
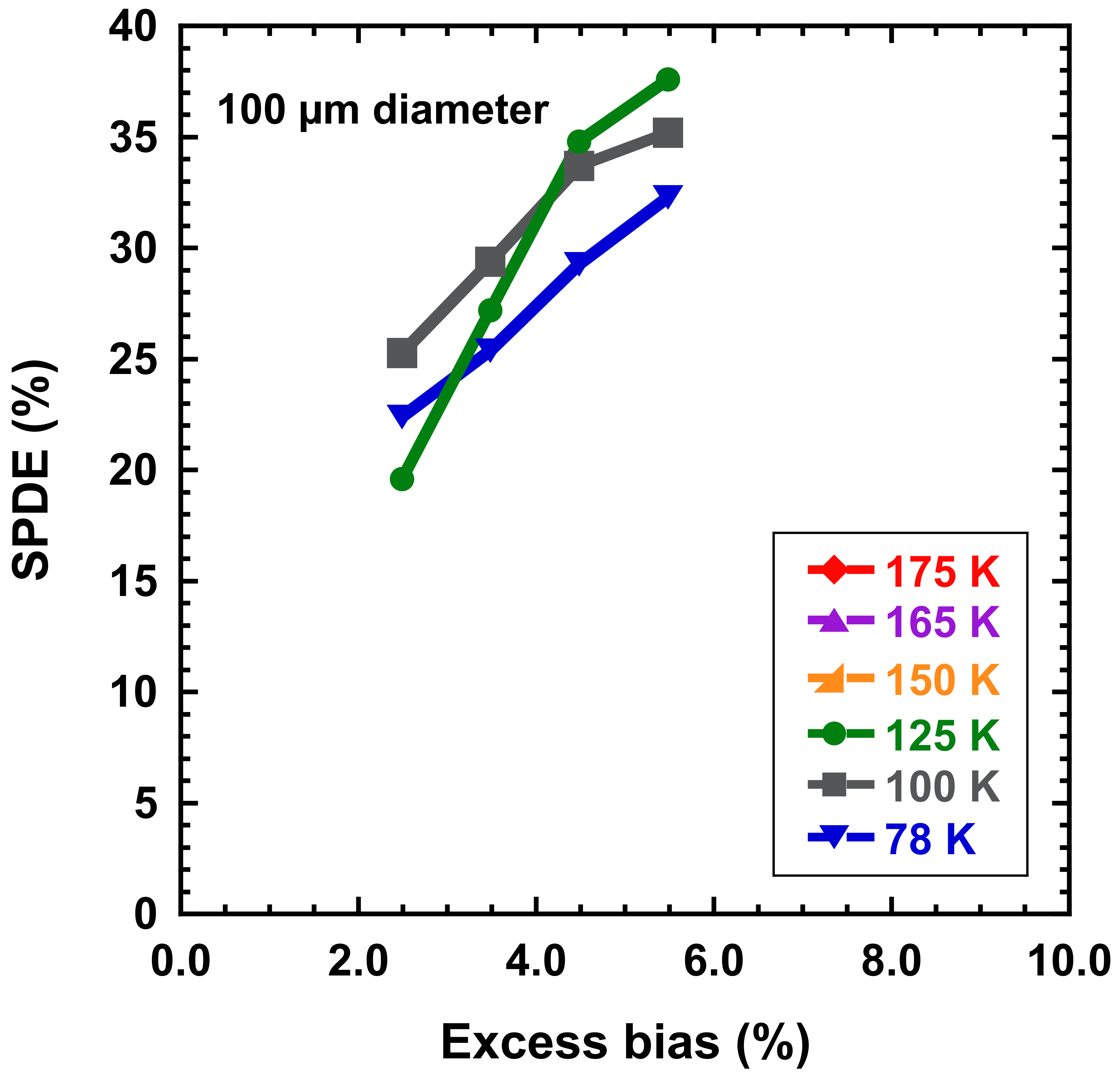
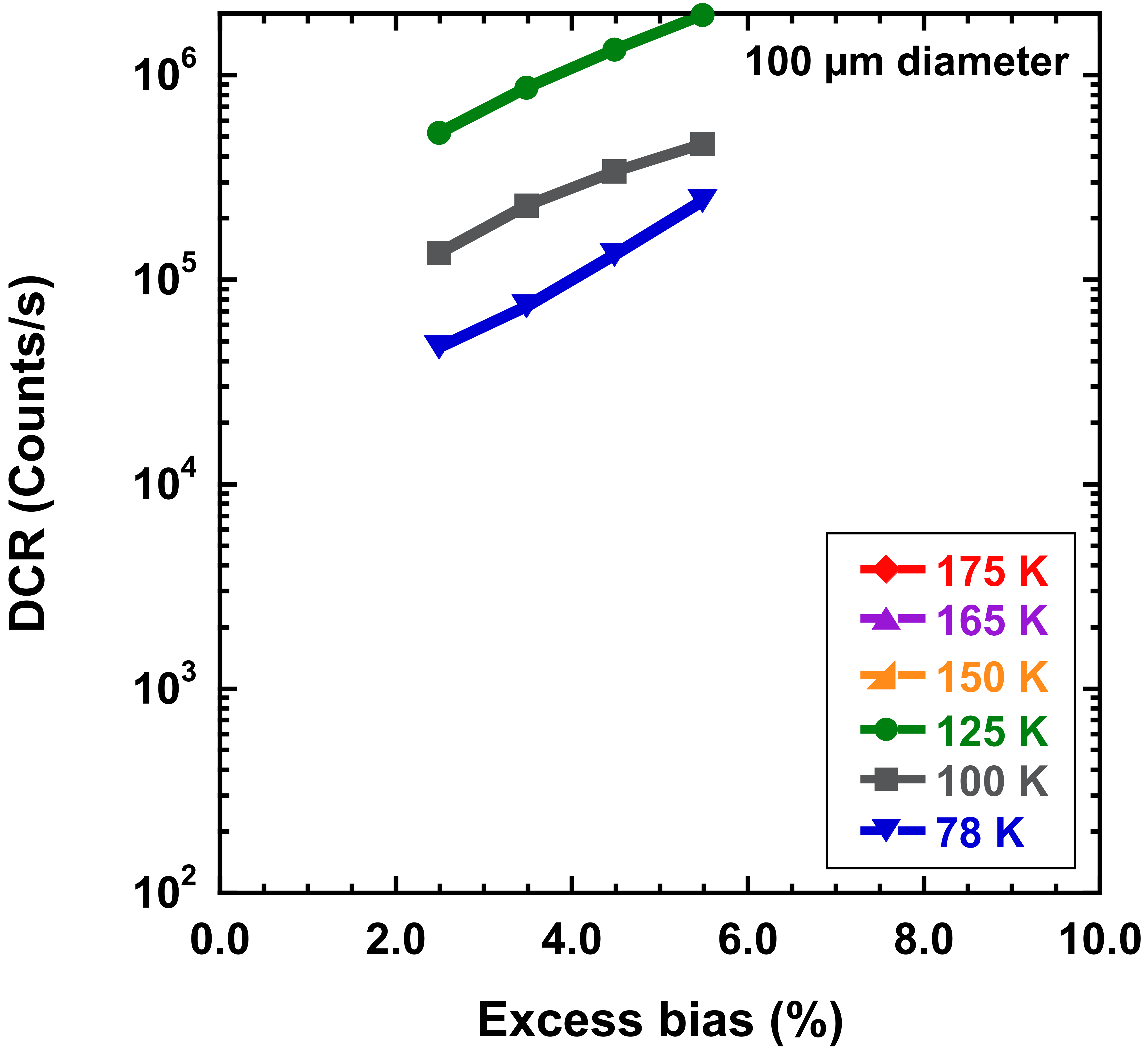




