EUCAS2023
Bologna, Italy
3rd-7th September

Superconducting strip photon detectors and quantum applications

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

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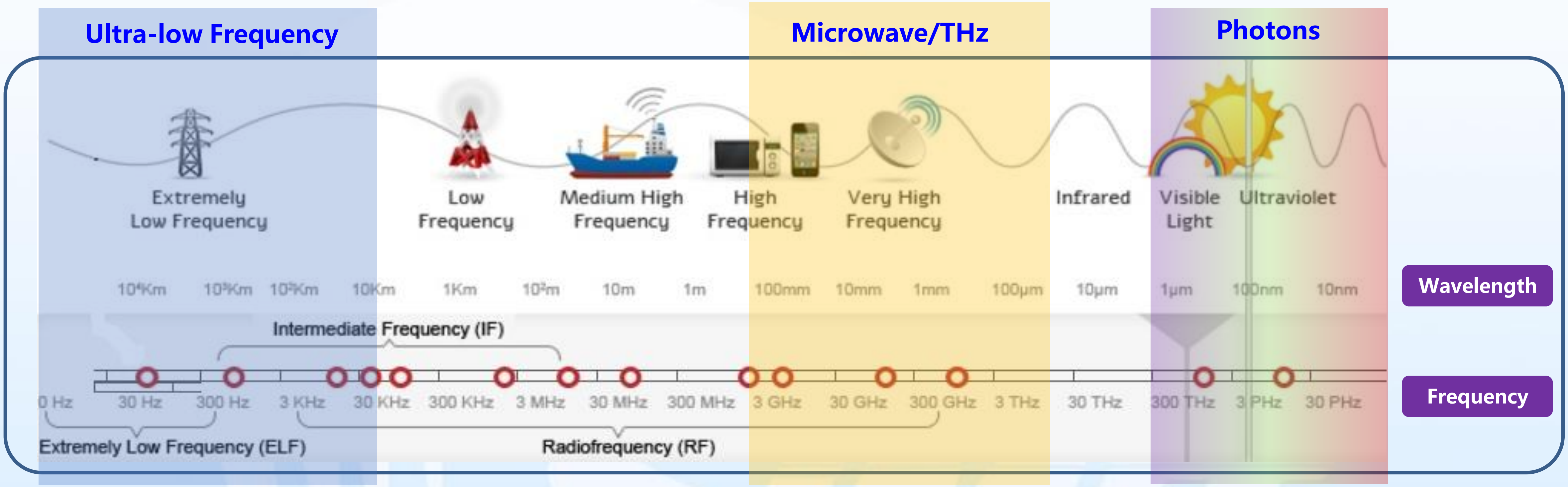
赋同量子
PHOTEC

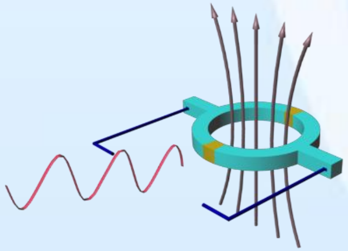
Content

- Background & Introduction
- SSPD with high SNR
- Quantum Applications
- Summary

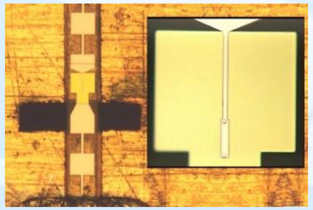
IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 55, January, 2024. Invited presentation given at EUCAS 2023, September 6, 2023, Bologna, Italy

Superconducting sensors and detectors

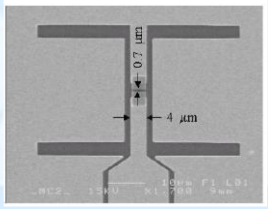




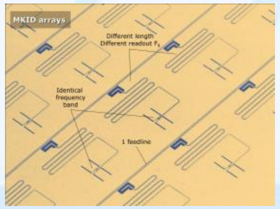
SQUID



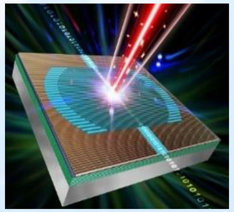
SIS/STJ



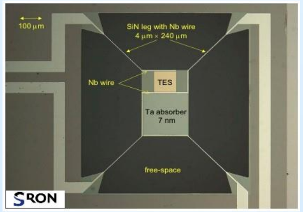
HEB



MKIDs



SSPD



TES

SC Sensors and Detectors may provide unparallel performance

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About a photon

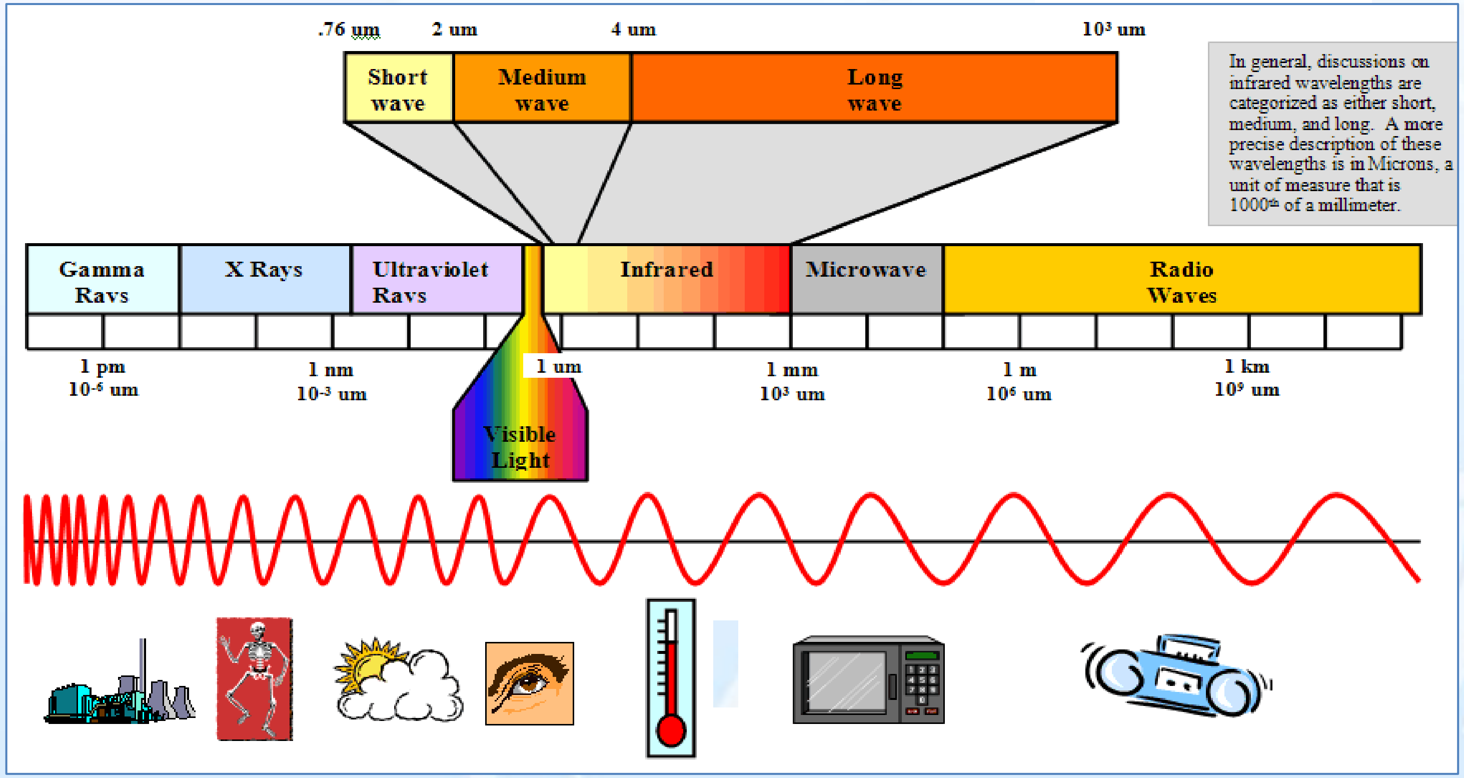
Photon Energy

$$E = \frac{hc}{\lambda}$$

h = 6.626 × 10^{-34} joule·s

c = 2.998 × 10^8 m/s

$$E(eV) = \frac{1.24}{\lambda(\mu m)}$$

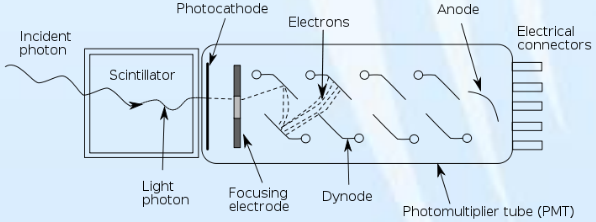


1.5 μm ~ 0.8 eV
~ 1.3 x 10^{-19} J
~ -169 dBm

There are ~ 10^{20} photons per sec for a 10 Watts lamp.

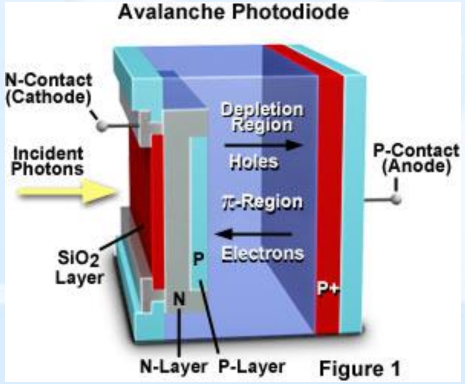
Single Photon Detector (SPD)

