



Superconducting strip photon detectors and applications

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

Lixing You



中国科学院上海微系统与信息技术研究所

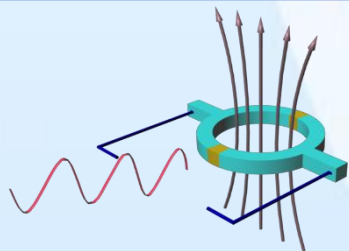
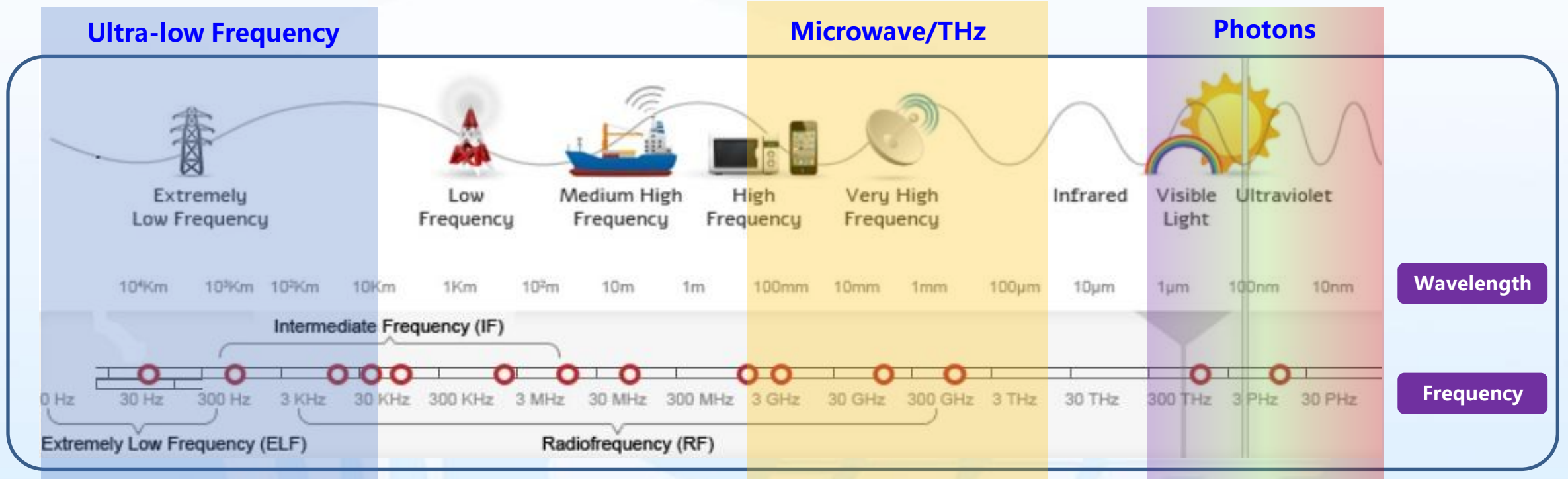
Shanghai Institute of Microsystem and Information Technology, Chinese Academy of Sciences



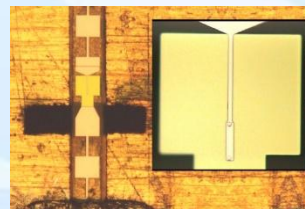
Content

- **Background & Introduction**
- **SSPD with high performance**
- **Applications**
- **Summary**

