Superconducting strip photon detectors and quantum applications

SSPD/SNSPD: also known as Superconducting Nanowire Single Photon Detector

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Content

- Background & Introduction
- SSPD with high SNR
- Quantum Applications
- Summary
Superconducting sensors and detectors

SC Sensors and Detectors may provide unparallel performance
There are $\sim 10^{20}$ photons per sec for a 10 Watts lamp.
Single Photon Detector (SPD)

- **PMT**
  - High Bias Voltage ~ kV

- **APD**
  - Voltage Bias: ~ 10V
  - Current Bias: ~ 10μA

- **SSPD**
  - Since 2001

Gol'tsman APL 2001
Detection Mechanism

Cooper pair breaking by single photon

Photon energy vs Superconducting gap/Cooper Pair energy

hν (1eV) vs 2Δ (6.4 meV)

* Ultrathin nanowire (~5 nm thick and ~100 nm wide)

# SPD performances @ 1550 nm

<table>
<thead>
<tr>
<th>SPD</th>
<th>SDE (％)</th>
<th>DCR (cps)</th>
<th>CR (Hz)</th>
<th>TJ (ps)</th>
<th>Temp (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SSPD (NbN)</td>
<td>~ 98</td>
<td>≤ 1</td>
<td>≥ 1 G</td>
<td>≤ 10</td>
<td>~ 2.1 K</td>
</tr>
<tr>
<td>STJ (Al)</td>
<td>60</td>
<td>N/A</td>
<td>5 K</td>
<td>N/A</td>
<td>&lt; 1K</td>
</tr>
<tr>
<td>TES (W)</td>
<td>95</td>
<td>~ 0</td>
<td>100 K</td>
<td>100 ns</td>
<td>0.1 K</td>
</tr>
<tr>
<td>InGaAs APD</td>
<td>20</td>
<td>16K</td>
<td>100 M</td>
<td>55</td>
<td>200 K</td>
</tr>
<tr>
<td>IR PMT</td>
<td>2</td>
<td>200 K</td>
<td>10 M</td>
<td>300</td>
<td>Room Temp</td>
</tr>
</tbody>
</table>

**Notes:**
- **APD**
- **APD module**
- **SSPD**
- **15 x 15 x 10 mm**
- **Pride/Sumitomo**
- **600(H)**
- **IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 55, January, 2024. Invited presentation given at EUCAS 2023, September 6, 2023, Bologna, Italy**
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SSPD System

1. SSPDs
2.1 Cryostat
2.2 Mechan Pump
2.3 Compressor
2.4 Cryostat inside
3. Electronics

SSPD systems (1.2 m high Rack)

SSPD chip & cryostat
SDE & Optics

SDE = Opt Coupling × Absorption × IDE

Active area: 15*15 um²
OC > 95%

7 nm NbN for 1550 nm
Abs: ~30%

IDE ~100%

✓ Active Area
✓ Spot Size
✓ Thickness
✓ Linewidth
✓ pitch
✓ Opt Structure
✓ Thickness (Tc)
✓ linewidth
✓ Uniformity
✓ Current crowding

Challenges in Design: Entangled factors;
Challenges in Fabrication:
5 orders of Mag in 3-D, ultra uniform ~5nm thick, t: w: l ≈ 1: 20: 200,000

0.99x0.99x0.99=0.97

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Improvement on absorption

Simulation of absorption for different structures
High DE NbN SSPD @1550 nm

SCMPA 60: 120314, 2017

AIP Adv 8: 115022, 2018

NbN SSPD with SDE > 90% & DCR<100 cps @ 2.1 K

Compatible with compacted cryocooler, lower TJ, wider temperature range
High DE WSi and MoSi SSPD

WSi SDE 93% @120 mK @1550 nm by Marsili, NIST, Nat Photon 7, 210 (2013)

MoSi SDE 96% @700 mK @1550 nm by Reddy, NIST, FF1A CLEO 2019
Break the trade-off in NbN SSPD

\[ \eta_p(d) = \frac{\eta_0}{(1 + kd)^n} \]

Twin-Layer structure

Ion irradiation

IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 55, January, 2024. Invited presentation given at EUCAS 2023, September 6, 2023, Bologna, Italy
We were able to tune superconductivity of NbN nanowires, thus, tune IDE/SDE of SSSPD.
Tune ABS with twin-layer film

- Adopt twin-layer NbN film, guarantee the ABS and IDE simultaneously
- Highest SDE is 98%

Results from Other groups

Superconducting nanowire single-photon detectors with 98% system detection efficiency at 1550 nm

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MoSi on DBR mirror by NIST

Detecting telecom single photons with (99.5±0.5)% system detection efficiency and high time resolution

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NbTiN on SiO2/Au by TUDelft
Background DCR
~ 10-100 cps

Spectral dependencies of bDCR

Intrinsic DCR
Ib sensitive, vortex related
Origin of iDCR

Conclusion: iDCR of typical SSPDs is contributed by the single (weakest) defect/constriction
Fight with current crowding effect

Crowding effect in bending area
J. R. Clem and K. K. Berggren.
PRB 84 174510 . (2011)