PMT



High Bias Voltage ~ kV

APD

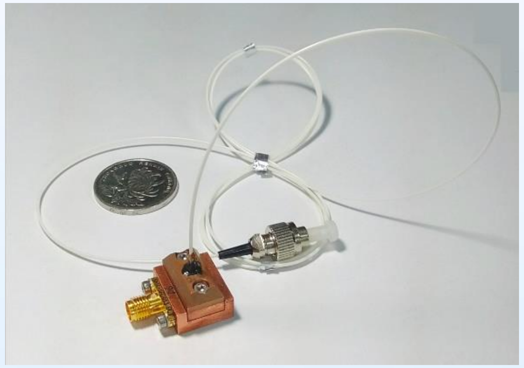


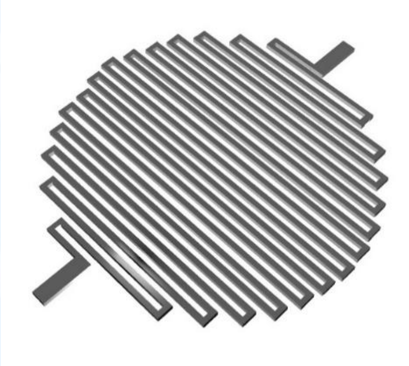
Voltage Bias： ~10V

SSPD

Since 2001

Gol'tsman APL2001



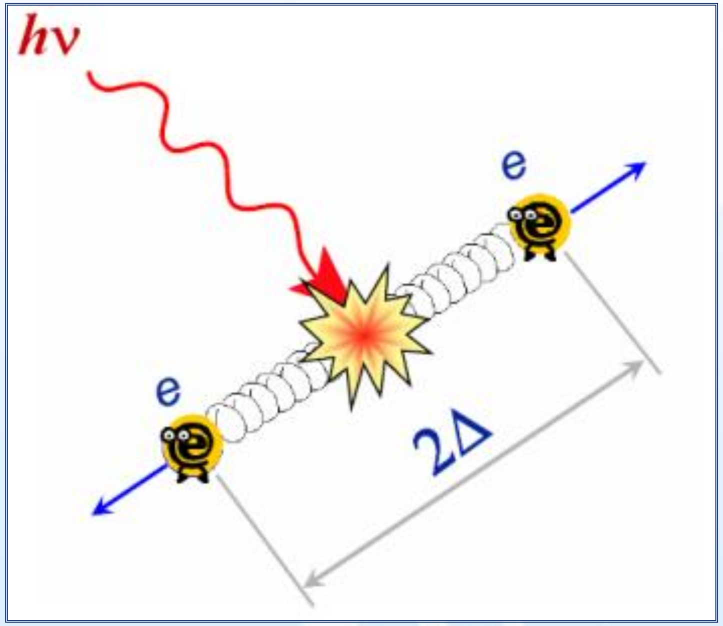


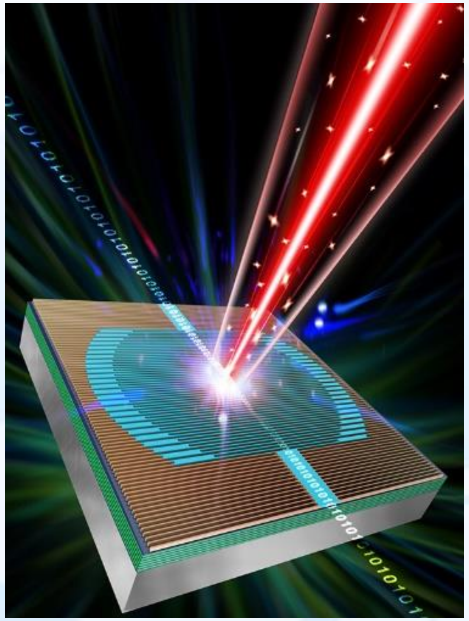
Current Bias： ~ 10μA

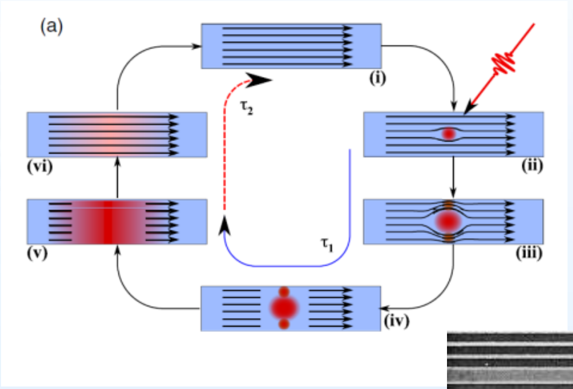
Detection Mechanism

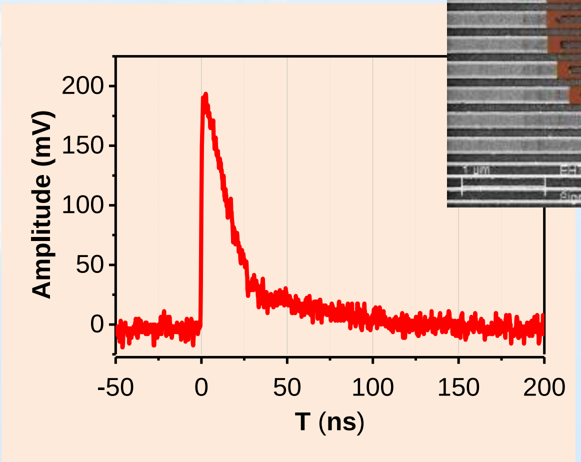
Cooper pair breaking by single photon

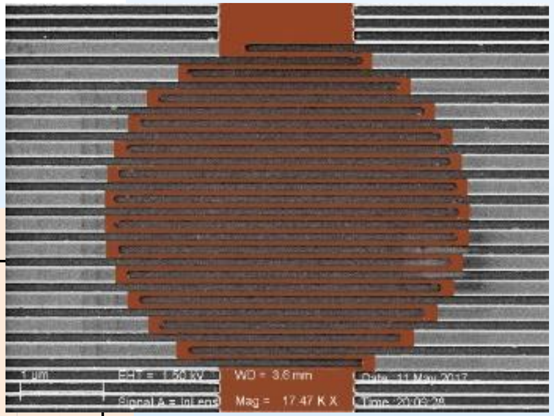
Goltsman et al, Appl Phys Lett, 2001, 79:705











Photon energy vs Superconducting gap/Cooper Pair energy

hν (1eV) vs 2Δ (6.4 meV)

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

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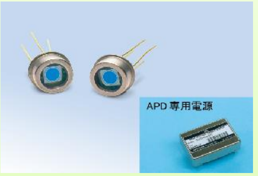
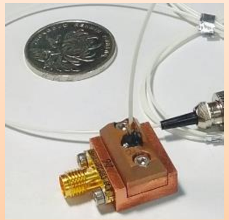
SPD performances @ 1550 nm

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



APD

APD module



SSPD
15 x 15 x 10 mm

l350 x 400 x 450mm
Power : 1.3 kW
Pride/Sumitomo

600(H)

Content

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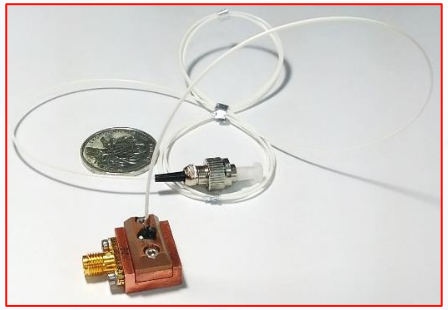
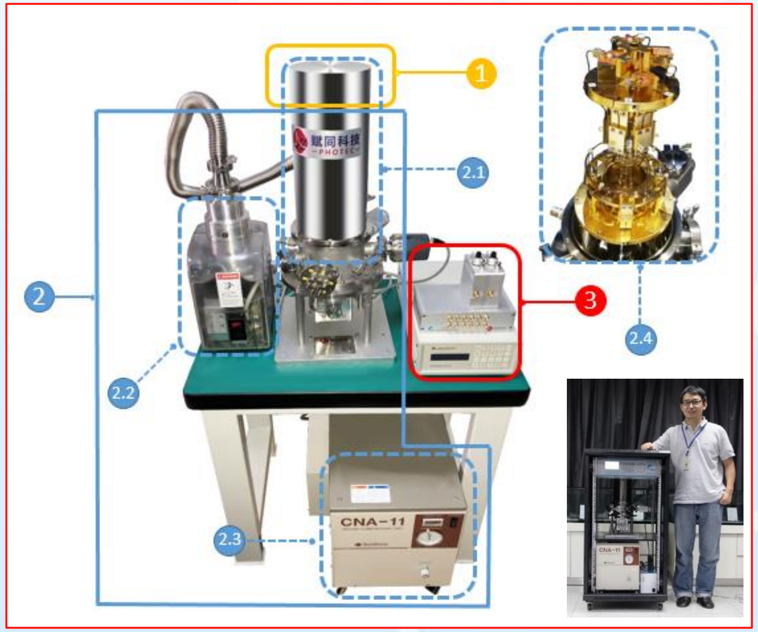
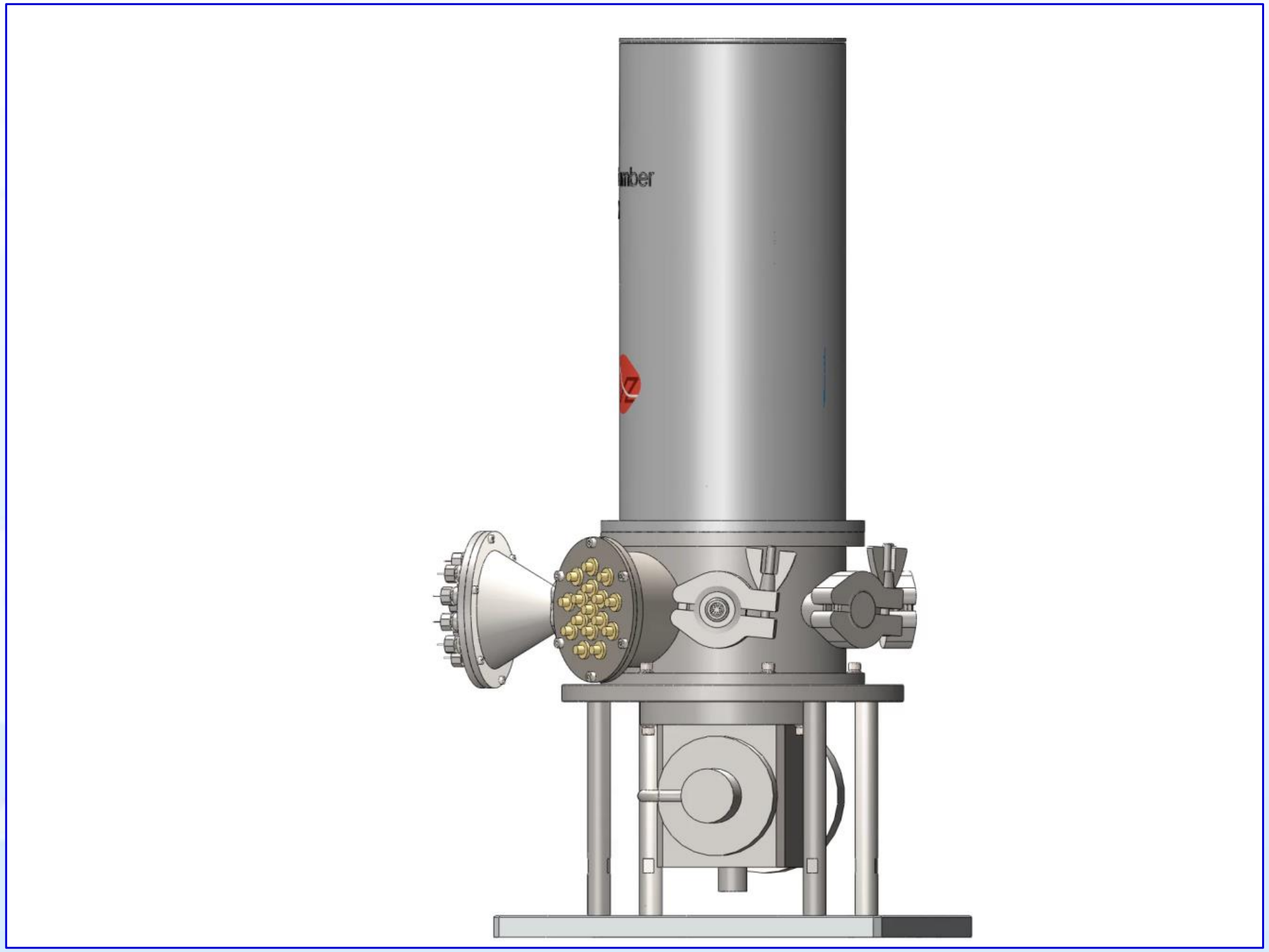
SSPD System

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





SSPD systems (1.2 m high Rack)

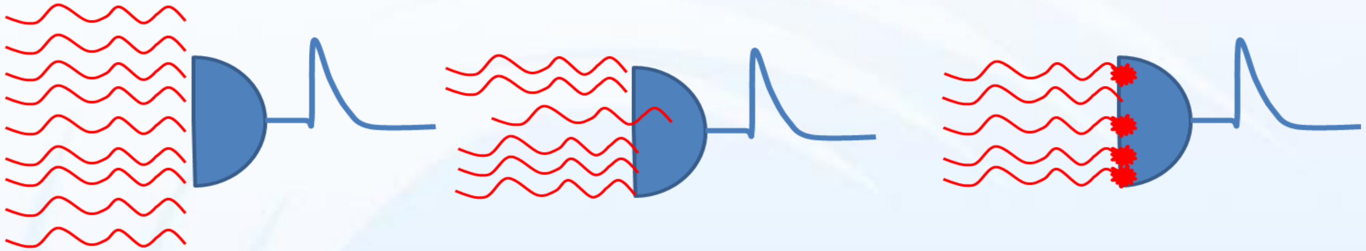


SSPD chip & cryostat

SDE & Optics

SDE = Opt Coupling × Absorption × IDE

0.99x0.99x0.99=0.97



Active area: 15*15 um^2
OC > 95%

7 nm NbN for 1550 nm
Abs: ~30%

IDE ~100%

- ✓ Active Area
- ✓ Spot Size

- ✓ Thickness
- ✓ Linewidth
- ✓ pitch
- ✓ Opt Structure

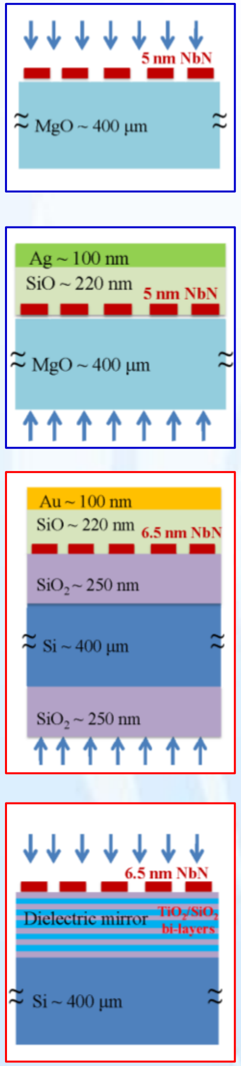
- ✓ Thickness（Tc）
- ✓ linewidth
- ✓ Uniformity
- ✓ Current crowding