1310 nm Performance





P. Vines et al., Nature Comms. 10, 1086 (2019)

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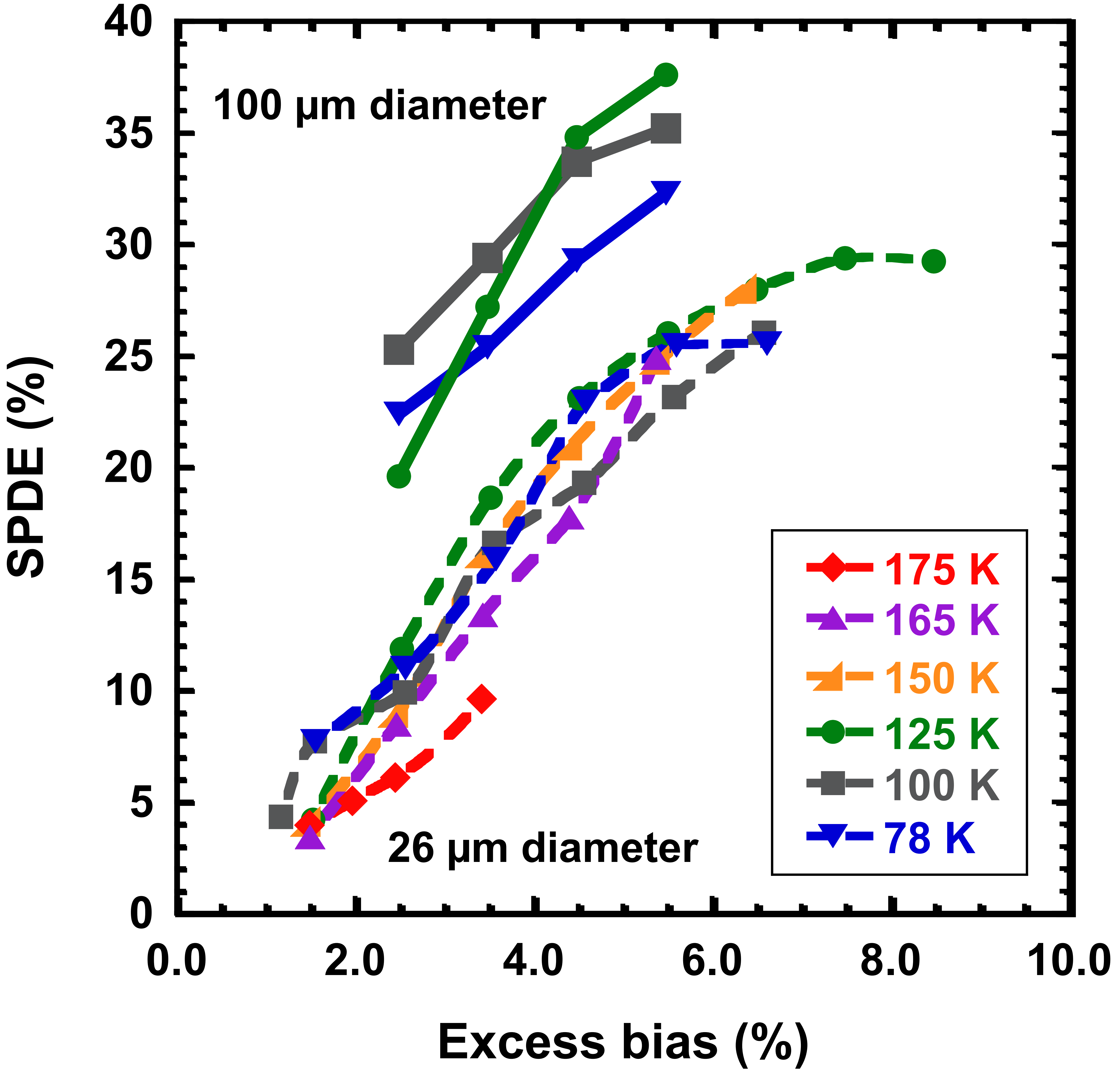
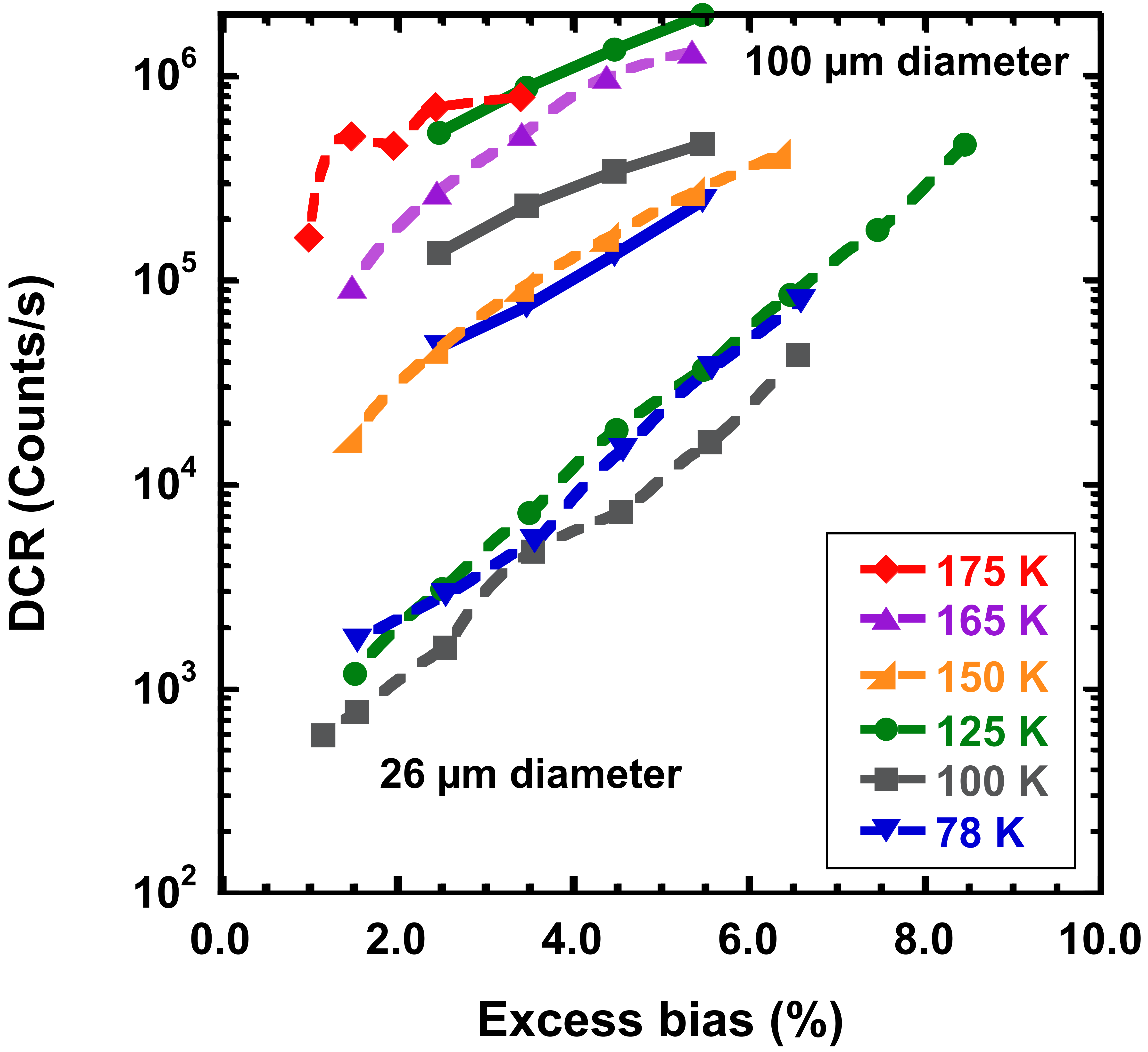
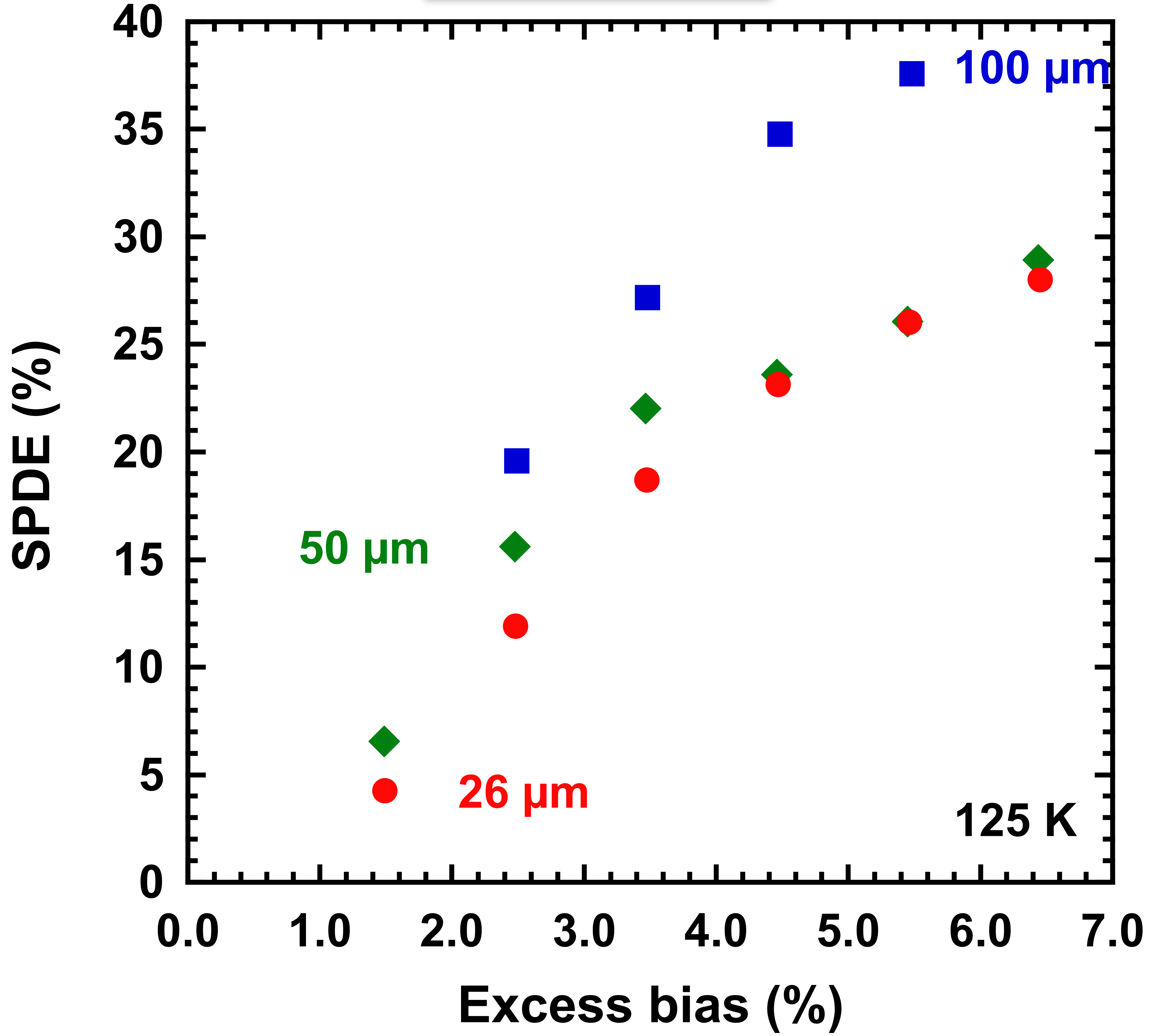
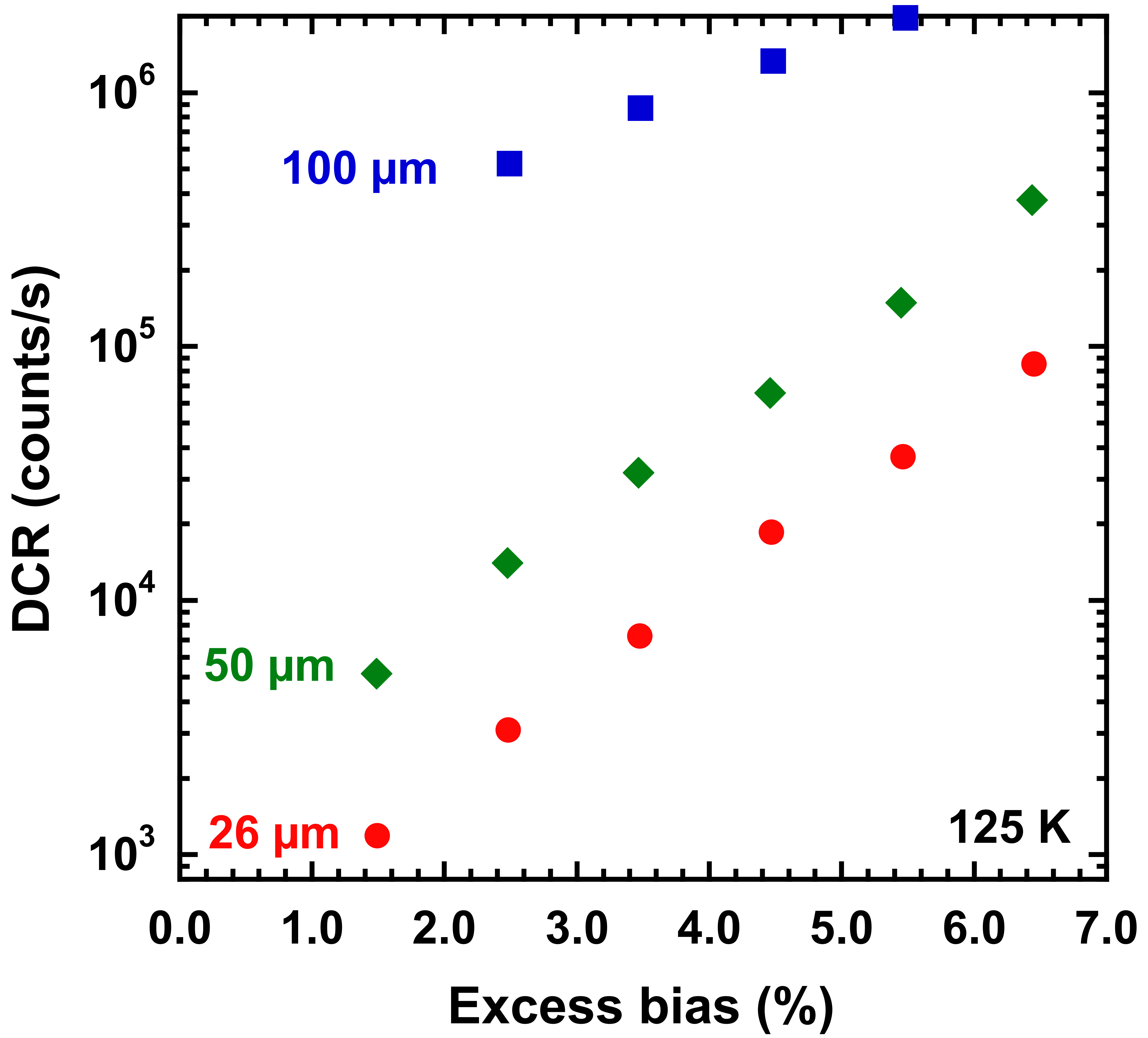