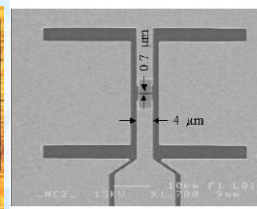
Superconducting sensors and detectors



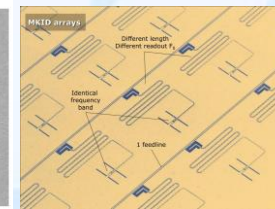
SQUID



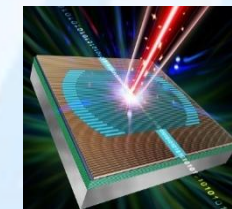
SIS/STJ



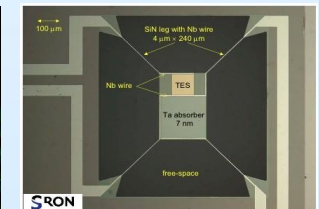
HEB



MKIDs



SSPD



TES

SC Sensors and Detectors may provide unparallel performance

About a photon

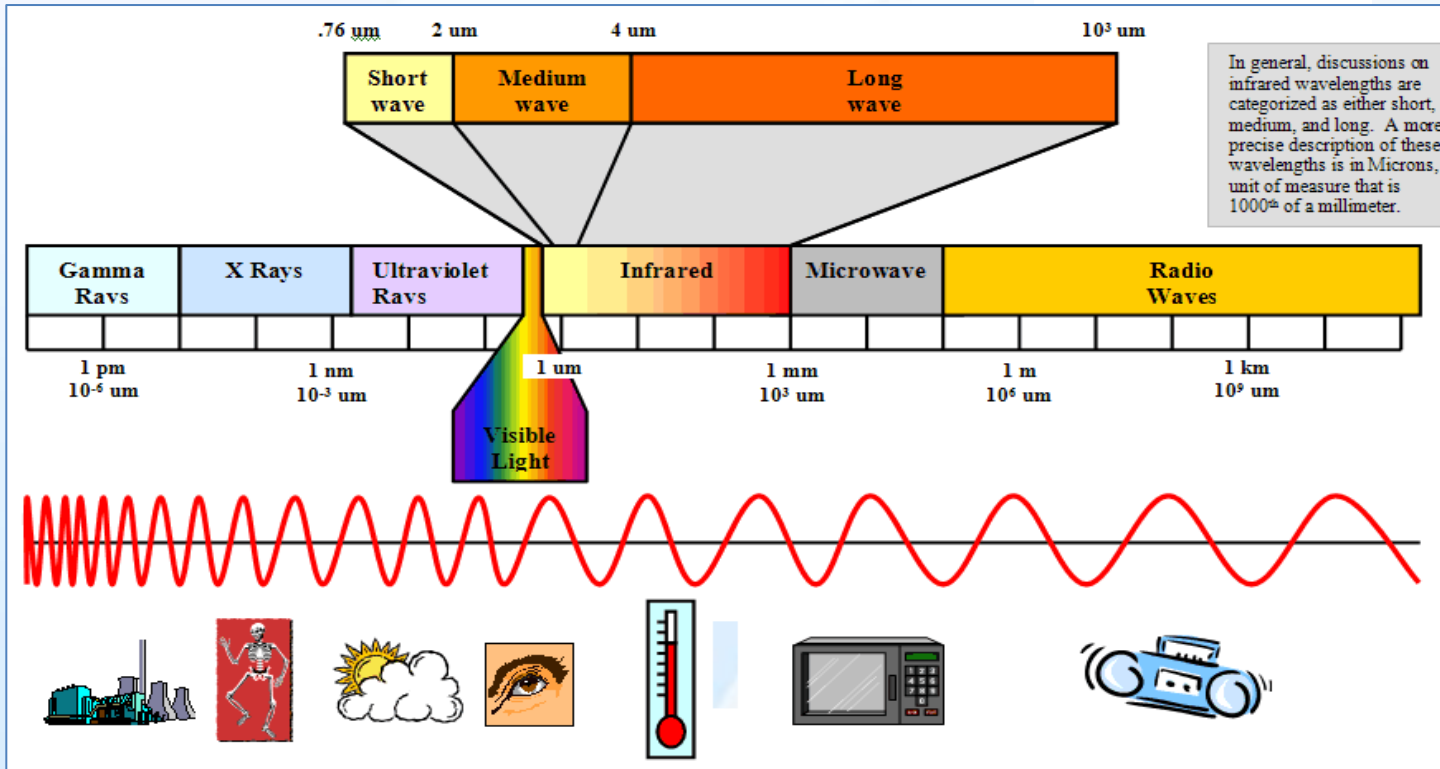
Photon Energy

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

$$h = 6.626 \times 10^{-34} \text{ joule} \cdot \text{s}$$

$$c = 2.998 \times 10^8 \text{ m/s}$$