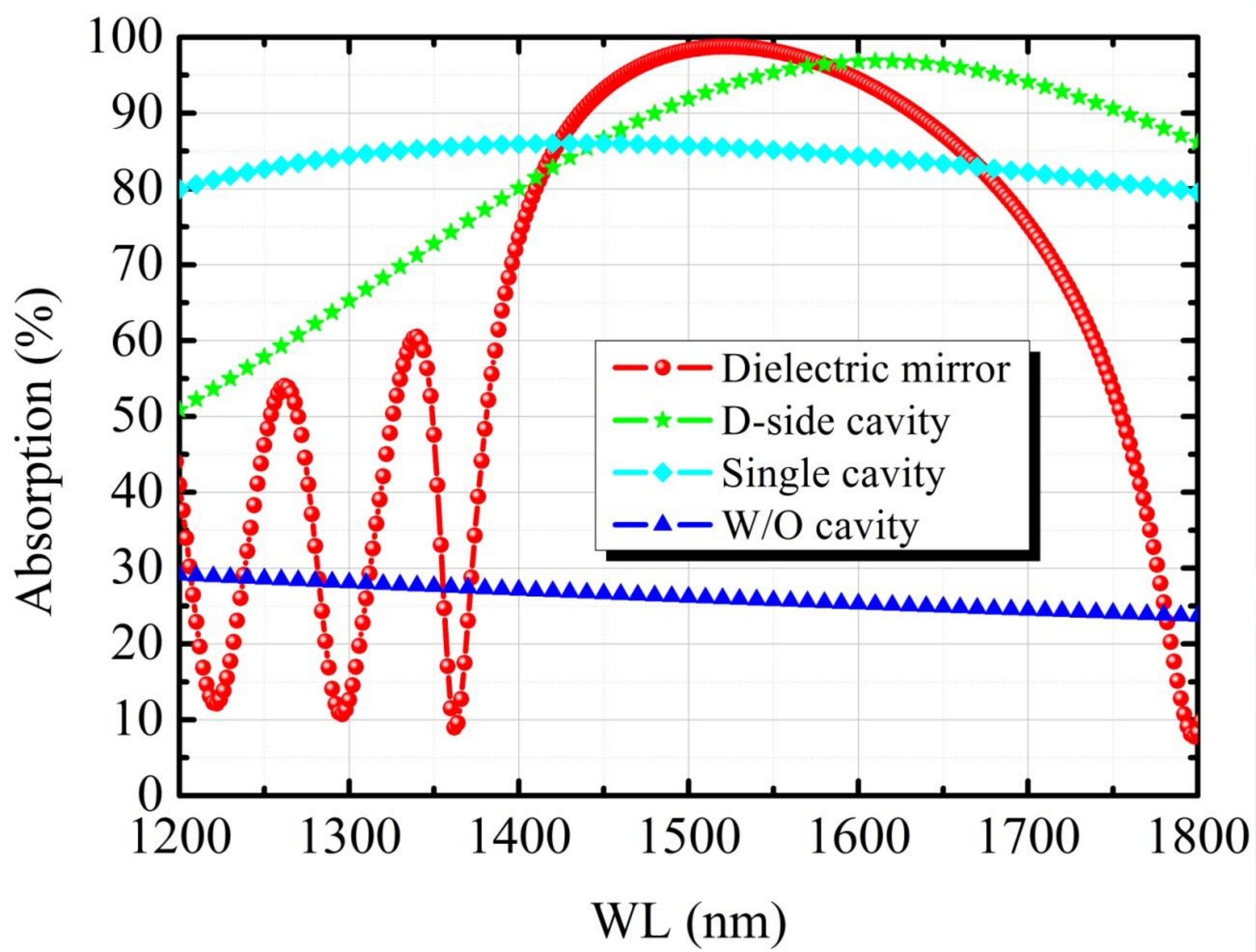
Challenges in Design: Entangled factors;

Challenges in Fabrication:

5 orders of Mag in 3-D, ultra uniform ~5nm thick, t: w: l ≈ 1: 20: 200,000

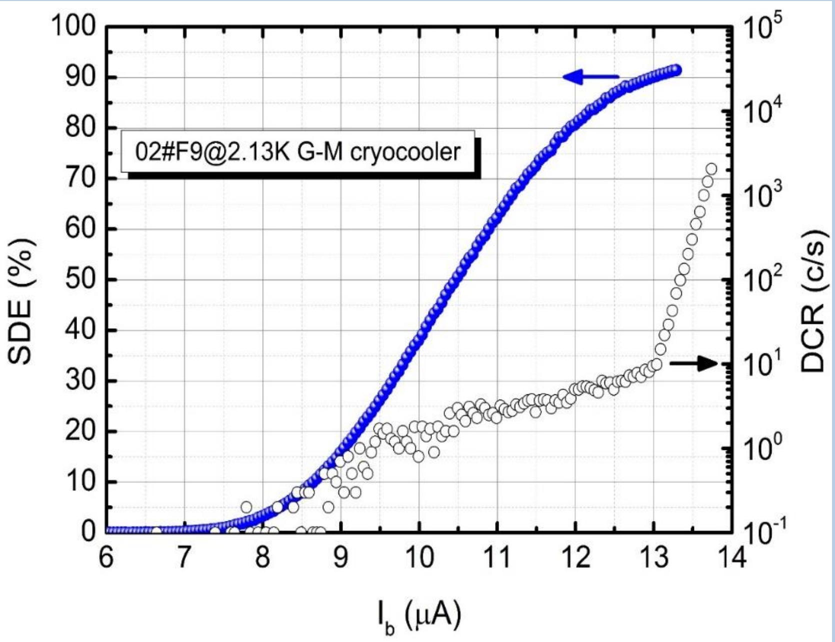
Improvement on absorption



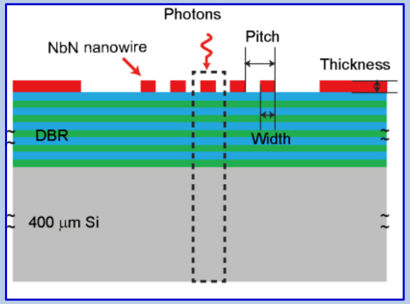


Simulation of absorption for different structures

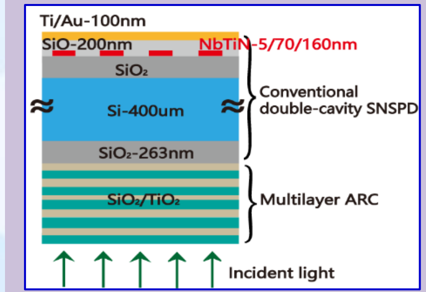
High DE NbN SSPD @1550 nm



SCMPA 60: 120314, 2017

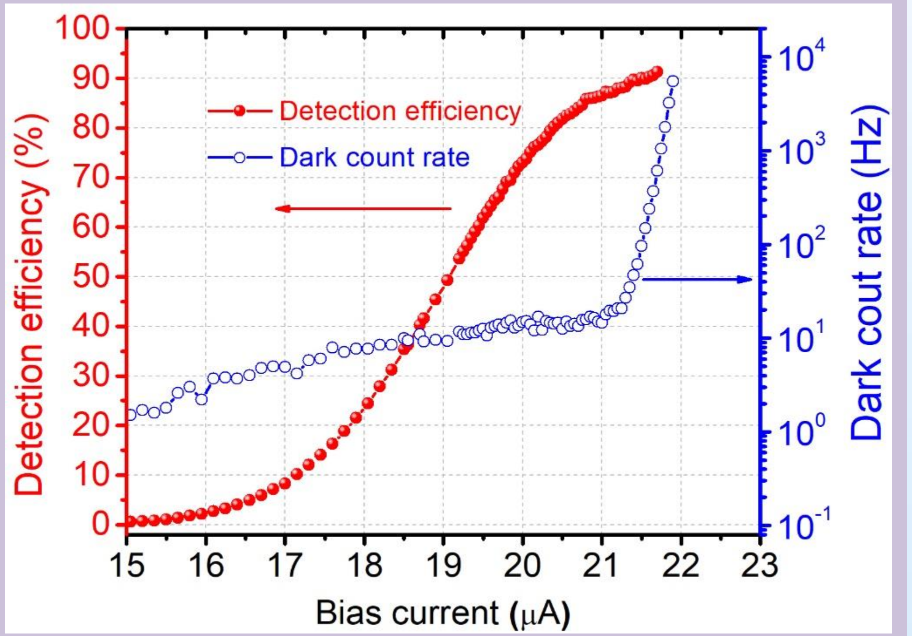


Top illumination



Bottom illumination

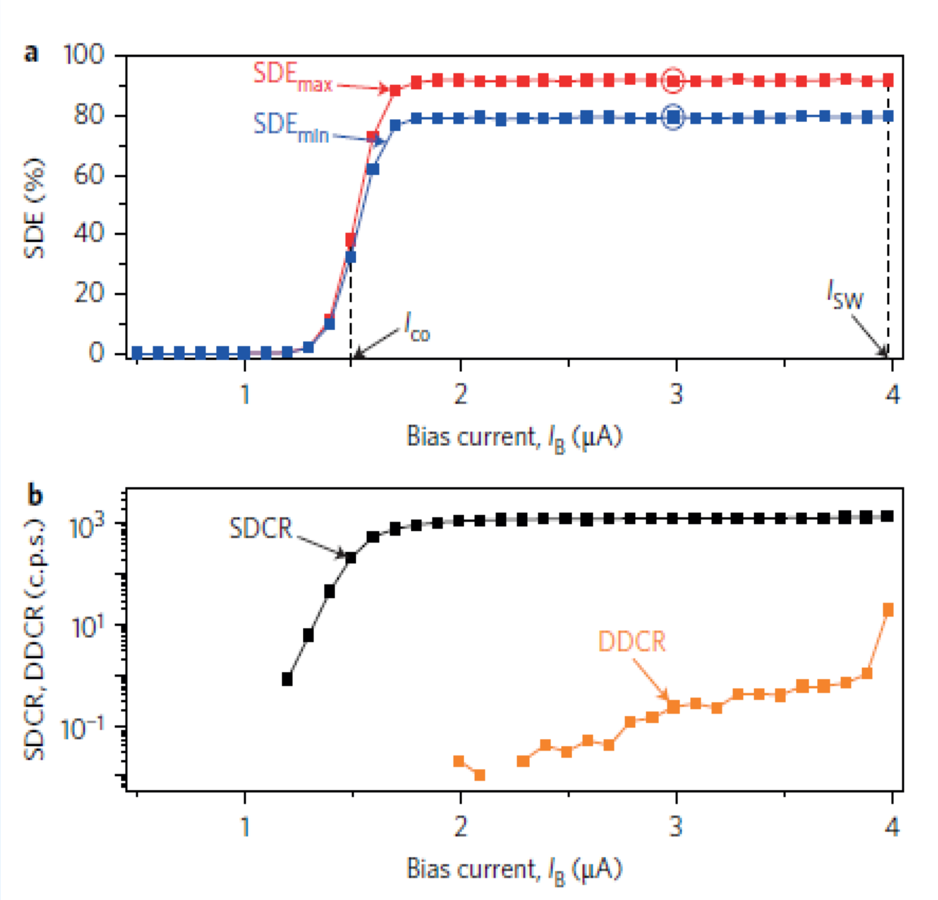
AIP Adv 8: 115022, 2018



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



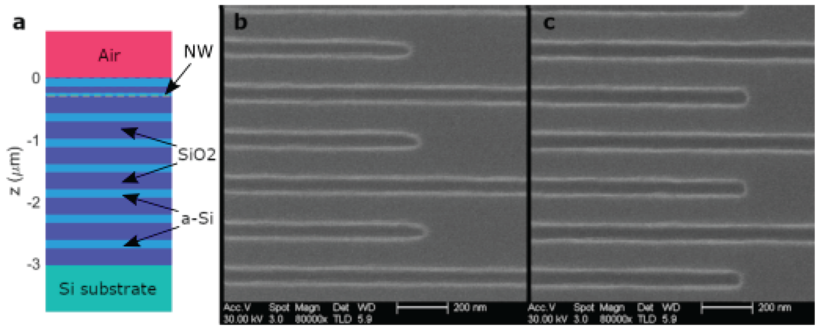


Fig. 1. (a) The full optical stack of the MoSi-SNSPD. NW = nanowire. (b) And SEM image of the bends in the nanowire pattern designed to minimize current crowding. (c) SEM image of circular-arc bends for the same wire-widths (110 nm) and pitch (170 nm) in the nanowire pattern. Switching current for (b) was 6% greater than for pattern (c).

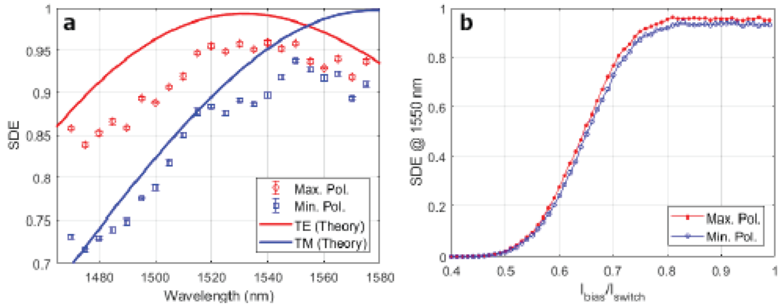
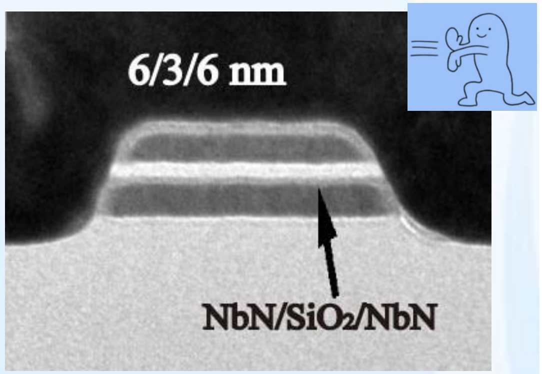


Fig. 2. (a) System detection efficiency (SDE) versus wavelength for a 3-layer (αSi/SiO_2/αSi) AR coating of thicknesses (136 nm, 89 nm, 60 nm) (top to bottom). (b) SDE for a 35 μm diameter active-area MoSi-SNSPD at 1550 nm, showing a maxima of 96%, and a polarization selectivity of 1.02. The count rates were ~ 50 kHz. Recovery time was 200 ns.