P. Vines et al., Nature Comms. 10, 1086 (2019)

Device Scaling





P. Vines et al., Nature Comms. 10, 1086 (2019)

F.E. Thorburn et al. Proc. SPIE 11386, 113860N (2020)

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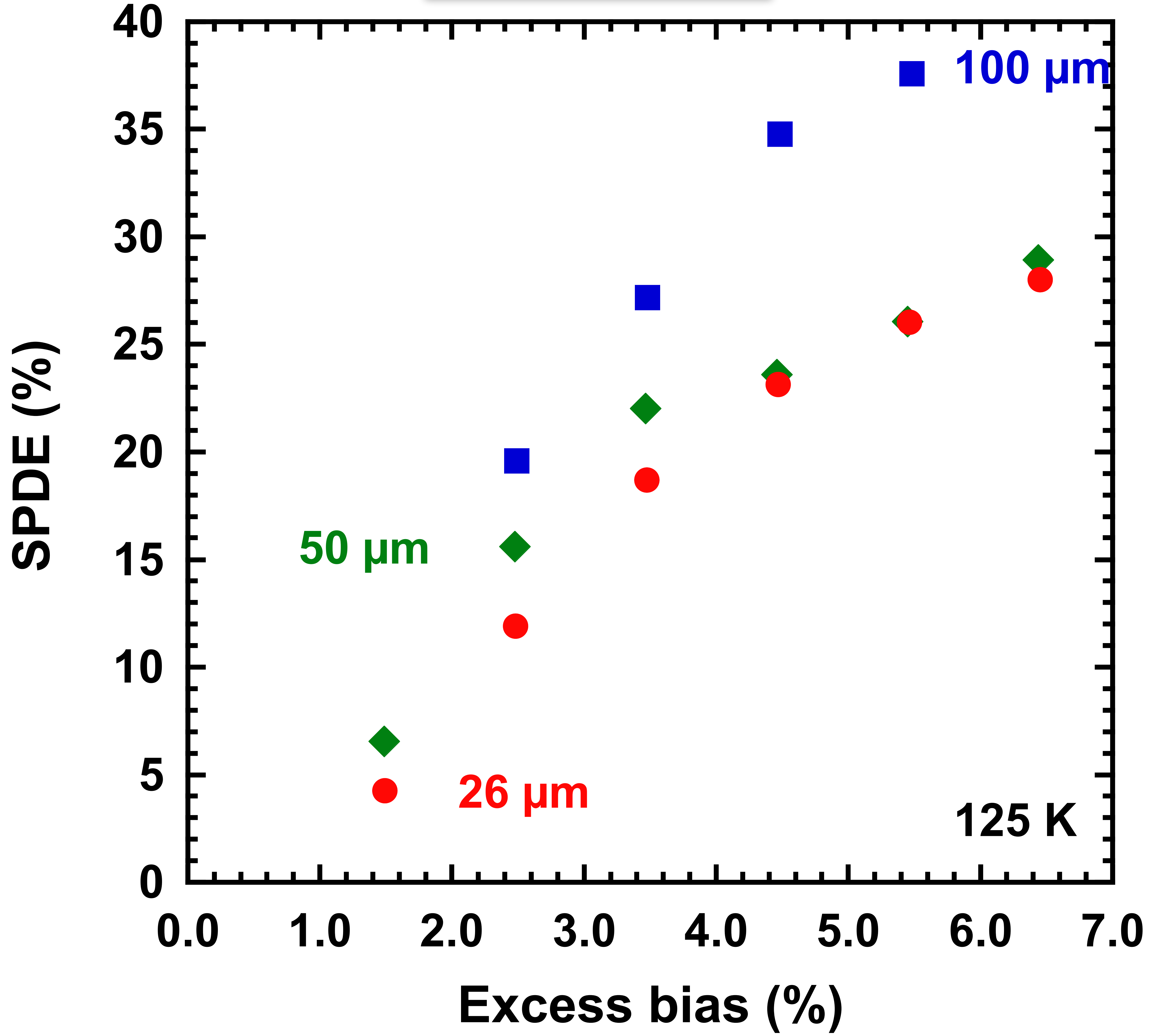
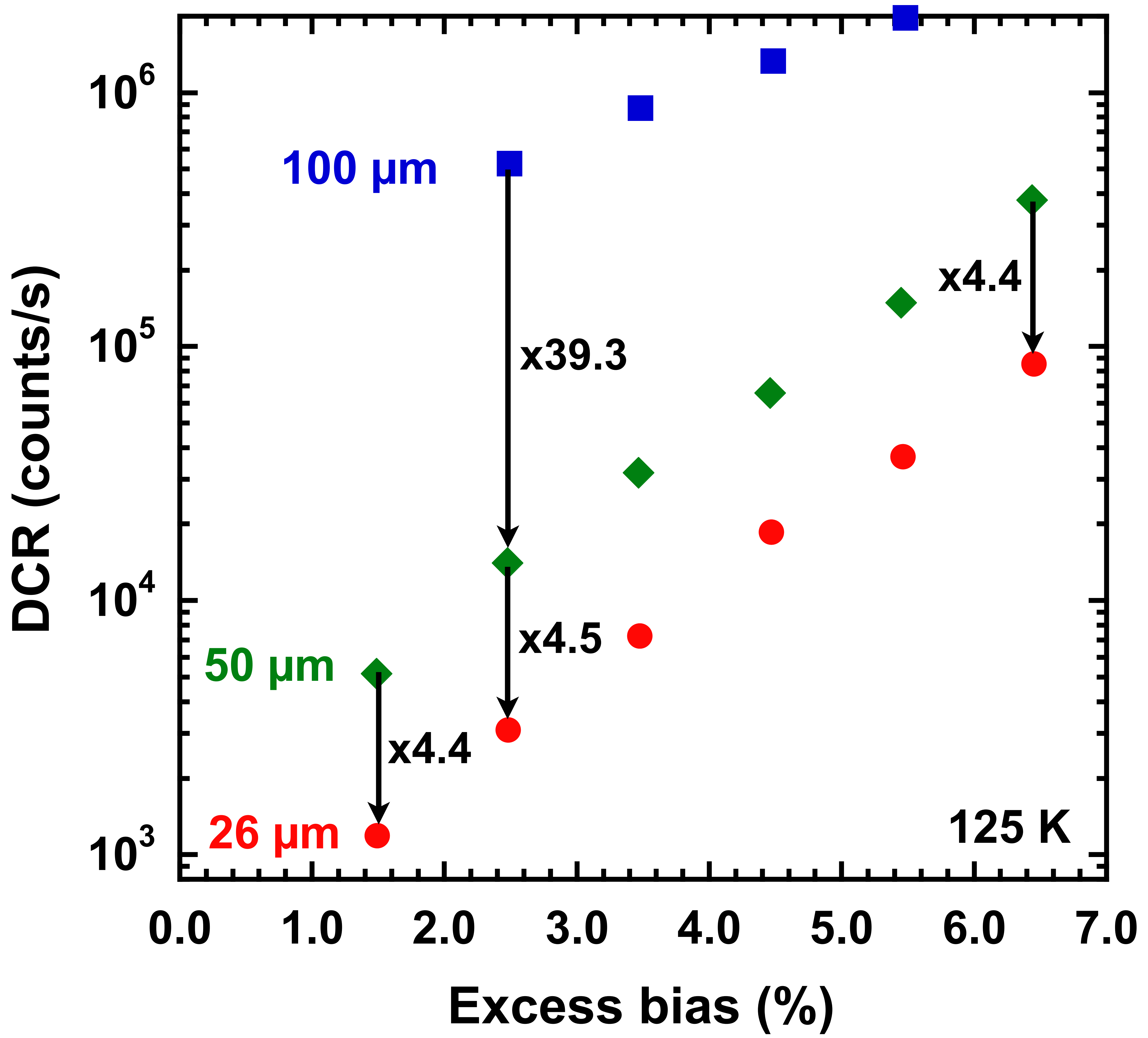