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



1.5 μm \sim 0.8 eV
 \sim 1.3×10^{-19} J
 \sim -169 dBm

There are $\sim 10^{20}$ photons per sec for a **10 Watts** lamp **theoretically**

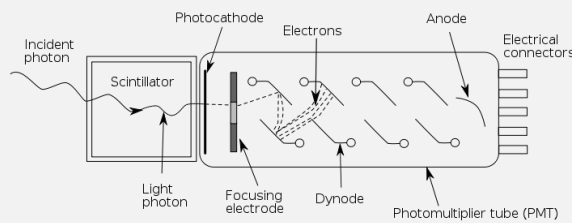
Single Photon Detector (SPD)



Gol'tsman APL2001

PMT

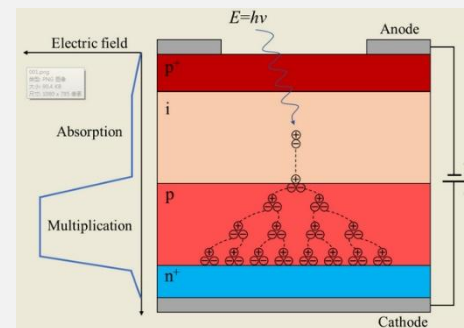
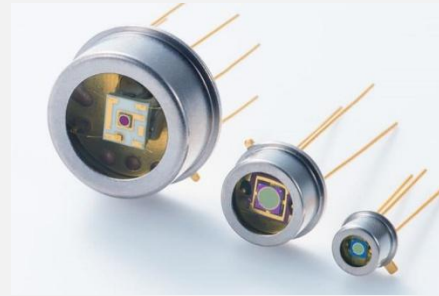
Since 1950s



External photoelectric effect

APD

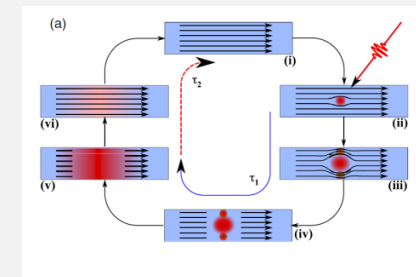
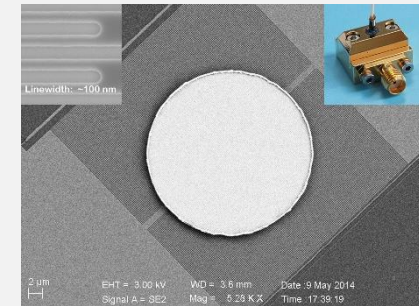
Since 1965