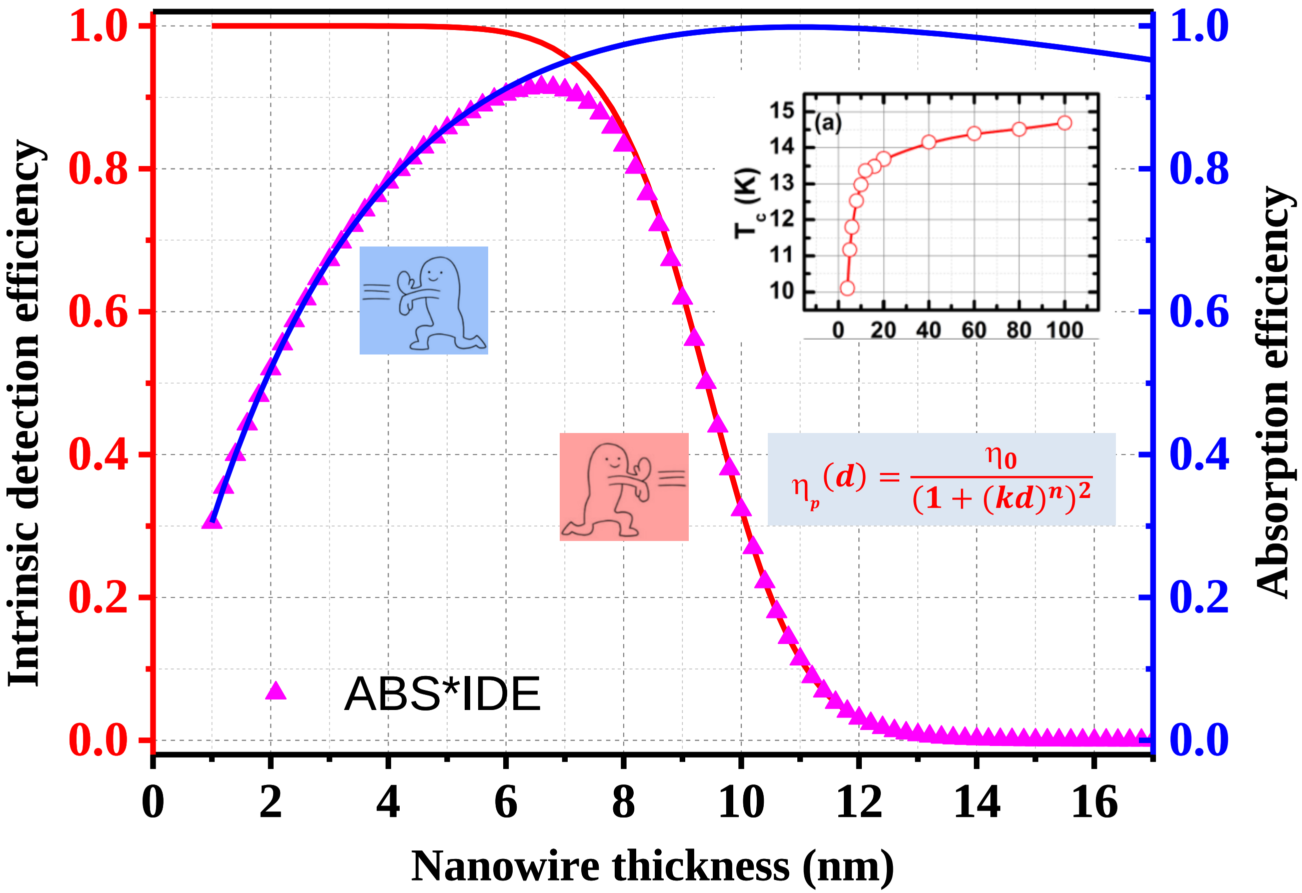
WSi SDE 93% @120 mK @1550 nm
by Marsili, NIST, Nat Photon 7, 210 (2013)

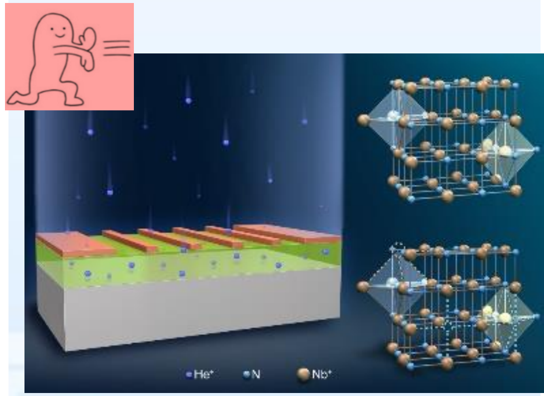
MoSi SDE 96% @700 mK @1550 nm
by Reddy, NIST, FF1A CLEO 2019

Break the trade-off in NbN SSPD



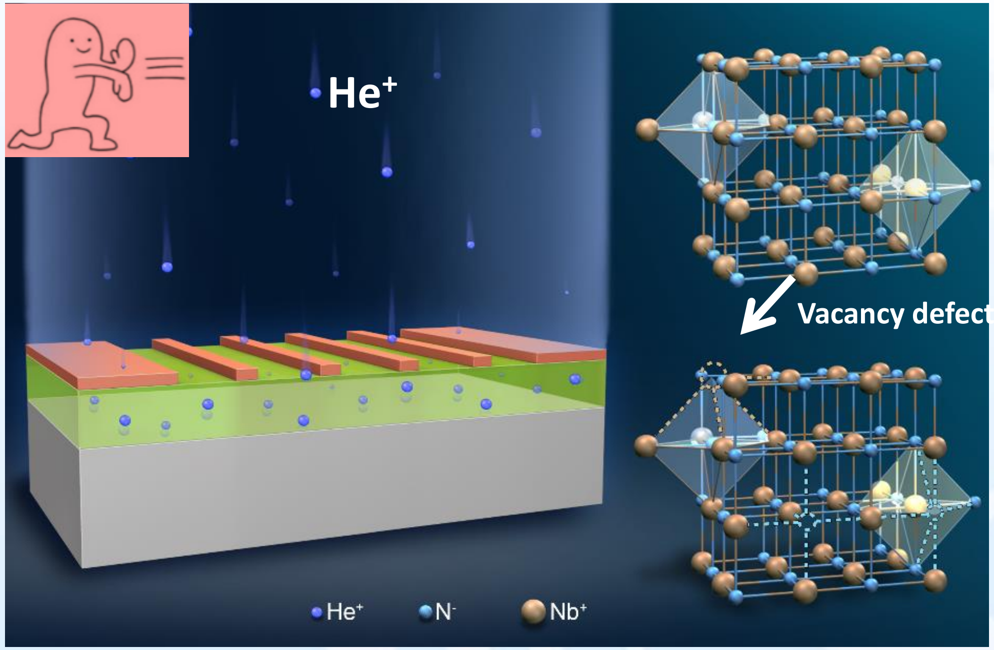
Twin-Layer structure



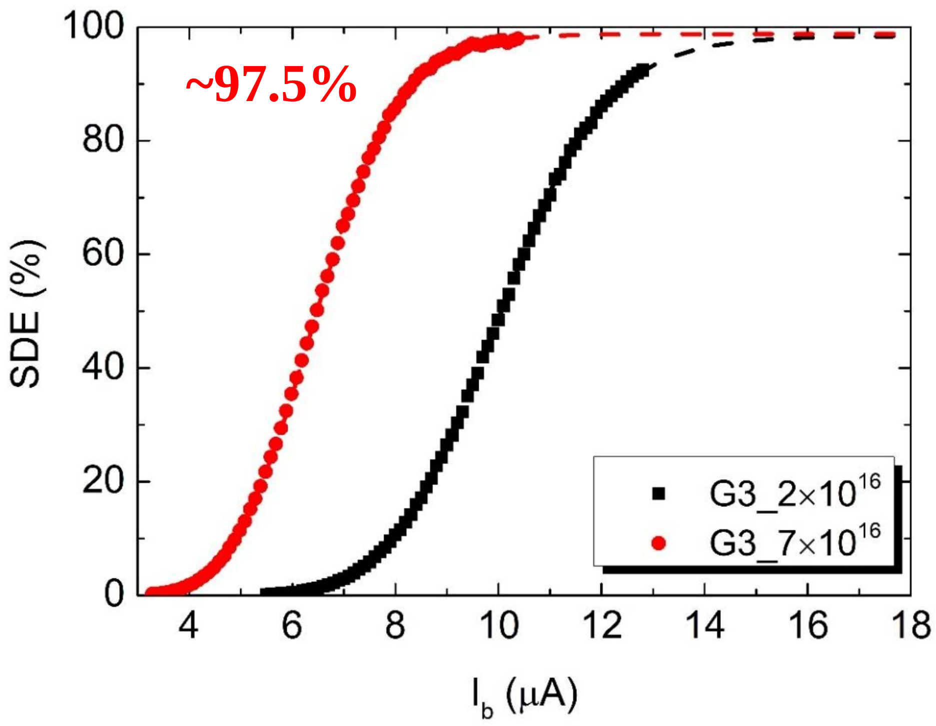


Ion irradiation

Tune SDE with He ion irradiation



W. J. Zhang Phys Rev App 12, 044040 (2019).

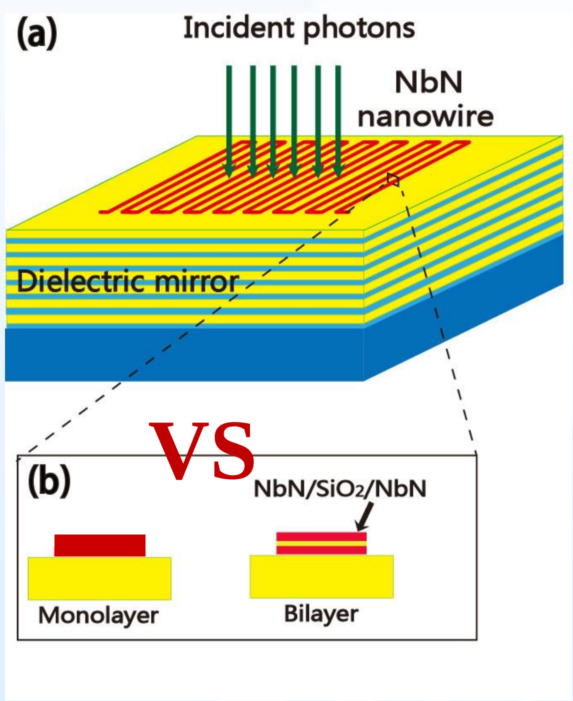


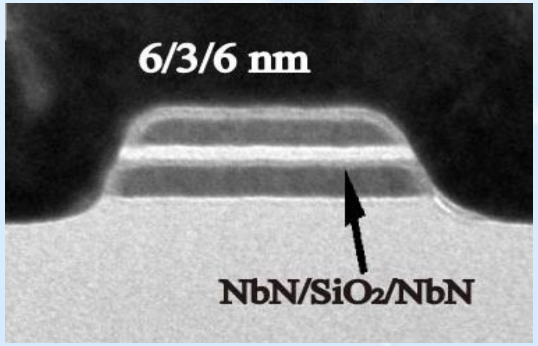
Schematic of He ion irradiation of the NbN thin film