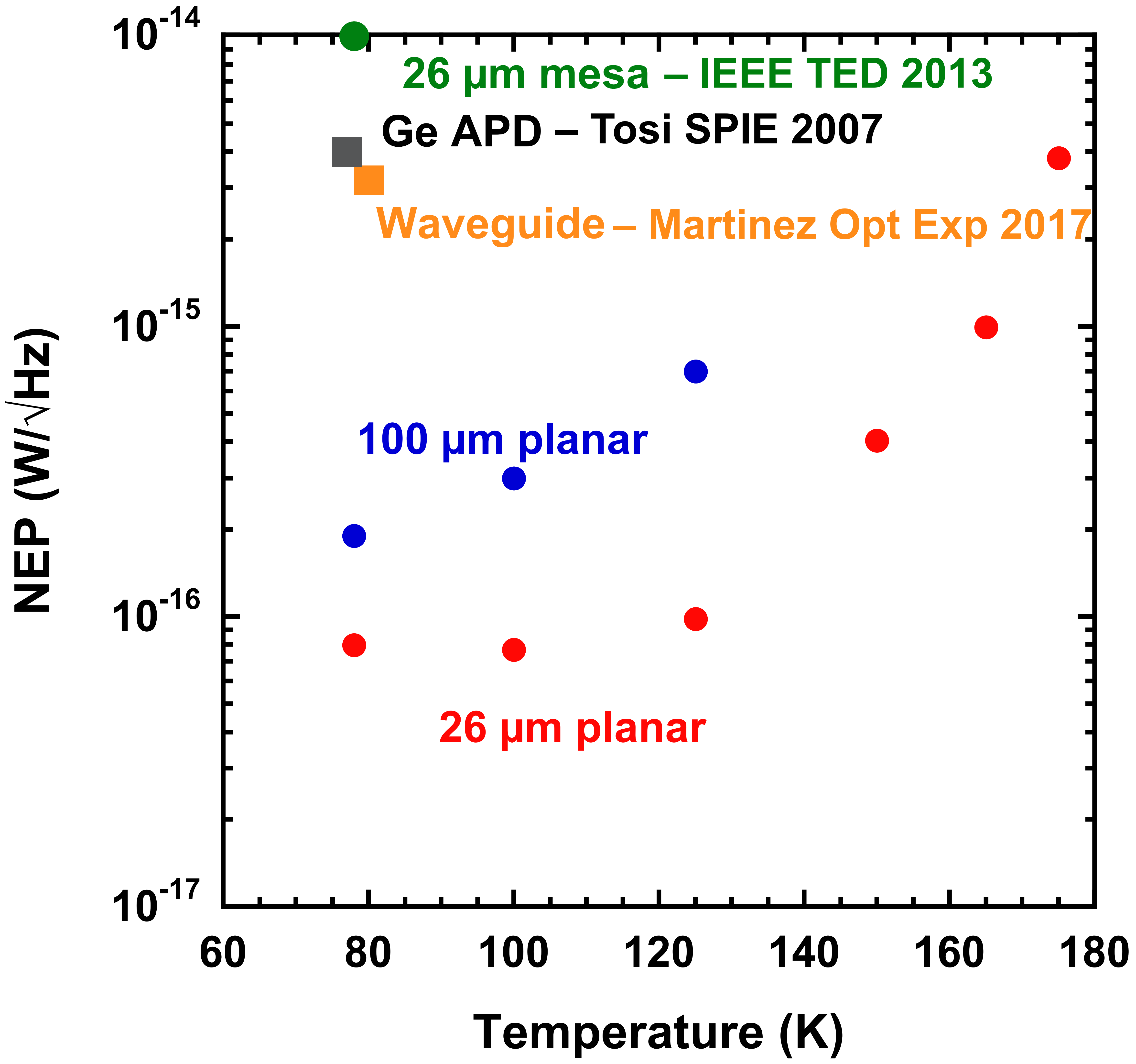


- DCR for 50 & 26 µm devices scales with Ge volume

P. Vines et al., Nature Comms. 10, 1086 (2019)

F.E. Thorburn et al. Proc. SPIE 11386, 113860N (2020)