Internal photoelectric effect

SSPD

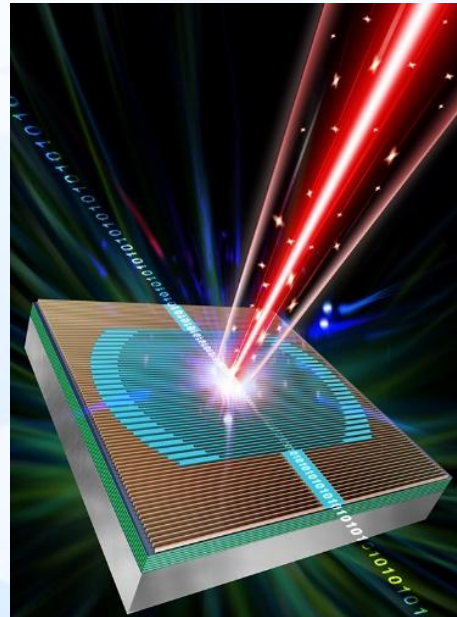
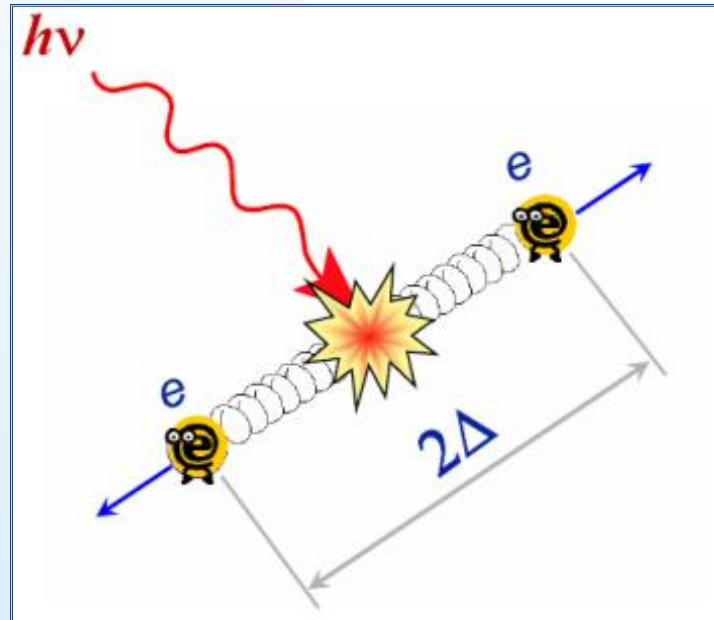
Since 2001



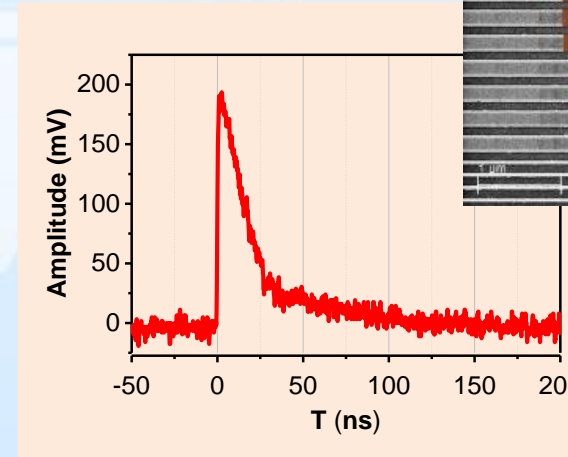
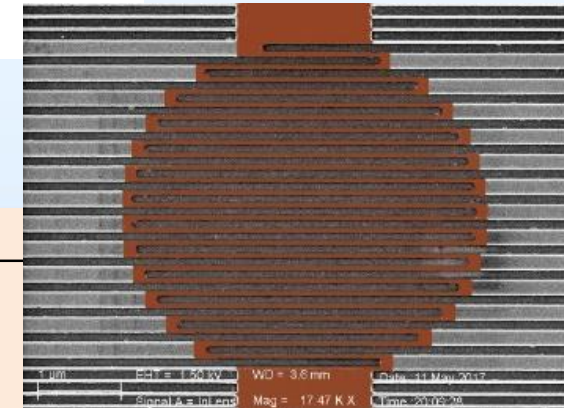
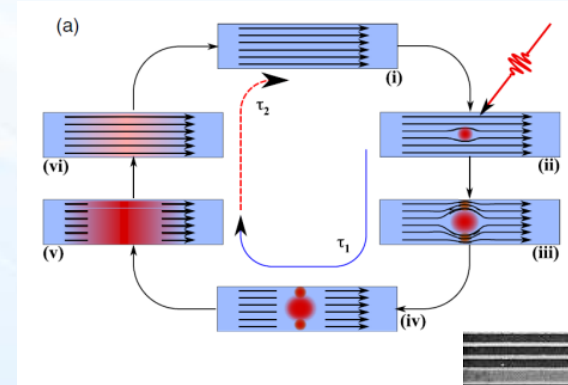
Cooper-Pair breaking effect