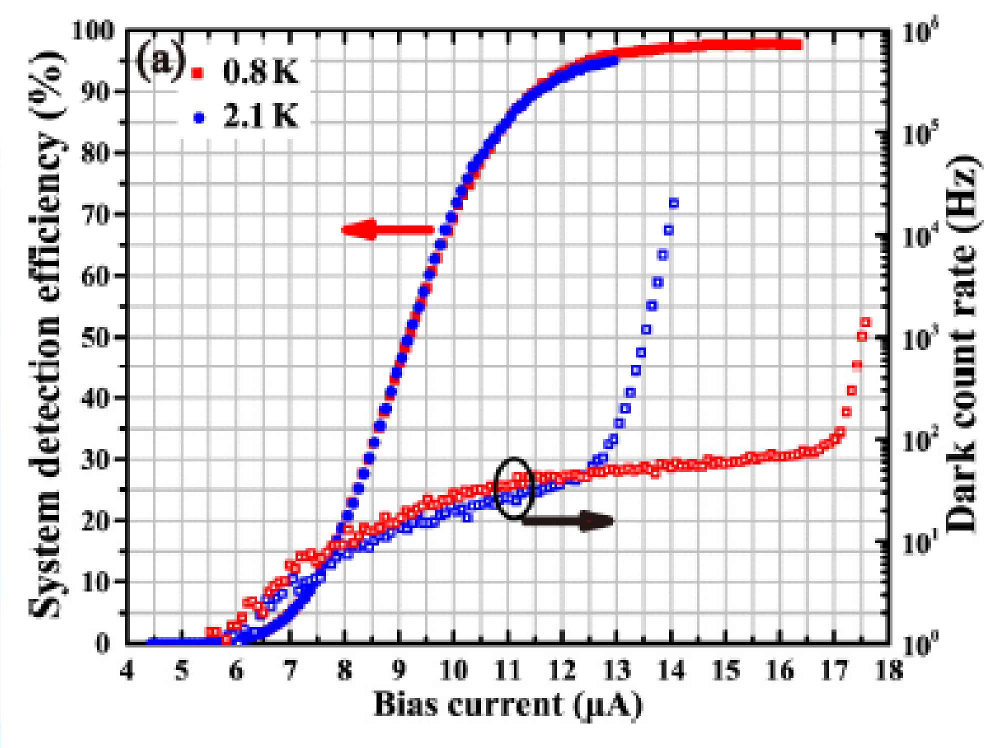
SDE vs Ib for SNSPDs with He ion irradiation

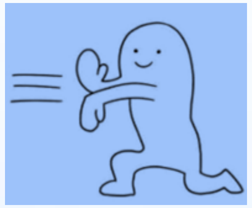
We were able to tune superconductivity of NbN nanowires, thus, tune IDE/SDE of SSPD.

Tune ABS with twin-layer film









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

Opt Exp 28: 36884. (2020), Spotlight of OSA

Results from Other groups

optica

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

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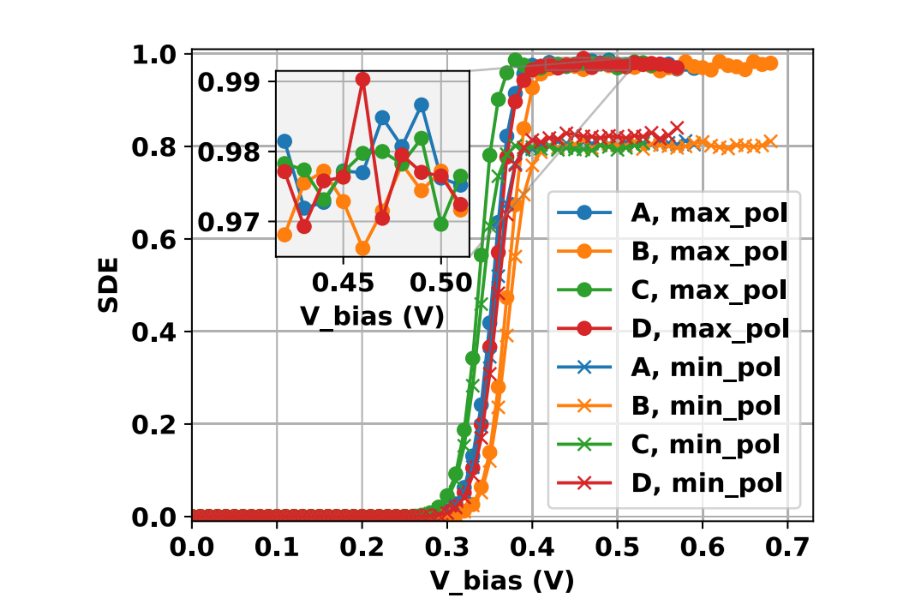

MoSi on DBR mirror by NIST

Detecting telecom single photons with $(99.5^{+0.5}_{-2.07})$% system detection efficiency and high time resolution

Cite as: APL Photon. 6, 036114 (2021); doi: 10.1063/5.0039772
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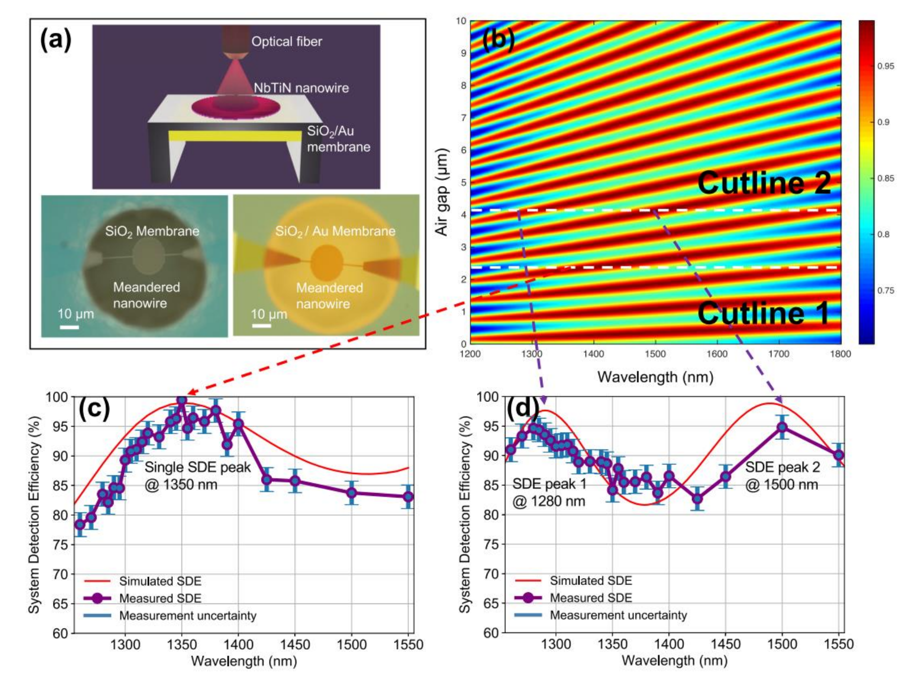
J. Chang,[1,2,a)] J. W. N. Los,[2] J. O. Tenorio-Pearl,[2] N. Noordzij,[2] R. Gourgues,[2] A. Guardiani,[2] J. R. Zichi,[3] S. F. Pereira,[1] H. P. Urbach,[1] V. Zwiller,[2,3] S. N. Dorenbos,[2] and I. Esmaeil Zadeh[1,2]

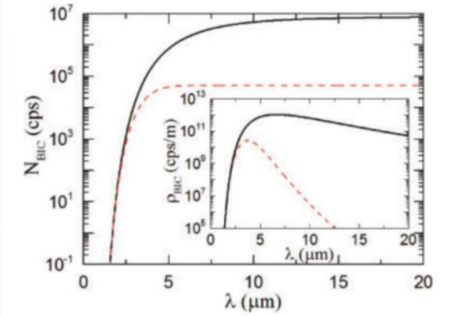


NbTiN on SiO2/Au by TUDelft

DCR of SSPD

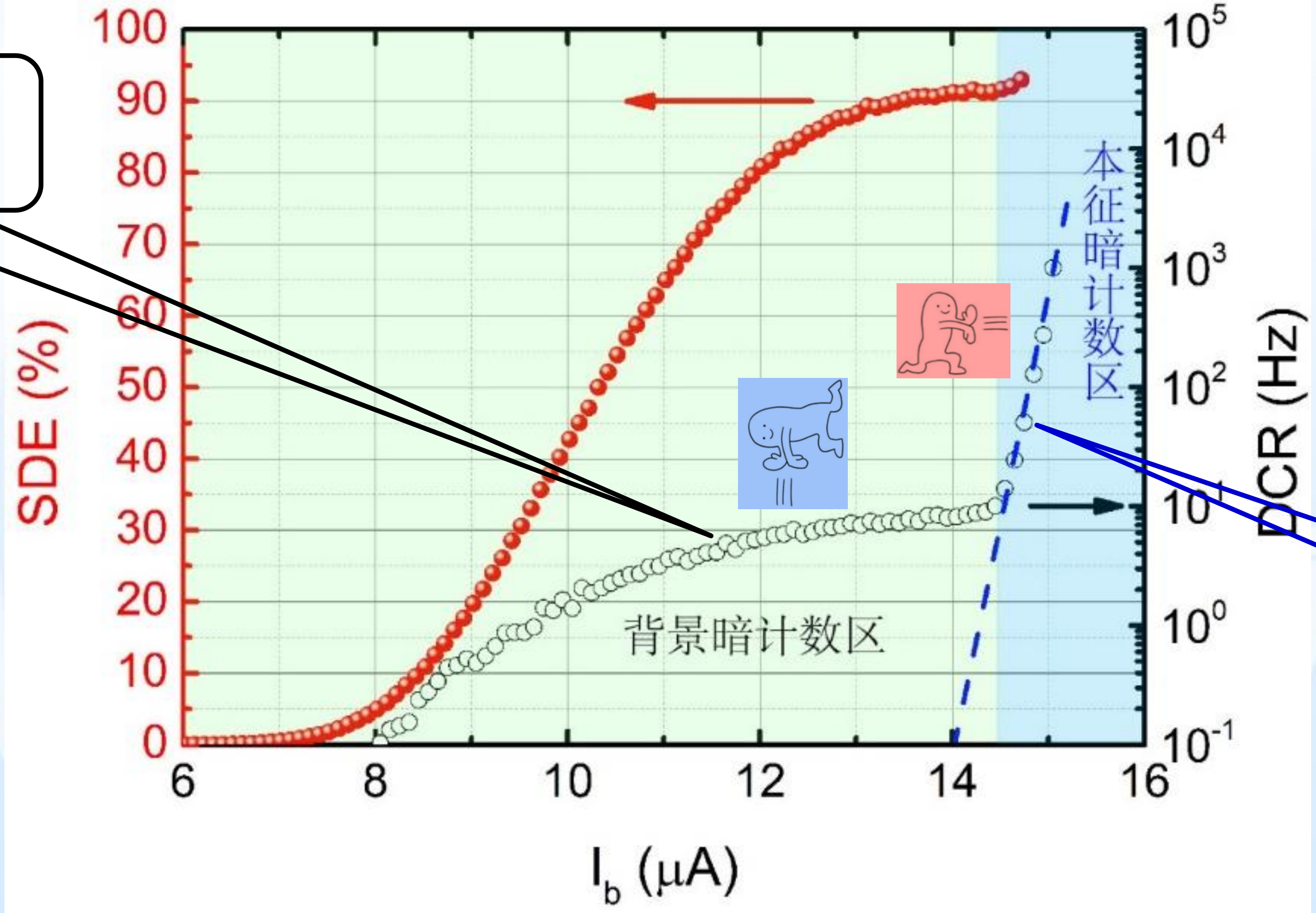
Background DCR
~ 10-100 cps

$$N_{\mathrm{BIC}} = \frac{\pi a^2 \mathrm{NA}^2}{16h} \int_{\lambda 1}^{\lambda 2} \lambda u_\lambda \eta(\lambda) t(\lambda)\, d\lambda$$



Spectral dependencies of bDCR

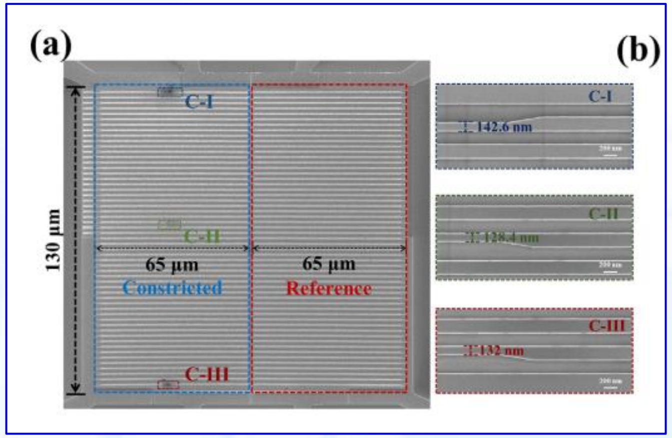
Konstantin, App Phy Exp 8: 022501. (2015)



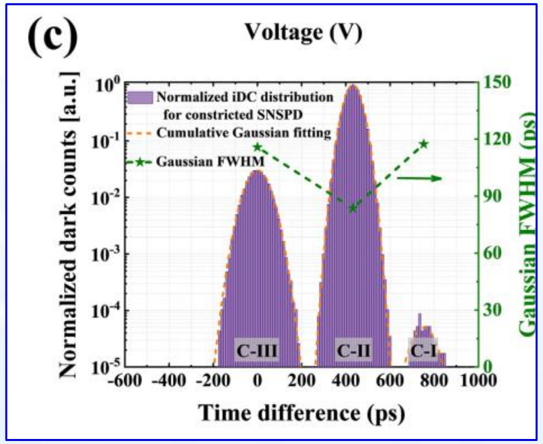
Intrinsic DCR
Ib sensitive, vortex related