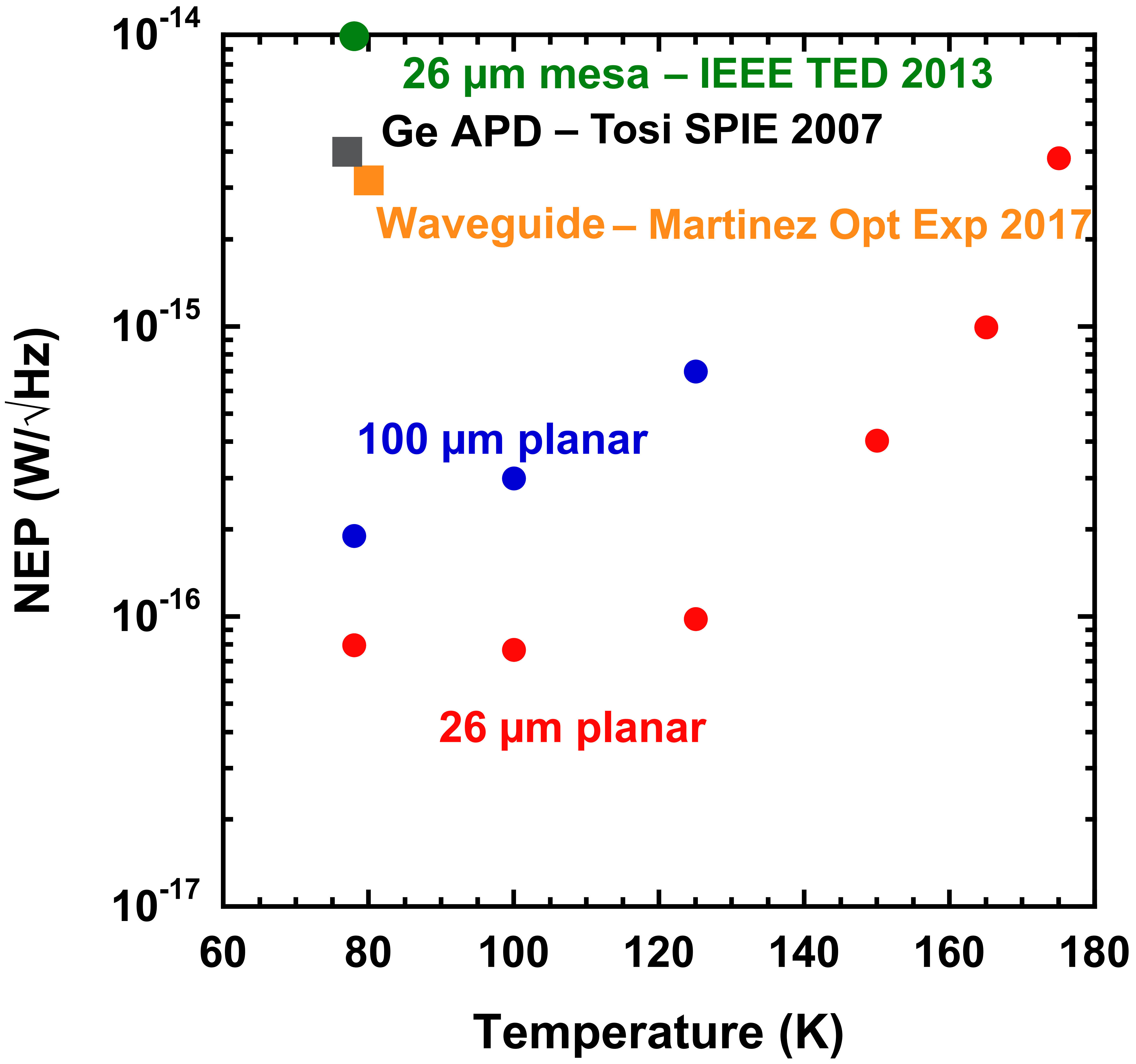
Performance @ 1310 nm



$$NEP = \frac{h\nu}{SPDE}\sqrt{2DCR}$$

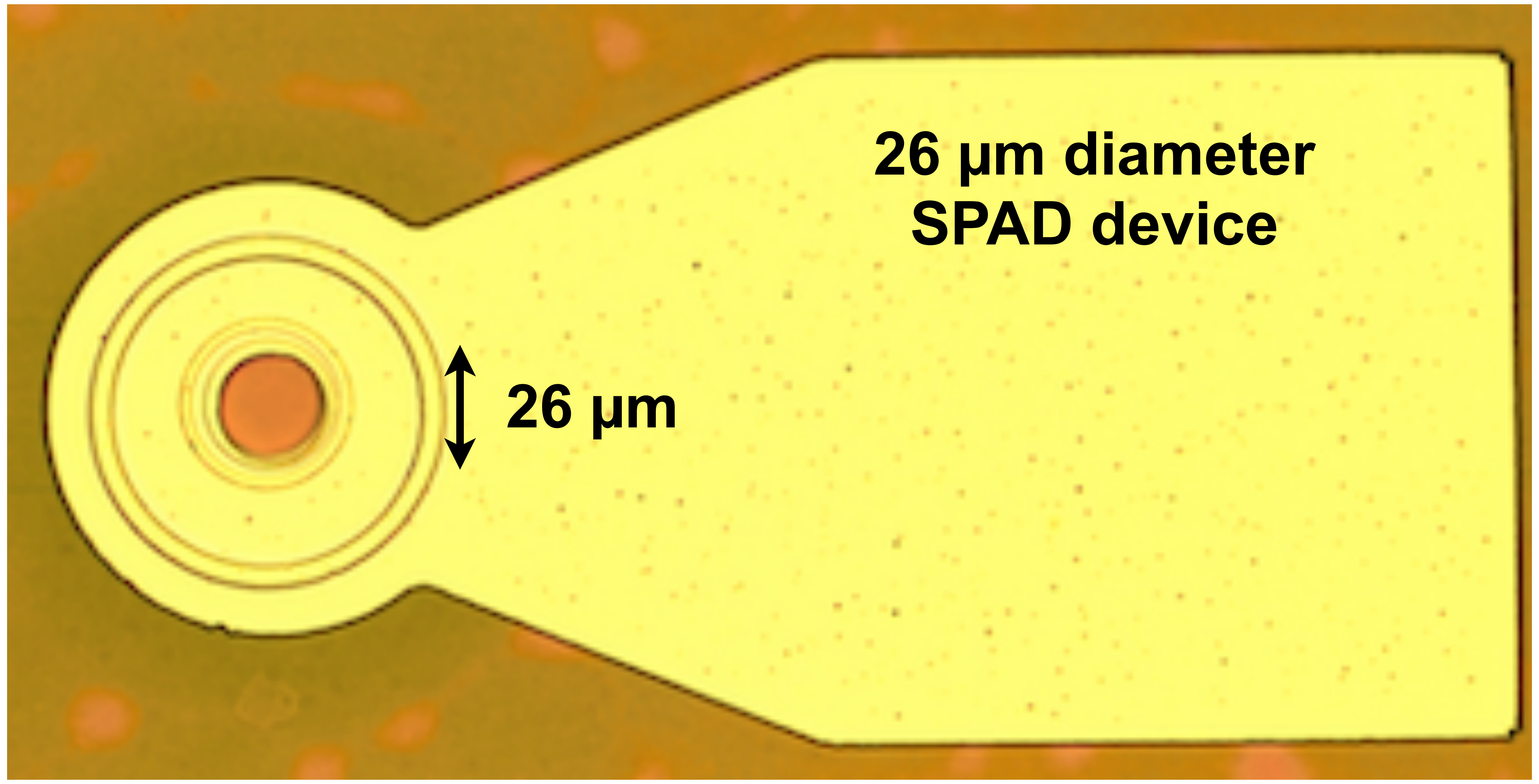
- 26 µm InGaAs NEP = 1 x 10^{-17} W/√Hz at 223 K and 1550 nm

Performance @ 1310 nm



$$\mathrm{NEP} = \frac{h\nu}{\mathrm{SPDE}}\sqrt{2\mathrm{DCR}}$$

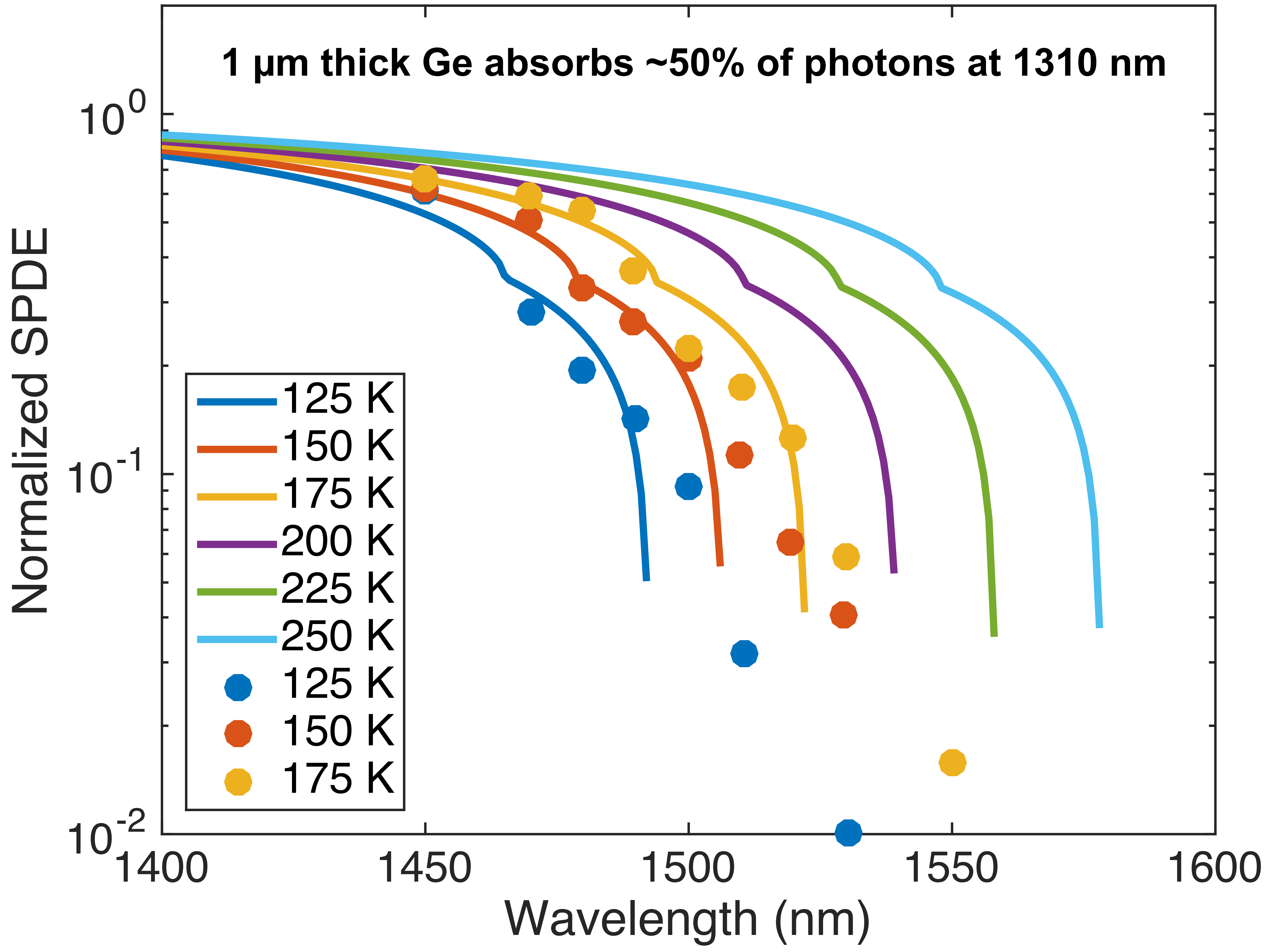
- 310 ± 10 ps jitter for 100 µm diameter SPAD @ 78 K
- 134 ± 10 ps jitter for 26 µm diameter SPAD @ 100 K



19.5 ps timing bin for jitter measurements

- 26 µm InGaAs NEP = 1 x 10^{-17} W/√Hz at 223 K and 1550 nm

Temperature Dependence

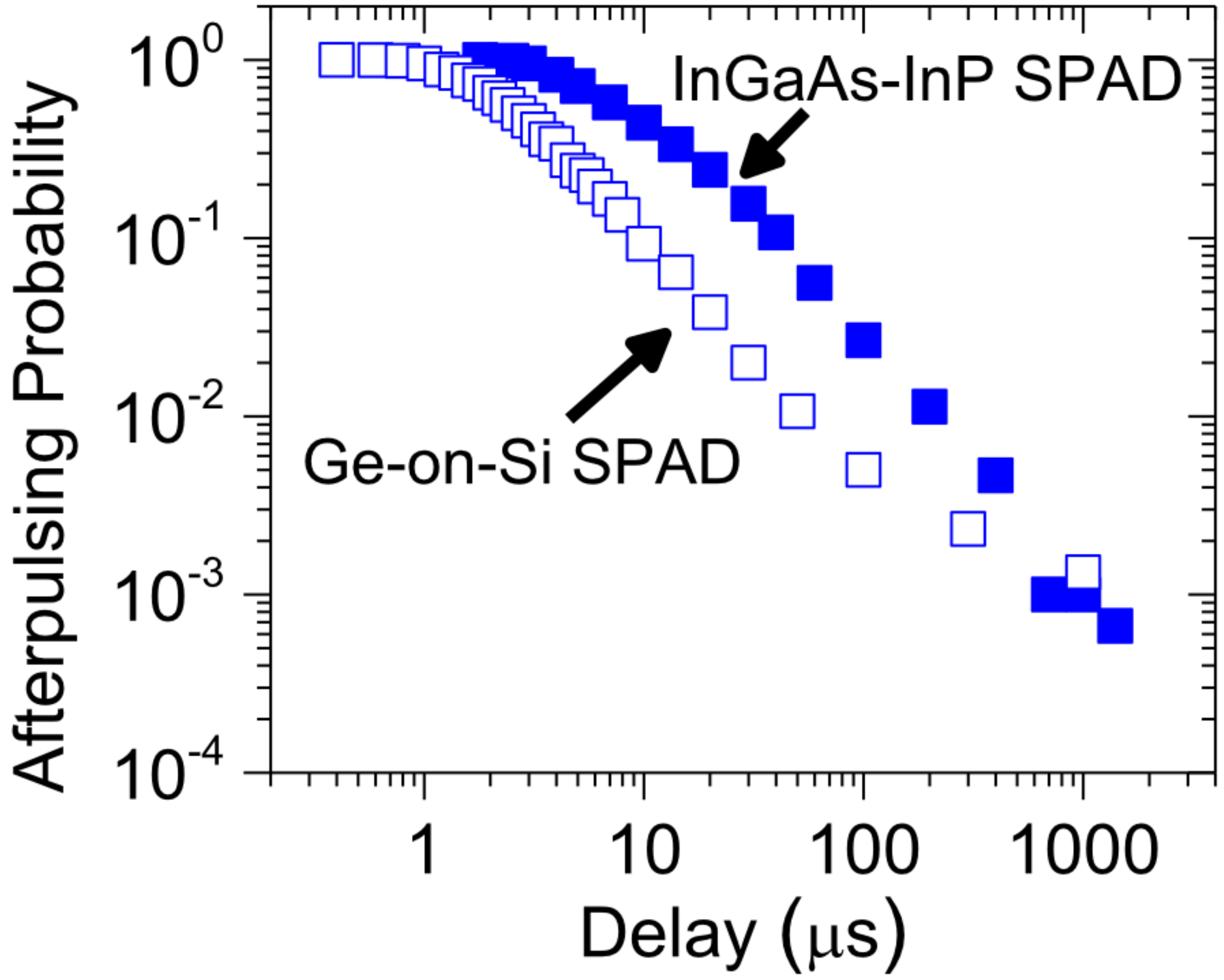


- Lines are model for direct band absorption coefficient normalised to 1 at 1.31 μm for 300 K
- Experimental data follows indirect tails
- Discontinuity is due to 0.2% residual strain in the Ge splitting LH & HH
- Thicker Ge will increase SPDE
- 1550 nm operation requires thicker Ge & higher temperature operation
- 1550 nm operation also being pursued with GeSn (direct-band >1.7 μm at 4 K)