Detection Mechanism

Cooper pair breaking by single photon



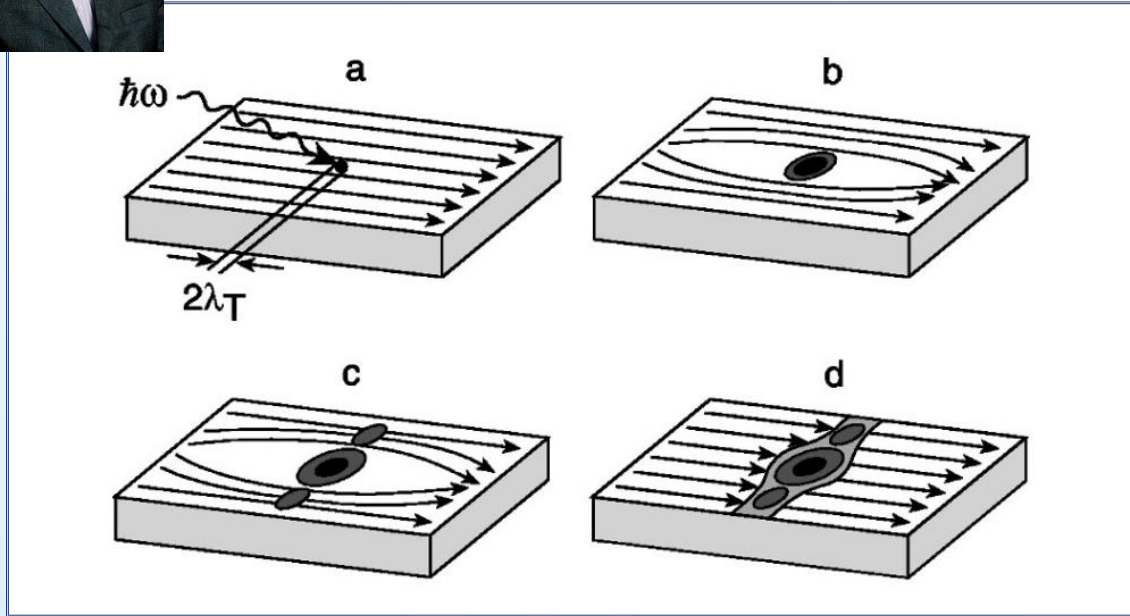
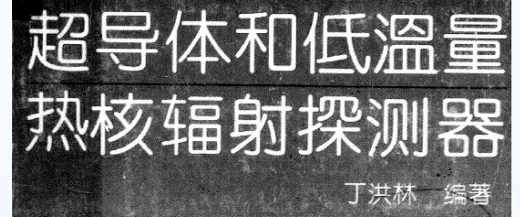
Goltsman et al, Appl Phys Lett, 2001, 79:705



Photon energy vs Superconducting gap/Cooper Pair energy
 $h\nu$ (1eV) vs 2Δ (6.4 meV)

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

More in History



量约为 0.7MeV , 作用半径约为 $1\mu\text{m}$. 因为拆散一个超导电子只需 1meV 的能量 (10^{-3}eV), 所以一个 6MeV 的 α 粒子和超导薄膜相互作用在 r_c 为 $1\mu\text{m}$ 、厚为 200nm 的圆柱体内可拆散 $10^{11}/\text{cm}^3$ 的超导电子, 这时在此小圆柱体内已没有超导电子存在, 因此在这小圆柱体内形成正常区域是确定无疑的, 如图 3.1 所示。

图 3.1 超导薄膜在 α 粒子作用下形成的正常态区域

如果我们在此超导薄膜或超导丝上通以一小于该超导薄膜或超导丝的临界电流的工作电流, 这时工作电流便沿正常区周围流动, 如图 3.1 所示。另一方面工作电流流动方向的变化, 使在正常区产生一感生电动势 E , 形成一闭合电流并产