Origin of iDCR

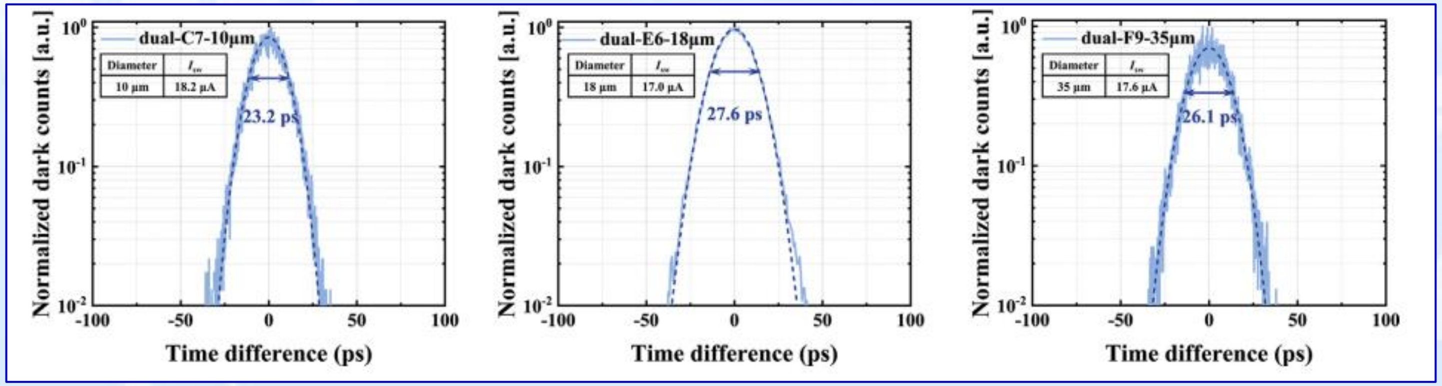
Superconductivity 1: 100006 (2022)



DUT with artificial defects



iDCR in time domain



iDCR of Conventioal SSPDs in time domain

Conclusion: iDCR of typical SSPDs is contributed by the single (weakest) defect/constriction

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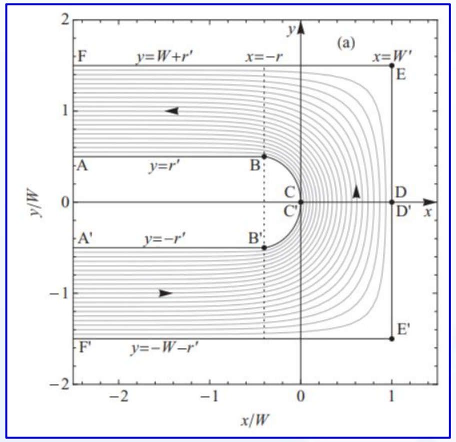
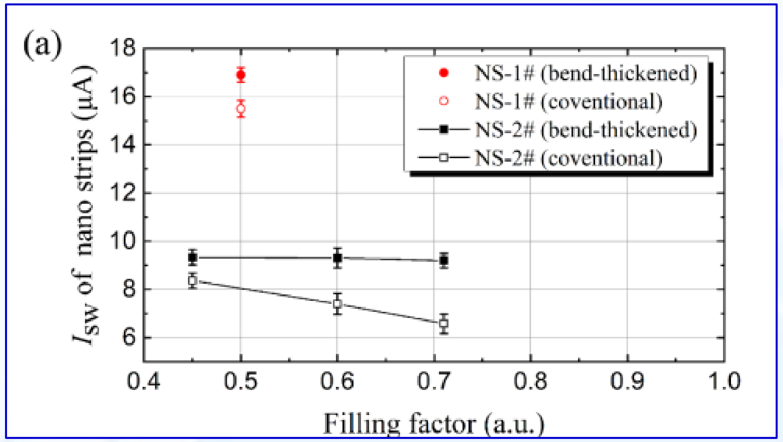
Fight with current crowding effect

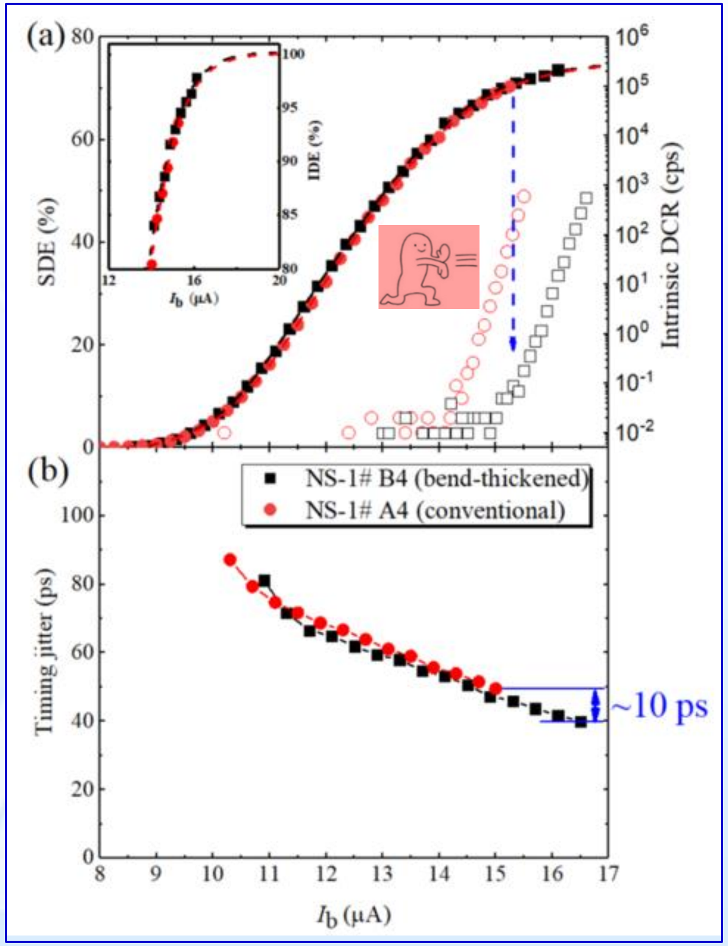


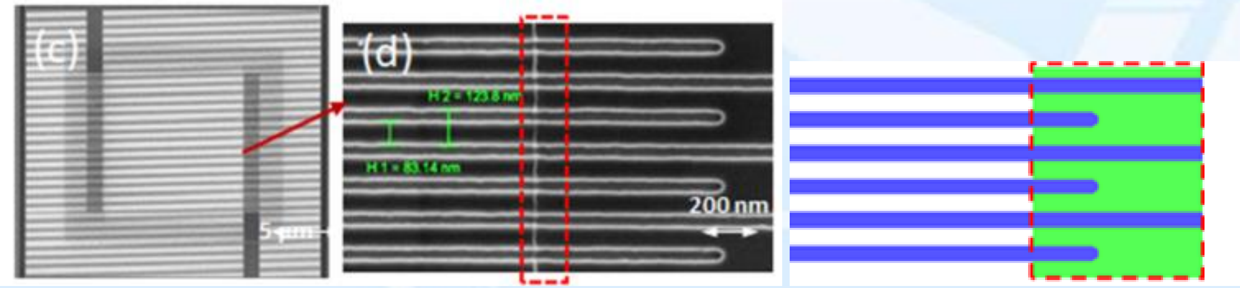
Crowding effect in bending area

J. R. Clem and K. K. Berggren. PRB 84 174510 . (2011)



Isw of SSPDs with thicker bending area for different filling ratios





SSPDs with thicker bending area

Maximum SDE ⇧， DCR & TJ ⇩

SUST 35: 055015 (2022)

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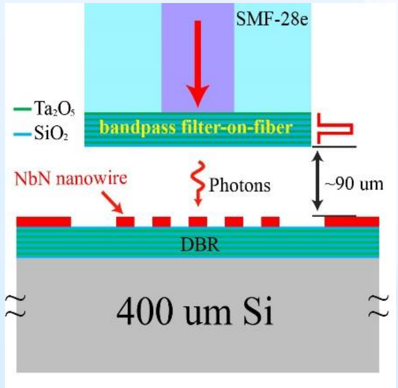
SSPDs with high SNR

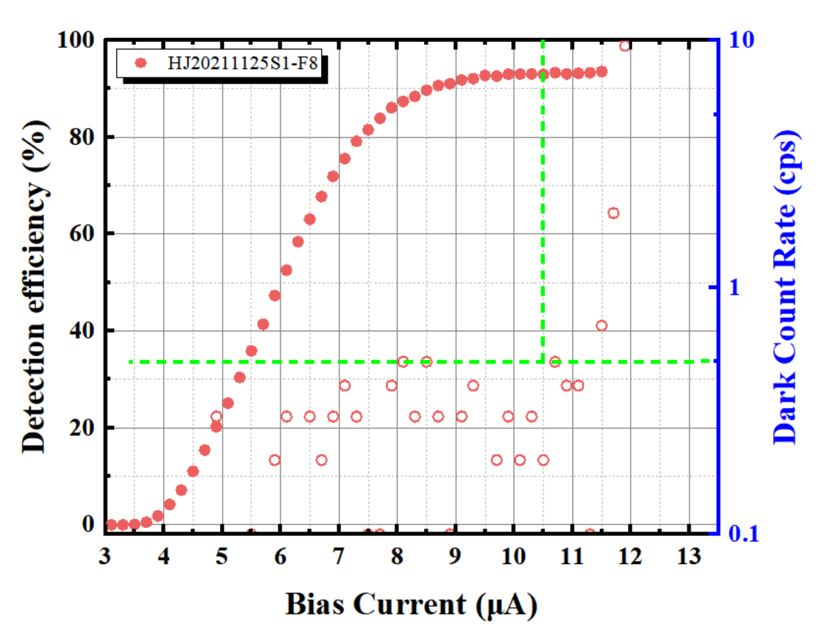
3-EP-ND-06I

Patents issued in USA, JP and CN

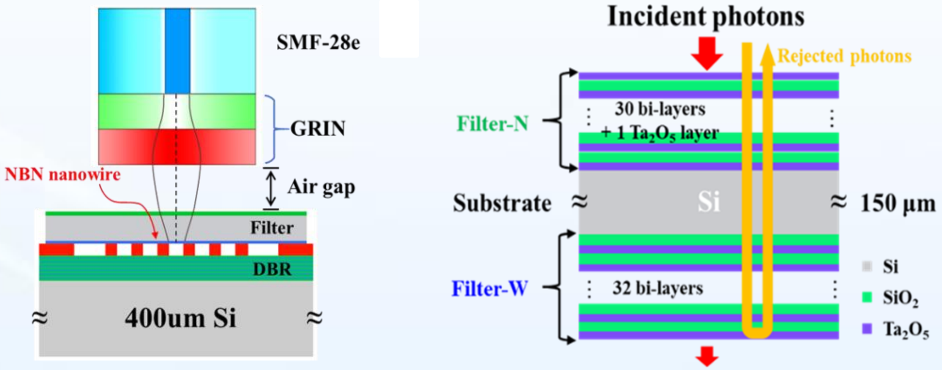
OE 22: 16267 (2014)
AO 54: 96 (2015)
SUST 31: 035012 (2018)



