Superconducting photon detectors: past, present & future

Plenary PL-4

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36th International Superconductivity Symposium, Wellington, New Zealand 29th November 2023
Superconducting detectors & circuits @UoGARC

SuperQuARC: Professors Martin Weides & Robert Hadfield

Superconducting Quantum Devices Workshop SQD23 July 2023
SQD23 Chair Dr Kaveh Delfanazari

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Virtual Tour: https://www.gla.ac.uk/research/az/jwnc/
What is a Photon?

• Einstein: a Photon is packet of electromagnetic energy

\[ E = h\nu = \frac{hc}{\lambda} \]

• Energy (E) inversely proportional to wavelength (\( \lambda \))
Photon-counting technology

Wavelength

Detectors

Hadfield Nat. Photon. 3 696 (2009) ; Hadfield et al. Optica 10 1124 (2023)

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Photon-counting technology

Wavelength

<table>
<thead>
<tr>
<th>Photomultipliers</th>
<th>IR PMTs</th>
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<tbody>
<tr>
<td>Si SPADs</td>
<td>InGaAs SPADs</td>
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Photon-counting technology

**Wavelength**

- Visible: 400 nm
- Near-InfraRed: 1.6 μm

**Detectors**

- Photomultipliers
-IR PMTs
- Si SPADs
-InGaAs SPADs

**Components**

- ROIC
- GmAPD
- PDA
- MLA
- Ceramic interposer
- Housing
- Lid
- TEC

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<tr>
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<tr>
<td>Near-InfraRed</td>
<td>IR PMTs</td>
</tr>
<tr>
<td>1.2μm</td>
<td>Si SPADs</td>
</tr>
<tr>
<td>1.4μm</td>
<td>InGaAs SPADs</td>
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Typically superconducting energy gap $\Delta \sim \text{meV}$.

$\Rightarrow$ Superconductors make extremely sensitive detectors from X-ray to Terahertz wavelengths.

One optical photon creates $\sim 100$–$1000$ excited electrons (superconducting gap $\sim 2 \text{ meV}$ for NbN). cf semiconductor – one optical photon creates one electron-hole pair, typical band gap 1-2 eV).
Photon detection in superconductors

**Review:** Superconducting Photon Detectors
D Morozov, A Casaburi, RH Hadfield
Contemporary Physics 1-23 (2022)

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Superconducting photon detectors

Superconducting Tunnel Junction (STJ)
Peacock Nature 381 135 (1996)

Transition Edge Sensor (TES)
Lita Optics Express 16 3032 (2009)
Fukuda Optics Express 19 870 (2011)

Kinetic Inductance Detector (KID)
Zobrist APL 115 213503 (2019)

Superconducting Nanowire Single-Photon Detectors (SSPDs/SNSPDs)
Gol’tsman APL 79 705 (2001)
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Superconducting Nanowire Single-Photon Detector (SNSPD)

Key Properties

• Wide spectral range (UV – mid IR)
• Near unity detection efficiency possible
• Operates at 4 K (not mK)
• Free running (no gating required)
• Low dark counts
• Low timing jitter
• Short recovery time

A rapidly improving technology which is commercially available!

Morozov et al Superconducting Photon Detectors Contemporary Physics 1-23 (2022)


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Worldwide SNSPD community:
Bad Honnef, Germany, November 2018
Commercialization of SNSPDs worldwide

**DETECTORS**
- Russia Scontel
- USA PhotonSpot
- NL Single Quantum
- USA Quantum Opus
- Switz. ID Quantique
- China Photon Technologies
- Germany Pixel Photonics

**CRYOGENICS**
- UK Chase Research Cryogenics
- Japan Sumitomo Heavy Industries
SNSPDs – increasing active area

**Basic Device**


**Meander**


**Fibre Coupling**

Dauler et al Optical Engineering (2014)
SNSPDs – maximising detection efficiency

**Basic Device**


**Optical Cavity**

Rosfjord *et al* Optics Express **14** 527 (2006)

Miki *et al* Optics Express **17** 23557 (2009)

93% Marsili *et al* Nat. Photon. **7** 210 (2013) $\lambda=1550\text{nm}$

98.5% Reddy *et al* Optica **7** 1649 (2020) $\lambda=1550\text{nm}$

99% Chang *et al* APL Photonics **6** 036114 (2021) $\lambda=1310\text{nm}$

90.5% Zhang *et al* IEEE JSTQE **28** 3803708 (2022) $\lambda=1550\text{nm}$

84% China *et al* Optics Express (2022) $\lambda=2\mu\text{m}$

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SNSPDs – waveguide integration