I_{sw} of SSPDs with thicker bending area
for different filling ratios

SSPDs with thicker bending area

Maximum SDE $\uparrow$, DCR & TJ $\downarrow$

SUST 35: 055015 (2022)
SSPDs with high SNR

Patents issued in USA, JP and CN

AO 54: 96 (2015)
SUST 31: 035012 (2018)

Customized Chip filter w/ loss of 0.34 dB in passband (1550+1 nm) and ultrawide stopband up to 2.2 um

SDE > 90% with DCR ~ 0.5 cps

SDE ~ 54.1%, DCR ~ 0.005 cps
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SSPD plays indispensable role in QIP
Requirements from QI

**QKD**

\[ K_u \text{ (final secure key rate)} \propto f \cdot \mu \cdot L \cdot \text{DE} \]

\[ \text{ER} \propto \frac{R_{dc}}{K_u} \]

SPD: High DE, Low DCR, High Speed

At least 4 SPDs for BB84

**Quantum Comput/Sim**

\[ CC(n) = \frac{R_{pump}}{n} \cdot \left( \eta_{QD} \cdot \eta_{de} \cdot \eta_{C} \cdot \eta_{SPD} \right)^n \cdot S \]

SPD: High Speed, High SDE, PNR

50 qubits need 100 SPDs

High performance SPD is indispensable for QI
SSPDs for Quantum Key Distribution

Univ of Geneva 2018: 420KM OW-QKD
PRL 121: 190502 (2018)

USTC 2014: 200 km MDI-QKD

NTT 2010 Tokyo QKD Network
OE 19: 10387 (2011)

USTC 2015-16:
200 km² MDI-QKD network
404 km MDI-QKD

NTT 2007: QKD over 40 dB loss fiber
DE (~1%@DCR50Hz)
Nat Photon 1, 343 (2007)

NIST 2006: 1st QKD demo using SSPD
With DE (10%) by R. Hadfield
APL 89: 241129. (2006)

USTC 2020/21 & Toshiba UK/21:
500-800 km TF-QKD Lab/Field

Collaborated with JW Pan
- PRL 113: 190501. (2014)
- PRX 6, 011024 (2016).
- PRL 125: 260503. (2020)
- PRL 126: 250502. (2021)
- PRL 128: 180502. (2022)
- PRL 130: 210801 (2023)
SSPDs for Optical Quantum Computation

UStC 2017:
1st Boson Sampling using SSPDs

USTC 2018:
➢ Scalable Boson Sampling with photon loss (13 SSPDs)
➢ 12-Photon Entanglement and Boson Sampling (24 SSPDs)

USTC 2019:
20-photon Boson Sampling (~48 qubits) (60 SSPDs)

USTC 2020/21:
➢ JIUZANG: 76/113 qubits Boson Sampling
➢ 100/144 SSPDs in 7/10 cryostats, SDE ~0.81/0.83

Collaborated with JW Pan
- PRL 118, 190501 (2017)
- Science 4: 070501. (2020)
- PRL 127: 180502. (2021)
- PRL 130: 190601 (2023) for graph theory

IEEE-CSC, ESAS and CSSJ SUPERCONDUCITIVITY NEWS FORUM (global edition), Issue No. 55, January, 2024. Invited presentation given at EUCAS 2023, September 6, 2023, Bologna, Italy
**Bell inequalities**

2 WSi SNSPDs: DE ~91% @1550nm

*PRL 115, 250402 (2015)*

**Strong Loophole-Free Test of Local Realism**

**QRNG**

2 SNSPDs: DE ~90% @1550nm

*PRL 120, 010503 (2018)*
*Nature 562: 548 (2018)*

**QRNG w/o both detectors and nonlocality loop holes**

**Quantum Memory**

2 SNSPDs: DE ~50% @1342nm

*Nature 578: 240. (2020)*

**Entangl. of two quant mem via fibres over 50 km**
SNSPDs for LIDAR

LIDAR system for Atmosphere

Continuous measurements for 3 days, 6 km (CO2, HDO, Wind Speed, direction et al ...)

SNSPD with $\varphi200\mu m$ by USTC group (Prof. DouXK & XiaHY) for distributed free-space spectroscopy
Latest Quantum Applications

### Long haul QKD

- 2 ULDCR SSPDs: DE60%@DCR0.014cps

**PRL130: 210801 (2023)**

- 1002 km Fiber based SNS-TF-QKD, 48kbps in 202 km fiber

### High rate QKD

- 8-pixel SSPD array: DE78%max, 552Mcps@DE62%

**Nat Photon 17: 416 (2023)**

- First SKR QKD over 110 Mb/s in 10 km fiber

### Solving Graph Problems

- 144 SNSPDs: Ave. SDE ~83%@1550nm

**PRL 130: 190601 (2023)**

- Solving Graph Problems using NISQ JIUZHANG 3.0
Niche market

- ≥ 7 company players in the world;
- Estimated sales ~40MUSD (~ 240 sets) / Y2022
Conclusion

- SNSPD outperforms semiconducting counterparts
- Many applications of SNSPD for QIP
- Niche market available for SNSPD