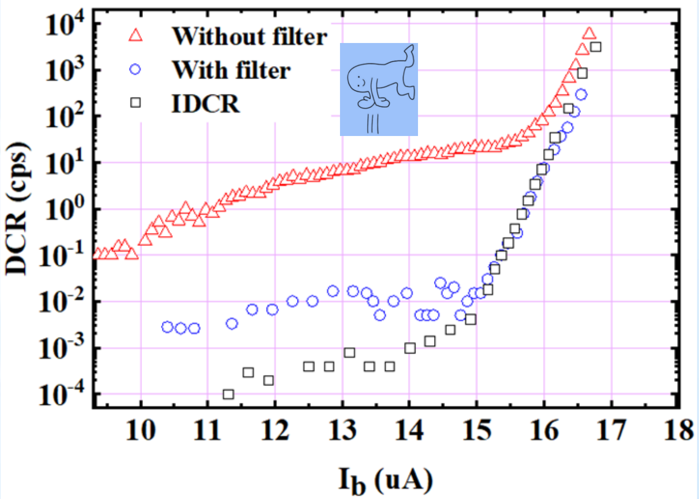
Filter on fiber end-face



SDE > 90% with DCR ~ 0.5 cps



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



SDE ~ 54.1%, DCR ~ 0.005 cps

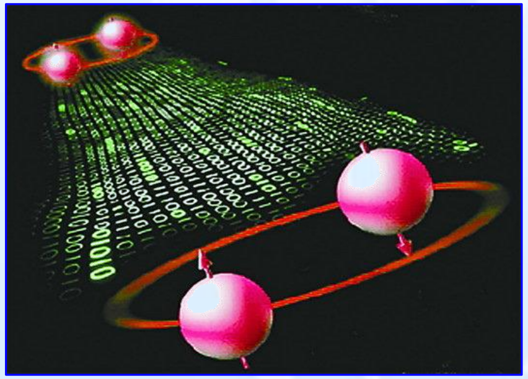
Content

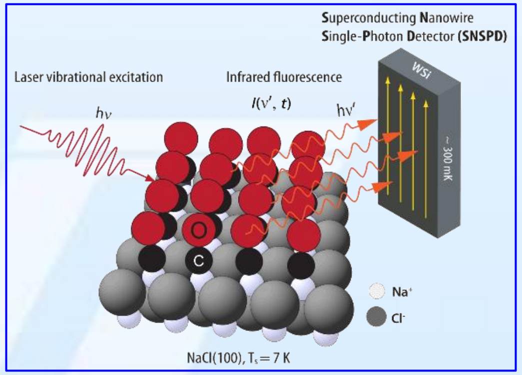
Quantum Information

Quantum Communication

Quantum Computation

Quantum Metrology

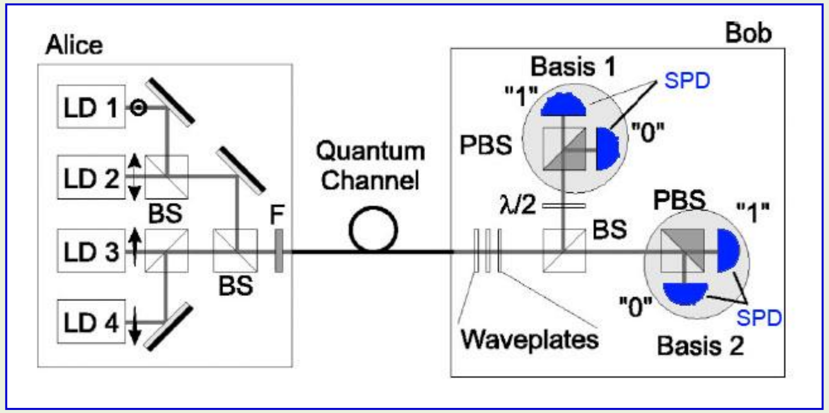




SSPD plays indispensable role in QIP

Requirements from QI

QKD



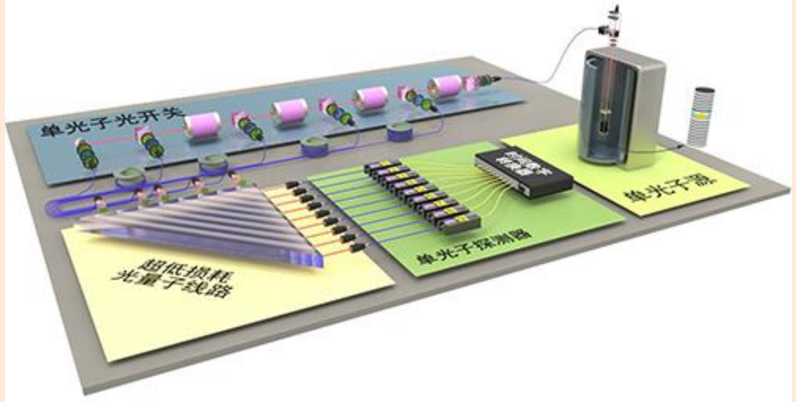
K_u (final secure key rate) $\propto$ f· μ · L· DE

ER $\propto R_{dc}/K_u$

SPD: High DE, Low DCR, High Speed

At least 4 SPDs for BB84

Quantum Comput/Sim



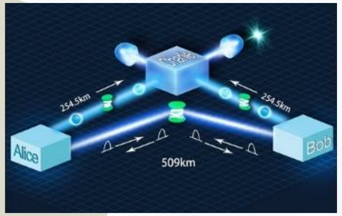
$$CC(n) = \frac{R_{pump}}{n} \cdot (\eta_{QD} \cdot \eta_{de} \cdot \eta_C \cdot \eta_{SPD})^n \cdot S$$

SPD: High Speed, High SDE, PNR

50 qubits need 100 SPDs

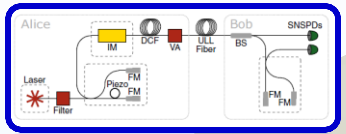
High performance SPD is indispensable for QI

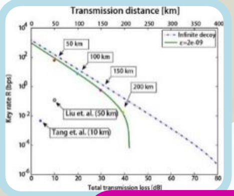
SSPDs for Quantum Key Distribution

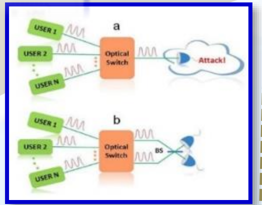


USTC 2020/21& ToshibaUK/21:
500-800 km TF-QKD Lab/Field

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

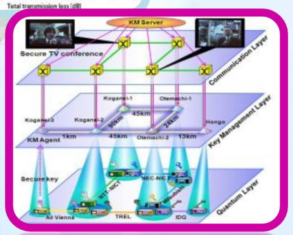




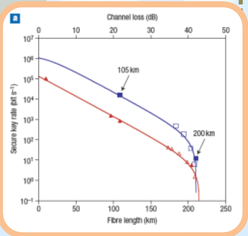


USTC 2015-16:
200 km² MDI-QKD network
404 km MDI-QKD

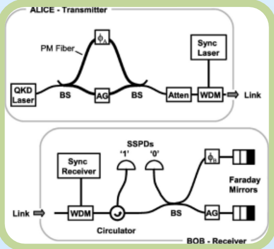
USTC 2014:
200 km MDI-QKD



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



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

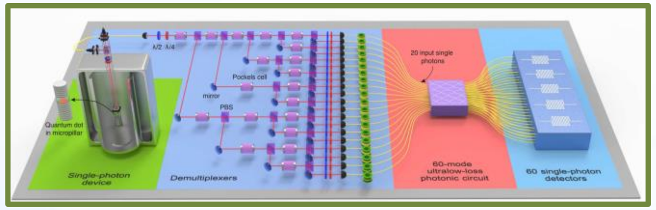


NIST 2006：1st QKD demo using SSPD
With DE (10%) by R. Hadfield
APL 89: 241129. (2006)

Collaborated with JW Pan

- PRL 113: 190501. (2014)
- PRX 6, 011024 (2016).
- PRL 117: 190501. (2016)
- PRL 123: 100505. (2019)
- PRL 124: 070501. (2020)
- PRL 125: 260503. (2020)
- Nat Photon 14: 422. (2020)
- PRL 126: 250502. (2021)
- Nat Photon 15: 570. (2021)
- PRL 128: 180502. (2022)

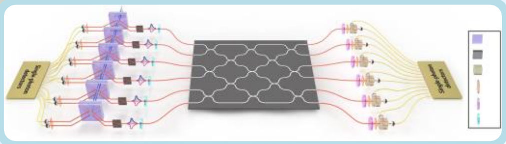
SSPDs for Optical Quantum Computation

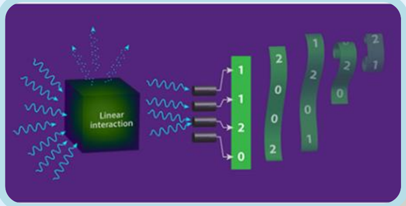


USTC 2019:
20-photon Boson Sampling (~48 qubits) (60 SSPDs)

USTC 2020/21:

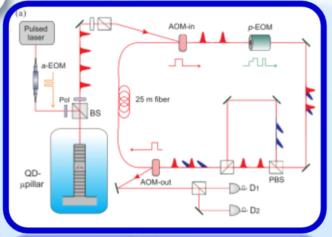
- **JIUZANG: 76/113 qubits Boson Sampling**
- **100/144 SSPDs in 7/10 cryostats, SDE ~0.81/0.83**





USTC 2018:

- **Scalable Boson Sampling with photon loss (13 SSPDs)**
- **12-Photon Entanglement and Boson Sampling (24 SSPDs)**



USTC 2017:
1st Boson Sampling using SSPDs

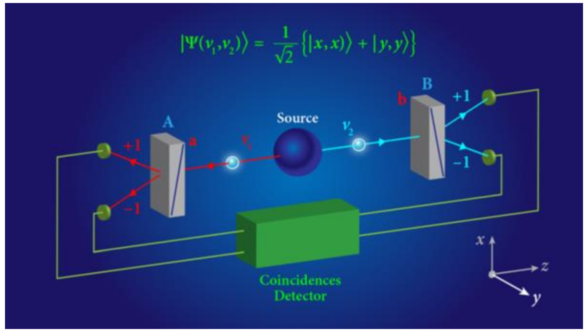
Collaborated with JW Pan

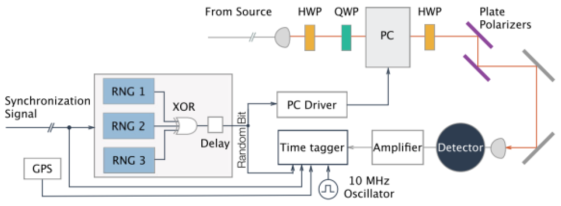
- PRL 118, 190501 (2017)
- PRL 120: 230502. (2018)
- PRL 121: 250505. (2018)
- PRL 123: 250503. (2019)
- Science 4: 070501. (2020)
- PRL 127: 180502. (2021)
- PRL 130: 190601 (2023) for graph theory

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

SNSPDs for other QI

Bell inequalities





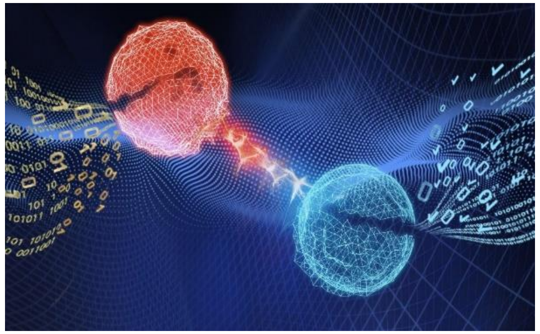
2 WSi SNSPDs: DE ~91 %@1550nm

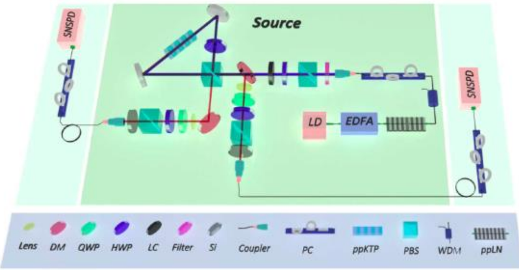
PRL115, 250402 (2015)

NIST

Strong Loophole-Free Test of Local Realism

QRNG





2 SNSPDs: DE ~90 %@1550nm

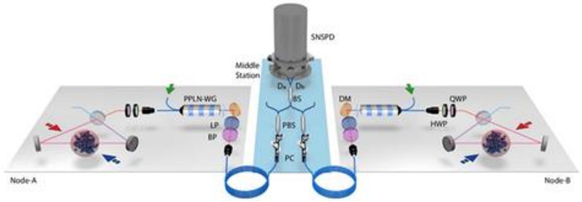
PRL 120, 010503 (2018)

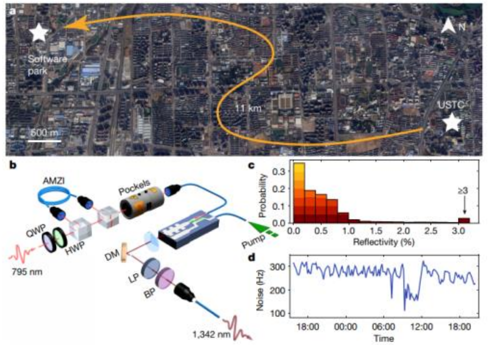
Nature 562: 548 (2018)

USTC

QRNG w/o both detectors and nonlocality loop holes

Quantum Memory





2 SNSPDs: DE ~50 %@1342nm

Nature 578: 240. (2020)