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量的核辐射的信号。

图 3.2 α 粒子的入射使得超导薄膜的横断面上形成一正常区域带

核辐射 (例如 α 粒子) 入射在超导薄膜形成半径为 r_c 的正常区域后所产生的热, 一方面如上所述以 α 粒子与超导薄膜作用点为圆心向四周围扩散, 另一方面它还要通过衬底和冷却剂之间进行热交换而耗散。如果热耗散得很快, 不能进一步扩大正常区使流经正常区域周围的超导电流增大到超过 J_c , 也就是说在粒子入射后重新达到热平衡时没有形成如图 3.2 所示的正常区域带, 就不产生电压降, 所以也就不能构成

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

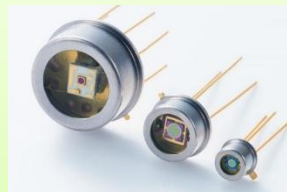
Book written by Honglin Ding in **1993**

Ref.1: Liengme O. Superconduct Particle Detectors, Ed by Barone, World Sci Pub, **1988**
Ref.2: D. H. Andrews et al, Phys. Rev. 76, 154 (1949) info from Masakta Ohkubo @AIST

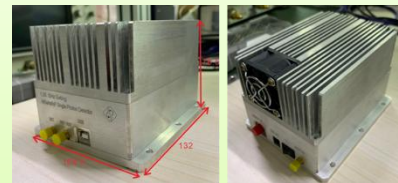
We may learn more from history (to read original papers)

SPD performances @ 1550 nm

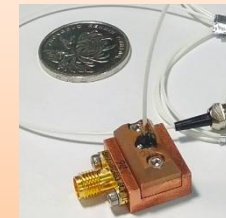
SPD	SDE (%)	DCR (cps)	CR (Hz)	TJ (ps)	Temp (K)
SSPD (NbN)	~ 98	≤ 1	≥ 1 G	≤ 10	~ 2.1 K
STJ (Al)	60	N/A	5 K	N/A	< 1K
TES (W)	95	~ 0	100 K	100 ns	0.1 K
InGaAs APD	20	16K	100 M	55	200 K
IR PMT	2	200 K	10 M	300	Room Temp



APD



APD module



SSPD
15 x 15 x 10 mm



1350 x 400 x 450mm
Power: 1.3 kW
Pride/Sumitomo



600(H)

Content

- Background & Introduction

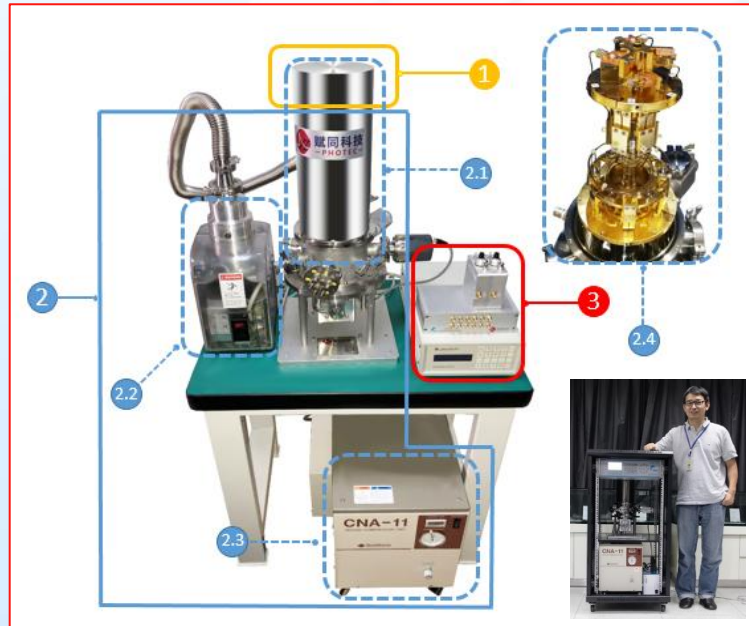
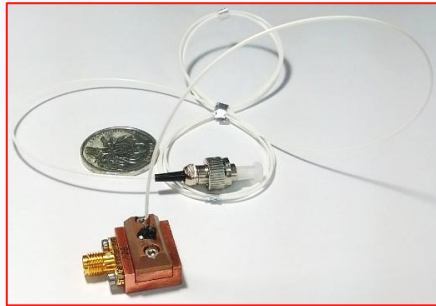
- SSPD with high performance