D.C.S. Dumas et al., Proc. SPIE 10914, 1091424-1 (2019)

Afterpulsing

- **Afterpulsing caused by traps in avalanche region: limit repetition rate due to dead time of detector**



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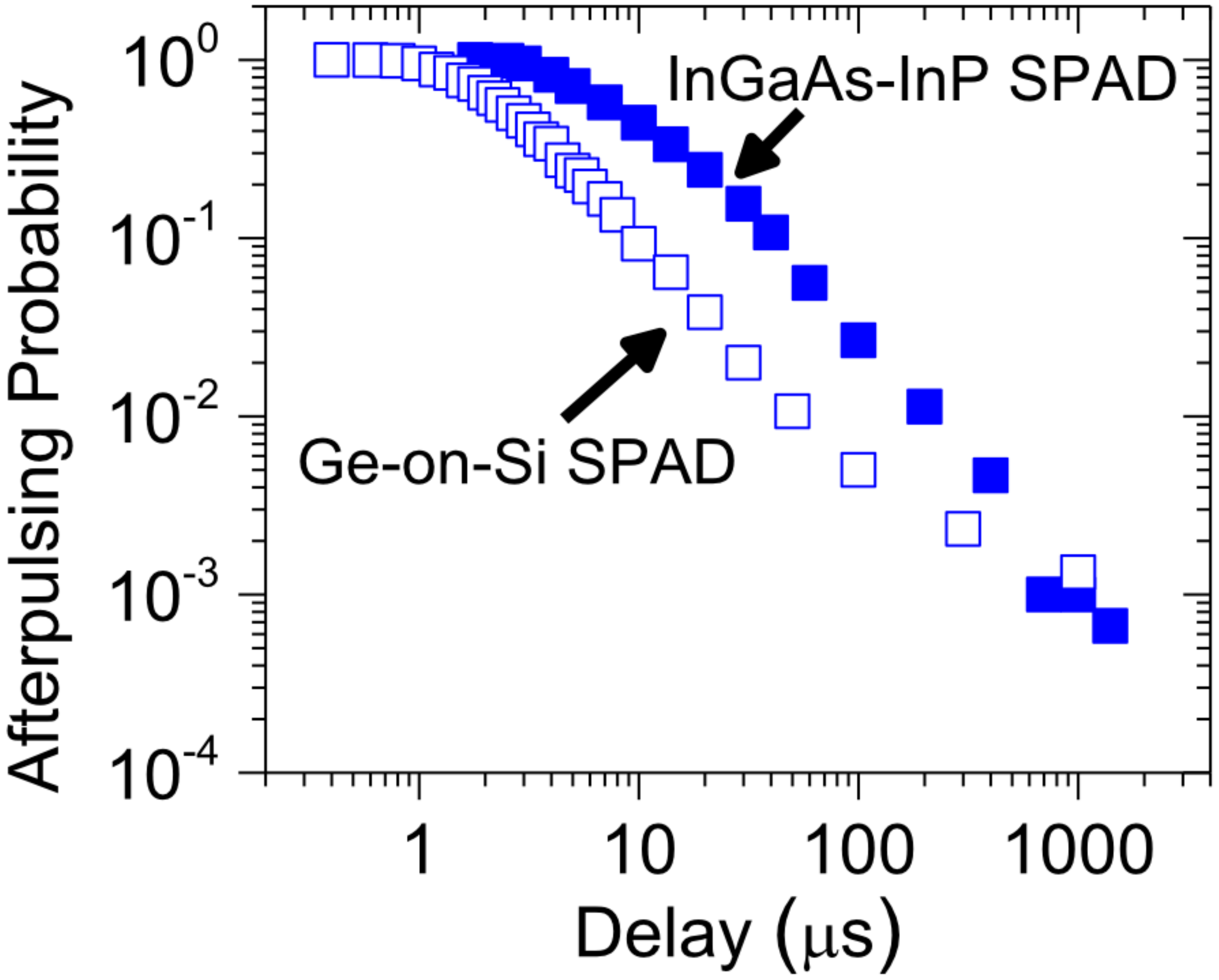
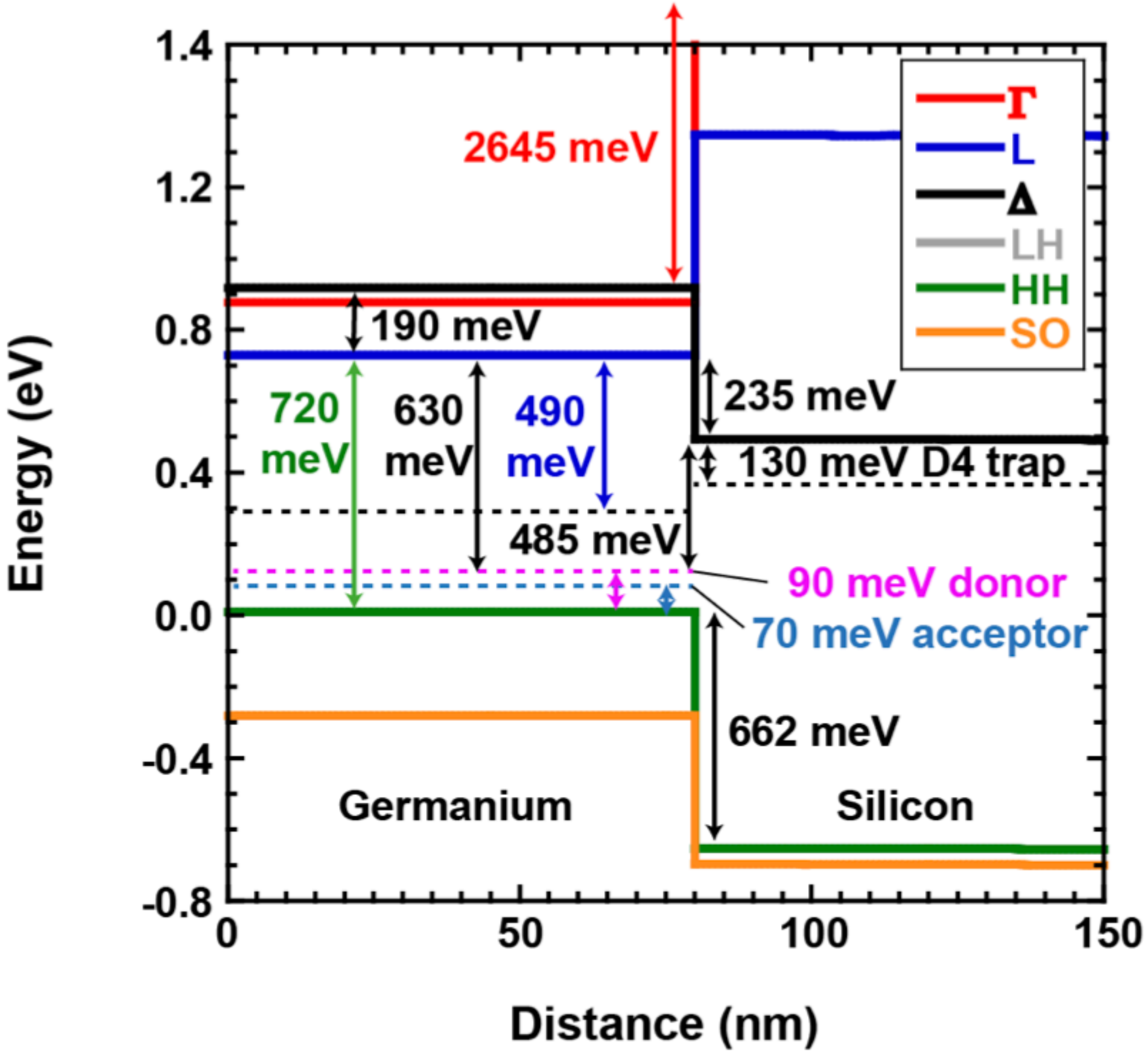