**Basic Device**


**Waveguide Integration**

TU Eindhoven Sprengers APL **99** 18110 (2011)

Yale Pernice Nat. Comms **3** 1325(2012)

**64-channel QKD receiver**

Terhaar *et al*. Optics Express **31** 2675 (2023)

Pernice Munster/Heidelberg

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SNSPDs – low jitter

**Basic Device**


**3 ps timing jitter**


**NIR-MIR timing jitter**


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SNSPDs – low jitter

**Basic Device**


**3 ps timing jitter**

Korzh *et al.* Nat. Photon. **14** 250 (2020)

**MIR single-photon LIDAR**

SNSPD photon counting LIDAR at $\lambda = 2.3$ $\mu$m Glasgow/NICT

Taylor *et al.* Optics Express **27** 8147 (2019)

Hadfield *et al.* Optica **10** 1124 (2023)

News & Views Hadfield Nat. Photon. **14** 201 (2020)

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From nanowires to microstrips

**Basic Device**


**Microstrip**


**Microstrip with UV Stepper**

Yabuno *et al* IEEE TAS 2200104 (2023)

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Scale up to large SNSPD arrays

Basic Device

Row-Column readout

SFQ integration


- 32 x 32 kilopixel array (JPL/NIST)

- Low bias

- High bias

- ISS 2023 ED-1-1-INVS Miyajima


- Miyajima et al APL 122, 182602 (2023)
Scale up to large SNSPD arrays

**Basic Device**


**Single photon imager**


**400,000 pixel SNSPD array**

- A McCaughan *et al.* APL **121**, 102602 (2022)
- B. Oripov *et al.* Nature **622**, 730 (2023)

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SNSPDs – materials development

**Sputtering**
Reactive sputtering of NbN, TiN & NbTiN on room temperature or heated substrates
Sputtering of amorphous superconductors WSi, MoSi on room temp or cooled substrates
Plassys VI tool JWNC: deposition across 150 mm/6” wafers

A Banerjee *et al* Superconductor Science & Technology 30 084101 (2016)

**Atomic Layer Deposition**
Layer by layer growth of NbN and TiN
Enhanced superconducting properties through substrate bias (OIPT Yatton)
Atomic layer etch (ALE) processes under development (TU Eindhoven)
Conformal growth across 200 mm/8” wafers

M Dineen, H Knoops, T Hemakumara
C Lennon *et al* Materials for Quantum Technology 3 045401 (2023)
New materials for SNSPDs

Magnesium Diboride (MgB$_2$) SNSPDs

Shibata et al. APL 97 212504 (2010)
Cherednichenko et al. SUST 34 044001 (2021)

Niobium diselenide (NbSe$_2$) photodetector

Orchin et al. APL 114 251103 (2019)
Glasgow/Cambridge/Manchester
High temperature superconductor
SNSPDs

Single-photon detection using high-temperature superconductors

I. Charras-García\textsuperscript{1,3,4,5,6}, D. A. Bandurin\textsuperscript{1,3,4,5,6}, A. T. Bollinger\textsuperscript{1,7}, I. Y. Phinney\textsuperscript{1,7}, I. Drozdov\textsuperscript{2,5,6}, M. Colangelo\textsuperscript{1,3,4,5,6}, B. A. Butterb\textsuperscript{1,7}, T. Taniguchi\textsuperscript{1,7}, K. Watanebe\textsuperscript{1,7}, X. He\textsuperscript{4,5}, O. Medeiros\textsuperscript{1,7}, I. Bozovic\textsuperscript{1,7,8}, P. Jarillo-Herrero\textsuperscript{1,7,8} \& K. K. Berggren\textsuperscript{1,7,8}

Two-dimensional cuprate nanodetector with single telecom photon sensitivity at $T = 20\,\text{K}$

Rafael Luque Merino\textsuperscript{1,5,6}, Paul Seifert\textsuperscript{1,5,6}, José Durán Retama\textsuperscript{1,5,6}, Roop K Mech\textsuperscript{1,5,6}, Takashi Taniguchi\textsuperscript{1,7}, Kenji Watanebe\textsuperscript{1,8}, Kazuo Kadokawa\textsuperscript{1,8}, Robert H Hadfield\textsuperscript{1,8} \& Dmitri K Efetov\textsuperscript{1,5,8}

\textsuperscript{1}IFIC—Institut de Ciencies Fotoniques, The Barcelona Institute of Science and Technology, Castelldefels, Barcelona 08860, Spain
\textsuperscript{2}Institute of Physics, Faculty of Electrical Engineering and Information Technology (EIT 2), University of Bundeswehr München.