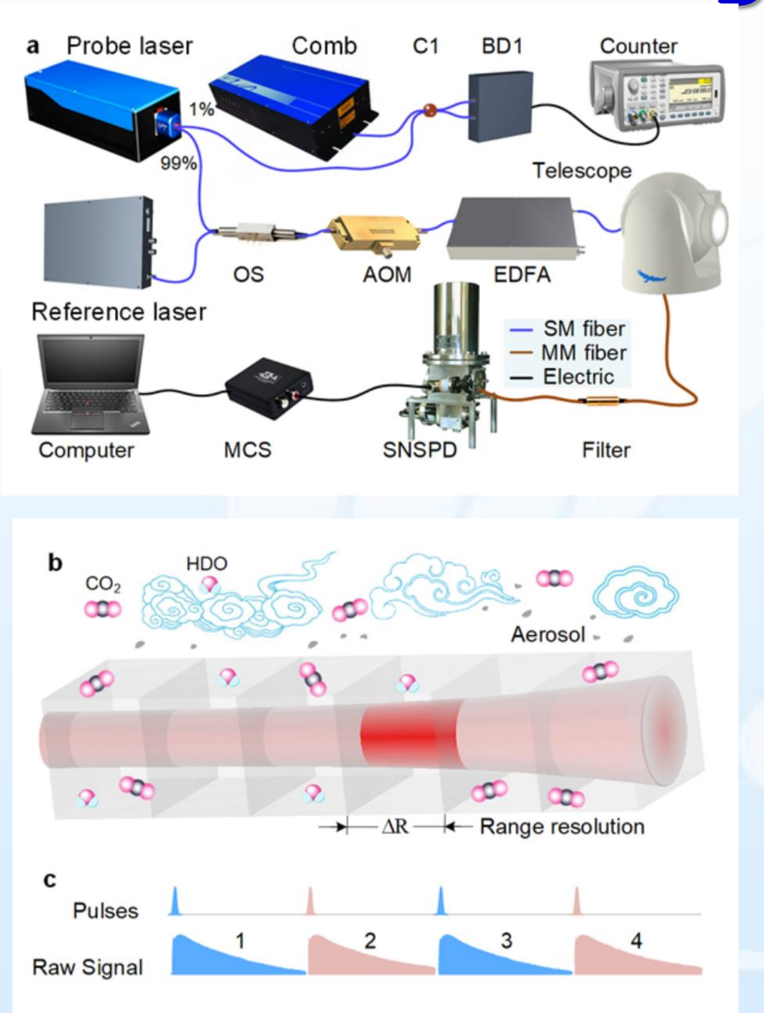
USTC

Entangl. of two quant mem via fibres over 50 km

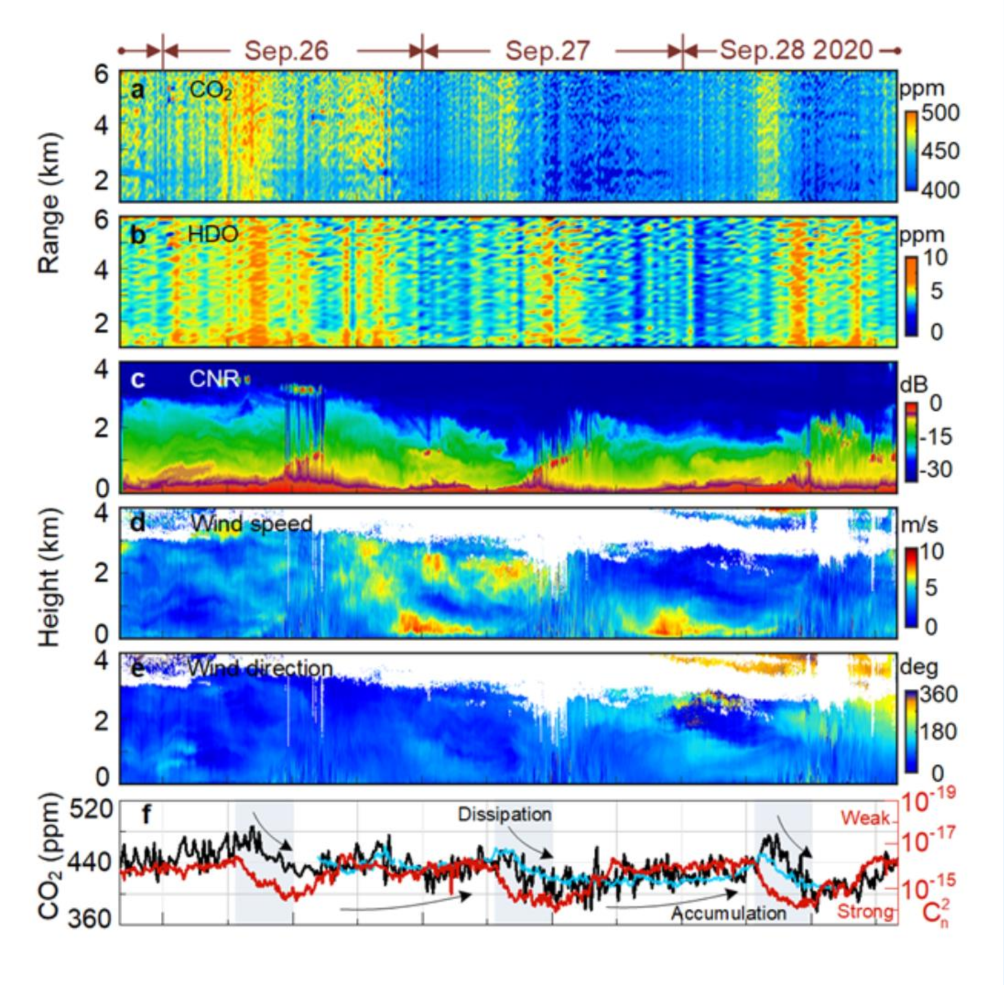
IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 55, January, 2024. Invited presentation given at EUCAS 2023, September 6, 2023, Bologna, Italy

SNSPDs for LIDAR

Light Sci App 10(1): 212. (2021)



LIDAR system for Atmosphere

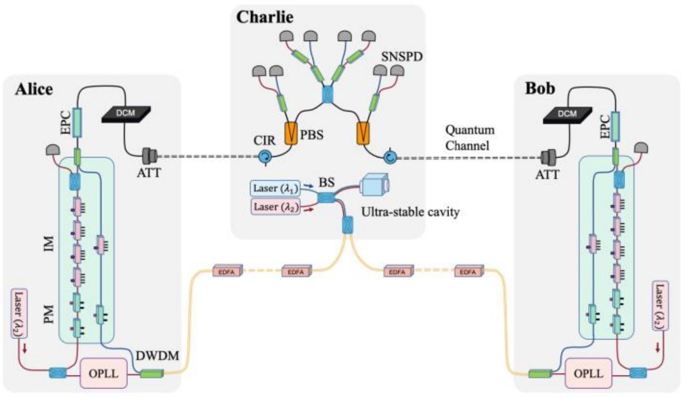


Continuous measurements for 3 days, 6 km
(CO2,HDO, Wind Speed, direction et al …)

SNSPD with Φ200μm by USTC group (Prof. DouXK & XiaHY) for distributed free-space spectroscopy

Latest Quantum Applications

Long haul QKD

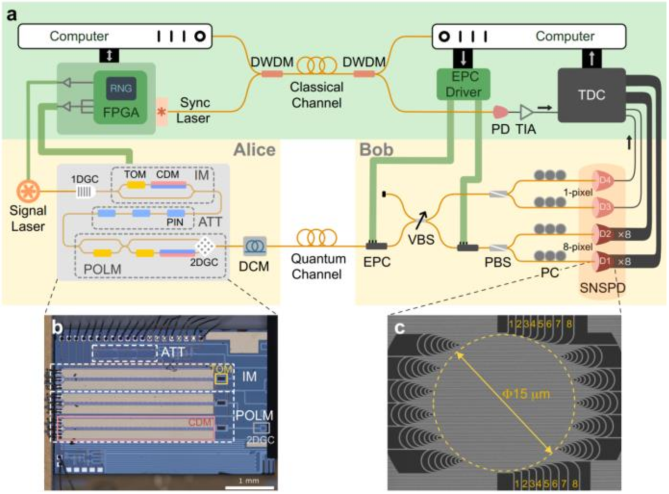


2 ULDCR SSPDs:
DE60%@DCR0.014cps

PRL130: 210801 (2023)

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

High rate QKD

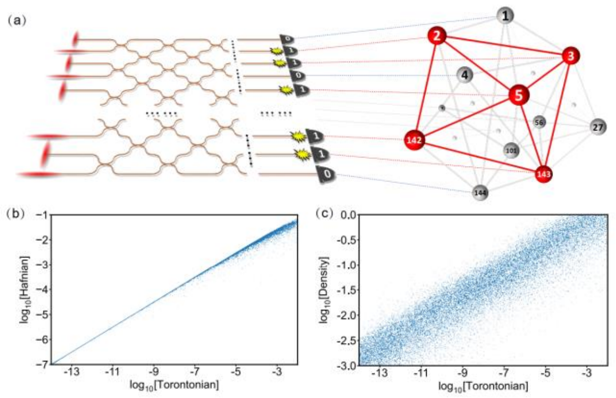


8-pixel SSPD array:
DE78%max，552Mcps@DE62%

Nat Photon 17: 416 (2023)

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

Solving Graph Problems

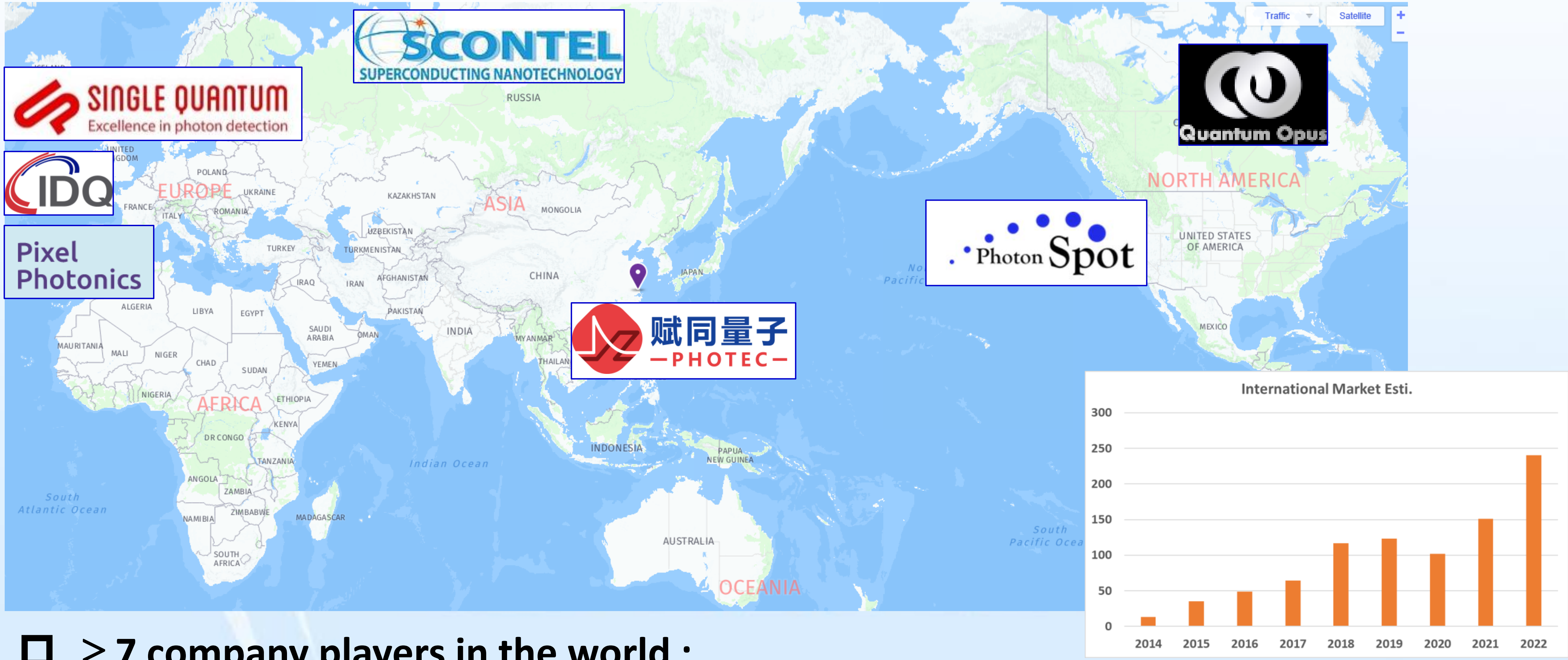


144 SNSPDs:
Ave. SDE ~83%@1550nm

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

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

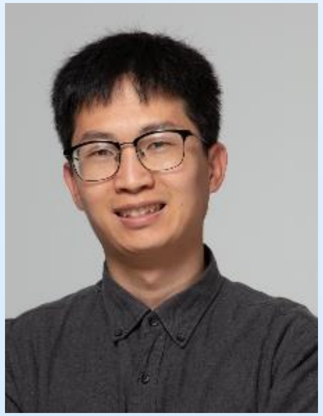
Conclusion

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

Hao LI
SIMIT

Weijun ZHANG
SIMIT

Chenjun ZHANG
PHOTEC



Chaolin LV
PHOTEC