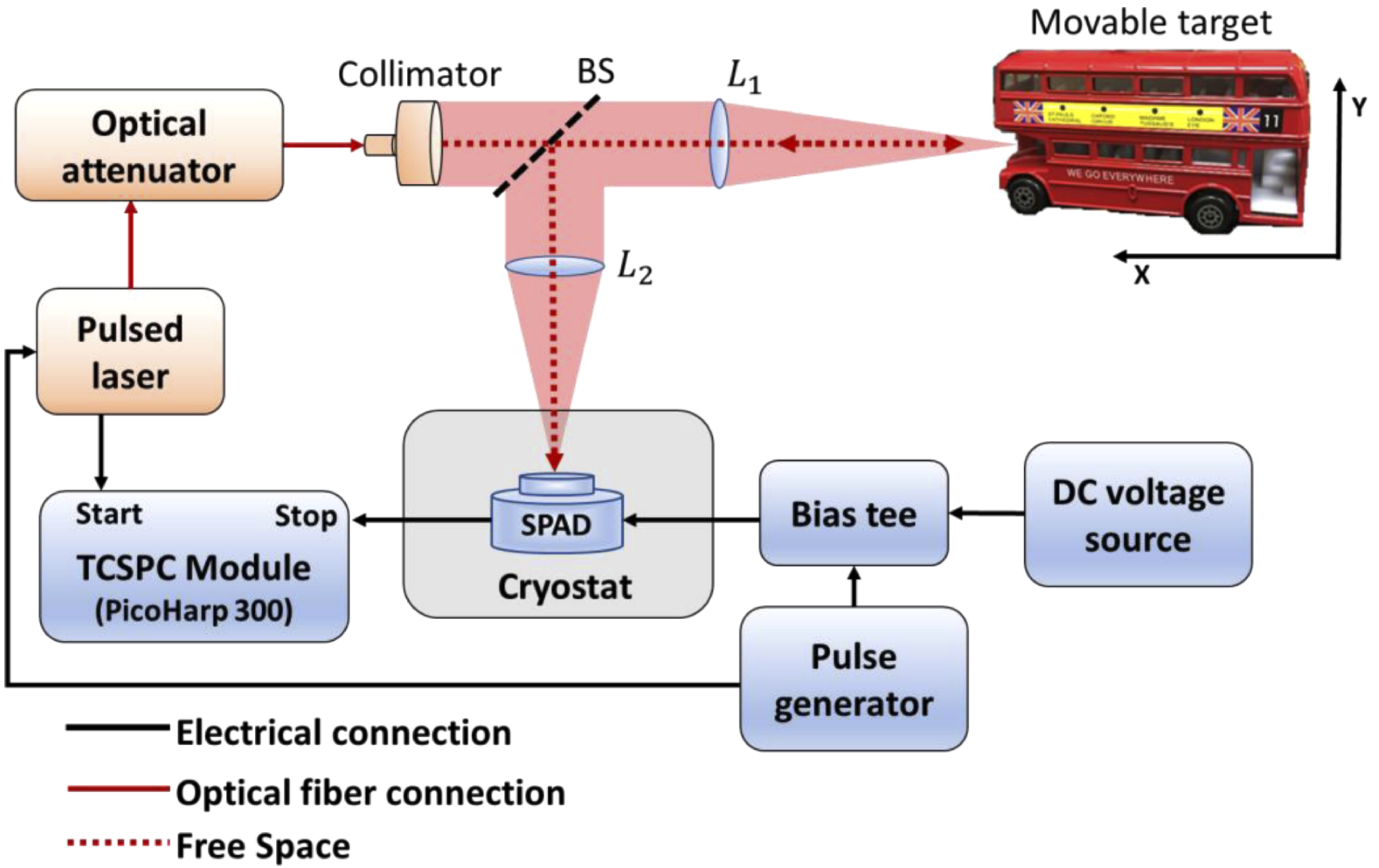
Ge and Si trap energies



P. Vines et al., Nature Comms. 10, 1086 (2019)

LIDAR Imaging

- 912 pW laser after attenuation
- λ = 1450 nm
- Repetition rate 104 kHz
- 100 μm diameter SPAD at 100 K
- V_{ex} = 1.5%, SPDE = 10%
- DCR = 4.7 MHz
- 23 mm aperture
- Mechanical raster of single pixel
- 100 x 70 pixel raster for images

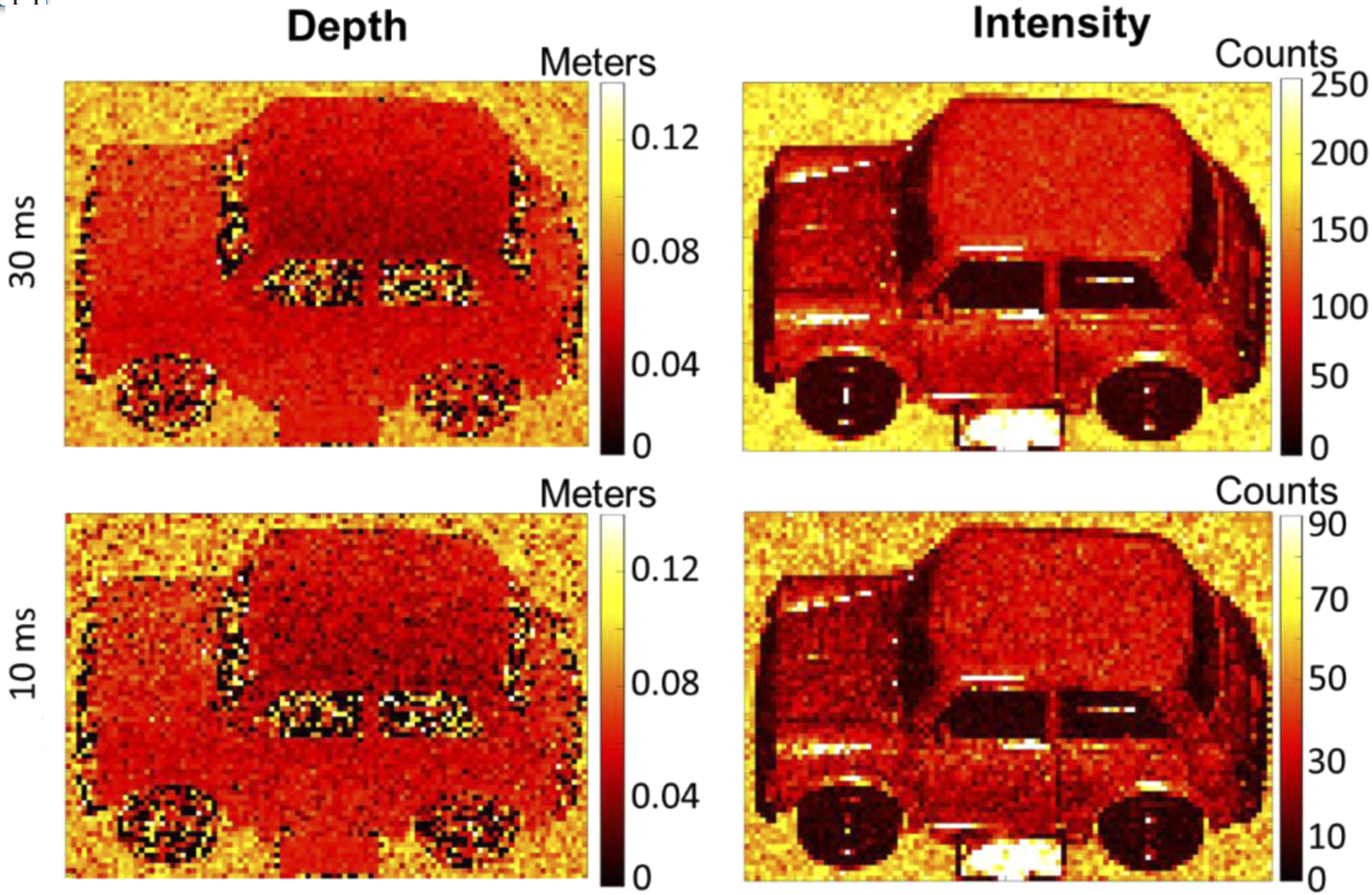


K. Kuzmenko et al., Opt. Exp. 28, 1330 (2020)

LIDAR with Ge on Si SPADs

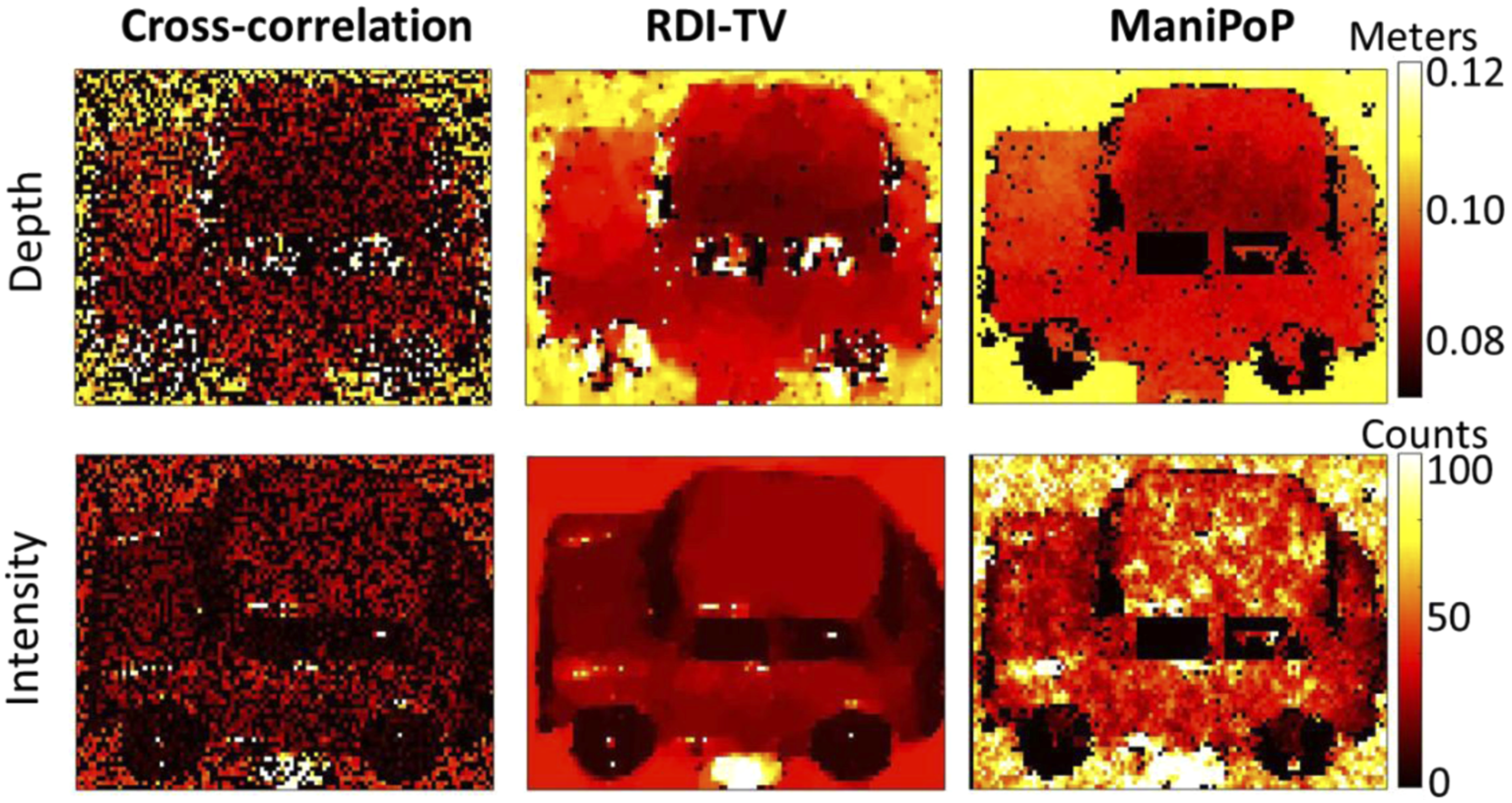
95mm x 60mm x 45mm (L x W x H)