- Applications

- Summary

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)

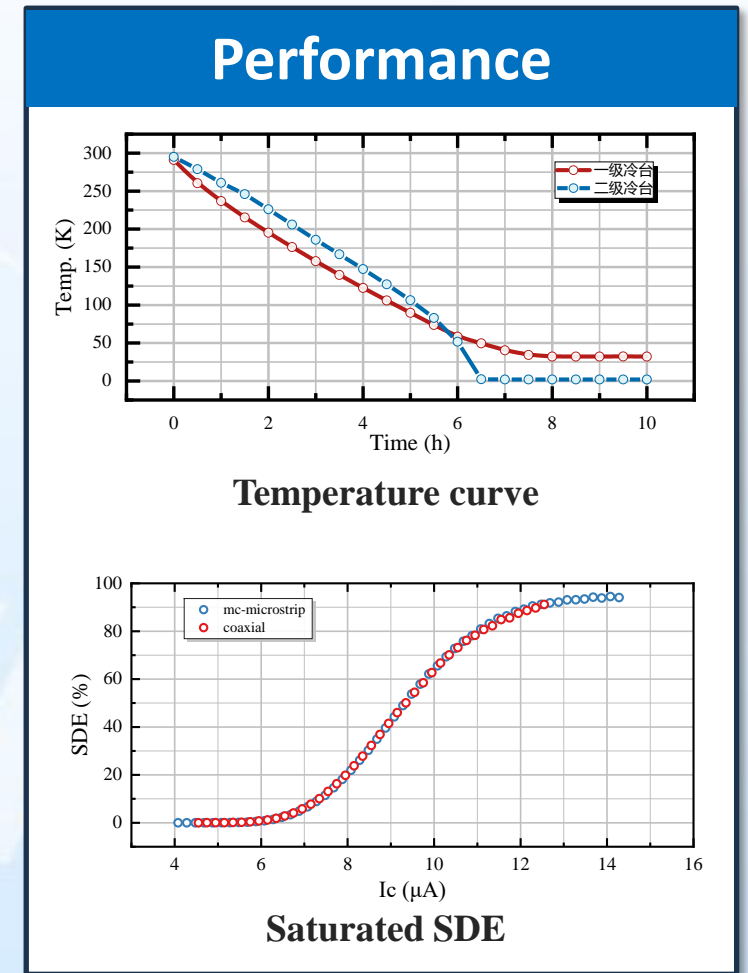
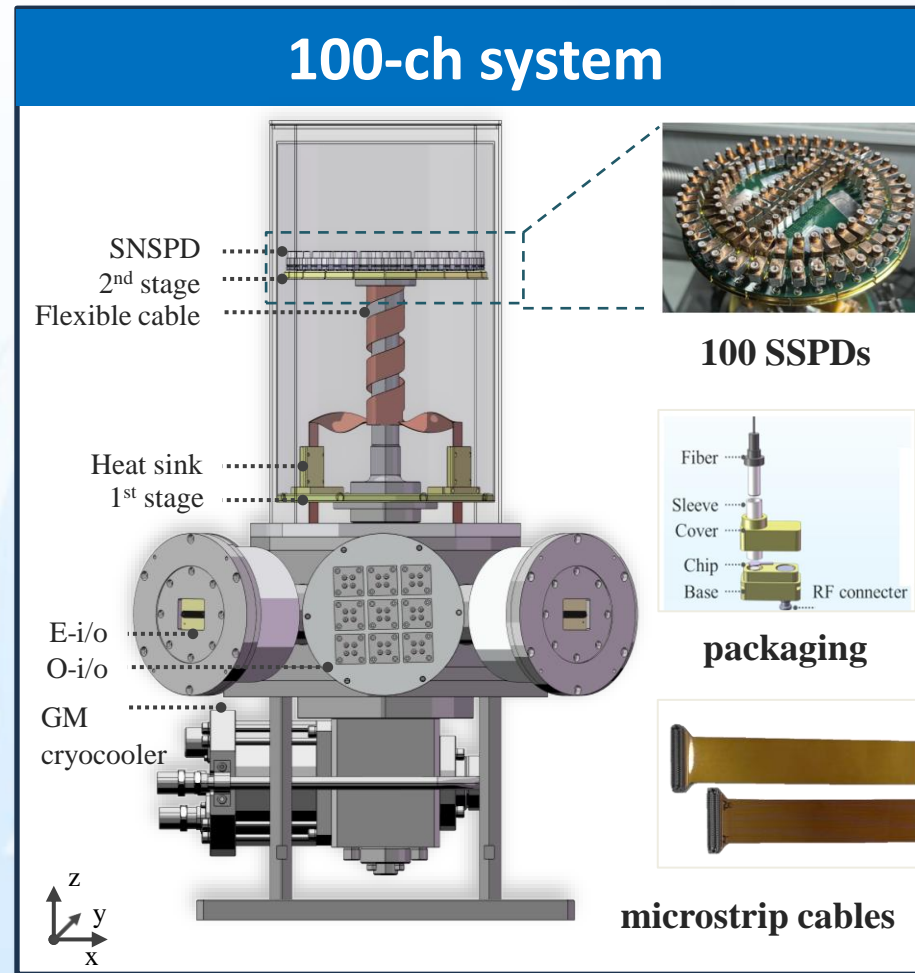