News & views

Superconducting single-photon detectors get hot

Jin Chang & Iman Esmaeeli Zadeh

High-T$_\text{c}$ superconducting nanowire detectors can detect single photons of telecom wavelengths at a temperature of 25 K and may enable applications in quantum sensing and quantum information processing.
**Frontier applications of superconducting photon detectors**

*Quantum Computing* (See session ED-5 & 9 for superconducting qubits)

- Photonic quantum computer platform with integrated SNSPDs (PsiQuantum/Global Foundries)
- Quantum advantage via boson sampling
  - SNSPDs (USTC China)
  - TES (Xanadu/NIST)
- Ion trap qubit with integrated SNSPD (NIST USA)

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**Photonic quantum computer platform with integrated SNSPDs**

- J L O’Brien *et al.* Quantum Australia (2023)
- Zhong *et al.* Science **370** 1460 (2020)
- Madsen *et al.* Nature **606** 75 (2022)
- Hampel *et al.* APL **122** 174001 (2023)
Frontier applications of superconducting photon detectors

Dark Matter Searches

If you look at what the universe is made of, like a pie chart:

- 5% - stuff we know
- 25% - dark matter
- 70% - we have no idea

The universe is made of dark matter, which has a mass 5 times as heavy as all the matter we know about.

Halo (dark matter)
Spiral disk (visible stars)
Subhalos (dark matter)

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Frontier applications of superconducting photon detectors

**Dark Matter Searches**

TES for ALPS II Dark Matter Experiment

SNSPDs for Dark Matter Searches

Sensitivity improves with larger mass (larger active area) SNSPD => challenge to scale from 100 μm devices to full wafers

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**Figure 1.** Sketch of the LAMPOST concept. The dark photon dark matter field A' converts to photons in a layered dielectric target. These photons are focused by a lens onto a small, low-noise SNSPD detector.

**Figure 2.** The LAMPOST prototype telescope apparatus. (a) Exploded view with element details. Inset:

J. Chiles et al Physical Review Letters 128 (23), 231802 (2022)

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Frontier applications of superconducting photon detectors

**Deep space optical communications**

- **Space to ground quantum comms**
  - Yin *et al.* Science 356 1140 (2017)

- **Single photon optical comms for space**
  - NASA LADEE lunar orbiter 2014
  - NASA DSOC on board Psyche mission launched October 2023

- **Interstellar optical comms:** Breakthrough Starshot
  - Phase 1 projects started 2021 – planned for launch 2050 & data 2075
Superconducting photon detectors: past, present & future

Conclusions

• Superconducting detectors are an important quantum technology for infrared photon counting.

• Superconducting Nanowire Single-Photon Detectors (SNSPDs) have undergone rapid development and commercial translation.

• Important avenues for ongoing SNSPD development include new materials, photonic integration enhancing mid-infrared performance and large scale arrays.

• New photon-counting applications for superconducting detectors include photonic quantum computing, dark matter searches and deep space optical communications.

Robert Hadfield PL-4
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Heriot-Watt University UK – Gerald Buller, Jonathan Leach, Peter Connolly, Aongus McCarthy

University of Edinburgh UK – V J Aravind, Robert Henderson

DESY Hamburg Germany – Axel Lindner, Friederike Januschek

PTB Germany – Joern Beyer

NIST USA – Sae Woo Nam, Adriana Lita

NICT Japan – Shigehito Miki, Masahiro Yabuno, Hirotaka Terai

NASA JPL USA – Matthew Shaw, Boris Korzh

ASU USA – Phillip Mauskopf

University of Cambridge UK – Andrea Ferrari, Domenico Di Facio

LMU Munich Germany UK – Rafael Luque Merino, Dmitri Efetov

University of Manchester UK – Roman Gorbachov

TU Eindhoven NL – Harm Knoops, Silke Peeters