- 912 pW laser
- λ = 1450 nm
- Repetition rate 104 kHz
- V_{ex} = 1.5%, SPDE = 10%
- DCR = 4.7 MHz
- 23 mm aperture
- 100 x 70 pixel raster



K. Kuzmenko et al., *Opt. Exp.* 28, 1330 (2020)

Noisy LIDAR Reconstruction



- **10 ms acquisition time with 50% of pixels removed**

K. Kuzmenko et al., Opt. Exp. 28, 1330 (2020)

LIDAR Performance Estimations

- Estimate of photon events recorded in timing bin corresponding to peak of photo return histogram:

$$n_p = \frac{E_{pulse} F \lambda}{hc} t \frac{A_{lens}\rho}{2\pi R^2} e^{-2\alpha R} C_{in} C_{det} \eta$$

- Background counts per bin:

$$n_b = tDCR\tau_b F$$

26 µm SPAD
DCR = 2.6kc/s

- Signal–to–noise

$$SNR = \frac{n_p}{\sqrt{n_p + n_b}}$$

- Average laser power required for successful imaging at distance R:

$$P_{out} = \frac{hc}{\lambda} \frac{2\pi R^2 n_p}{A_{lens}\rho t \eta C_{in} C_{det}}$$

E_{pulse} = laser pulse energy

F = laser rep. rate

λ = wavelength

t = acquisition time

A_{lens} = collection area of lens

ρ = reflectivity of target (= 10%)

R = distance to target

α = attenuation coefficient of environment

C_{in} = internal loss of system (= 10 dB)

C_{det} = temporal response of detector

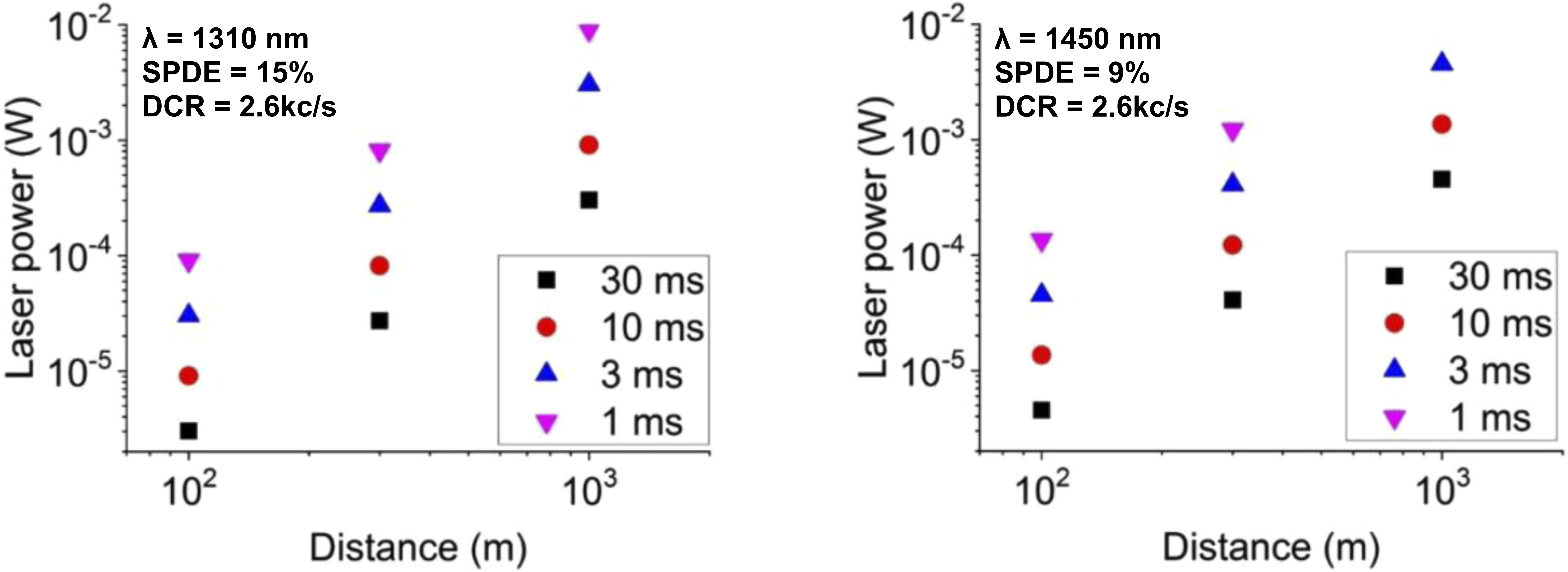
η = detector SPDE (= 15% or 9%)

τ_b = bin size (= 50 ns)

K. Kuzmenko et al., Opt. Exp. 28, 1330 (2020)

LIDAR Range

- 23 mm aperture lens with 26 µm Ge-on-Si SPAD operating at 125 K, 2.5% excess bias & 100 kHz rep. rate
- SNR = 1.4, internal system loss = 10 dB, reflectivity of target is Lambertian with 10% back-scatter

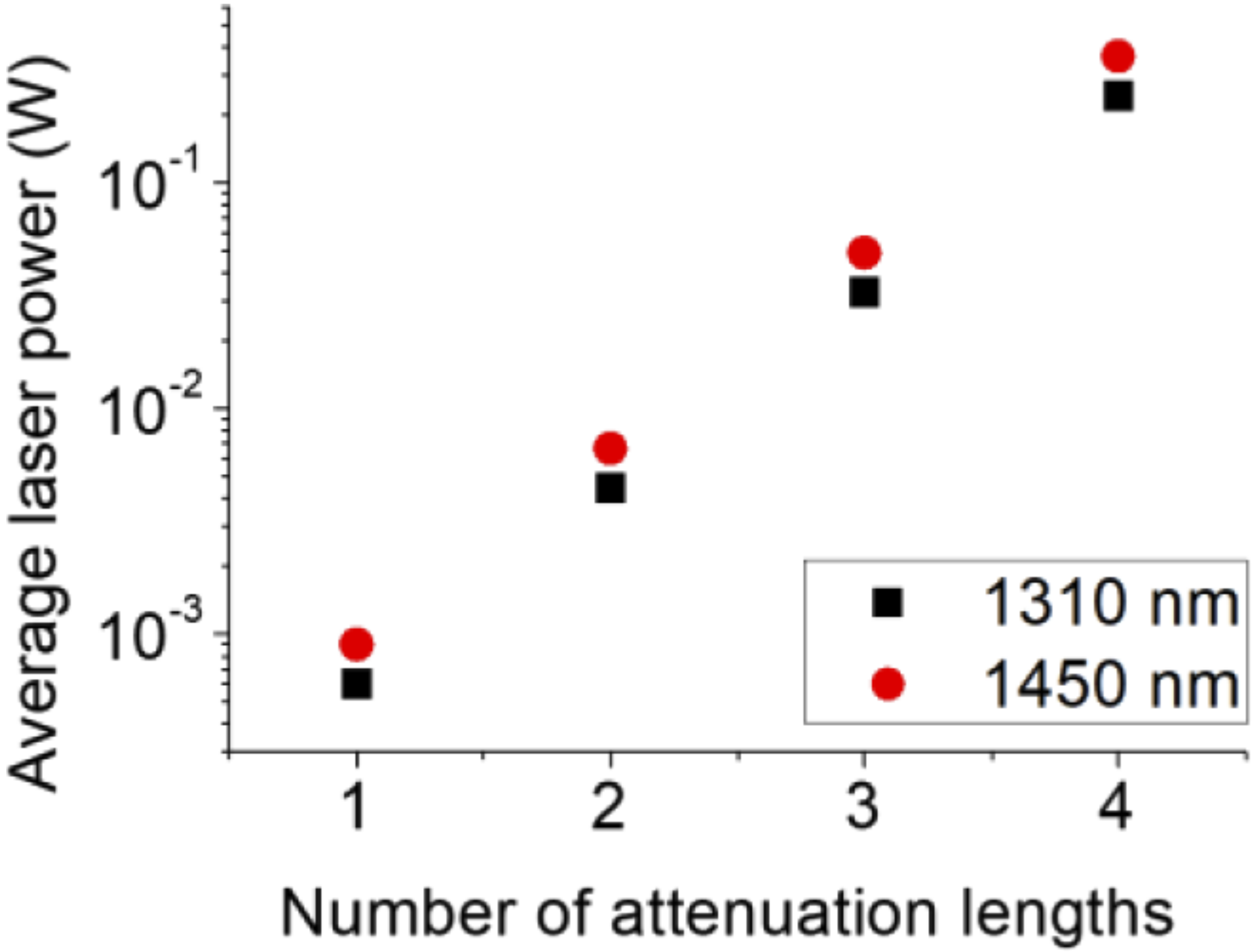


- ≥ 1 km range for LIDAR for eye-safe laser powers (IEC-60825-1) for ≥ 1 ms averaging per pixel

K. Kuzmenko et al., Opt. Exp. 28, 1330 (2020)

300 m Through Obscurants

- 23 mm aperture lens with 26 µm Ge-on-Si SPAD operating at 125 K, 2.5% excess bias & 100 kHz rep. rate



(to the target)

- 10 ms acquisition time per pixel
- Eye-safe lidar feasible for automotive motorway driving in weakly attenuating media
- Reconstruction algorithms & improved SPDE at longer λ will improve performance in obscurant media

K. Kuzmenko et al., Opt. Exp. 28, 1330 (2020)

Summary

- Planar design key resulting in 3 orders of magnitude reduction of DCR
- SPDE up to 38% at 1310 nm & 125 K
- NEP = 7.8 x 10^{-17} W/√Hz and 134 ± 10 ps jitter for 26 μm SPAD at 100 K
- Afterpulsing at least x5 lower than InGaAs under identical conditions
- Initial LIDAR demonstration at eye-safe wavelengths
- Aim for telecoms wavelengths on Si at Peltier cooler temperatures

- EPSRC QuantiC
- EPSRC Quantum Comms Hub
- EPSRC SPEXS Programme Grant
- InnovateUK AquaSec
- InnovateUK SPIDAR
- Dstl PhD scholarship

P. Vines et al., "High performance Ge-on-Si SPAD detectors" Nature Comms. 10, 1086 (2019)

K. Kuzmenko et al., "3D LIDAR imaging using Ge-on-Si SPAD detectors" Opt. Exp. 28, 1330 (2020)

Further details:
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