SSPD chip & cryostat

Latest practical systems



**Commercial
Compacted SSPDS
(from 22U to 14U)**

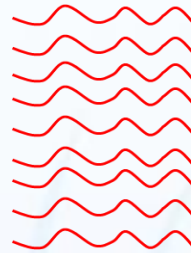


100-ch SSPD systems

SDE & Optics

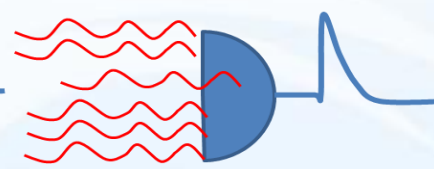
$$\text{SDE} = \text{Opt Coupling} \times \text{Absorption} \times \text{IDE}$$

$$0.99 \times 0.99 \times 0.99 = 0.97$$



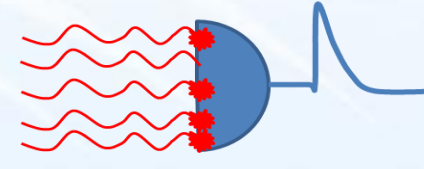
Active area: 15*15 μm^2
 OC > 95%

- ✓ Active Area
- ✓ Spot Size



7 nm NbN for 1550 nm
 Abs: ~30%

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



IDE ~100%

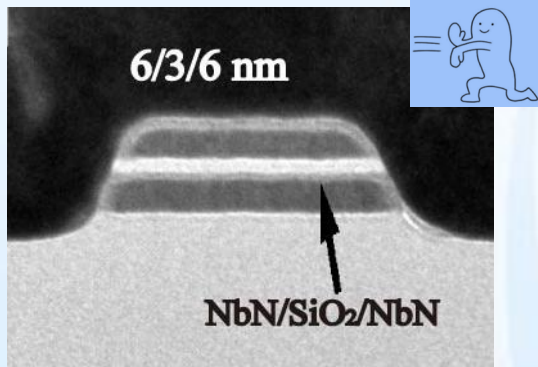
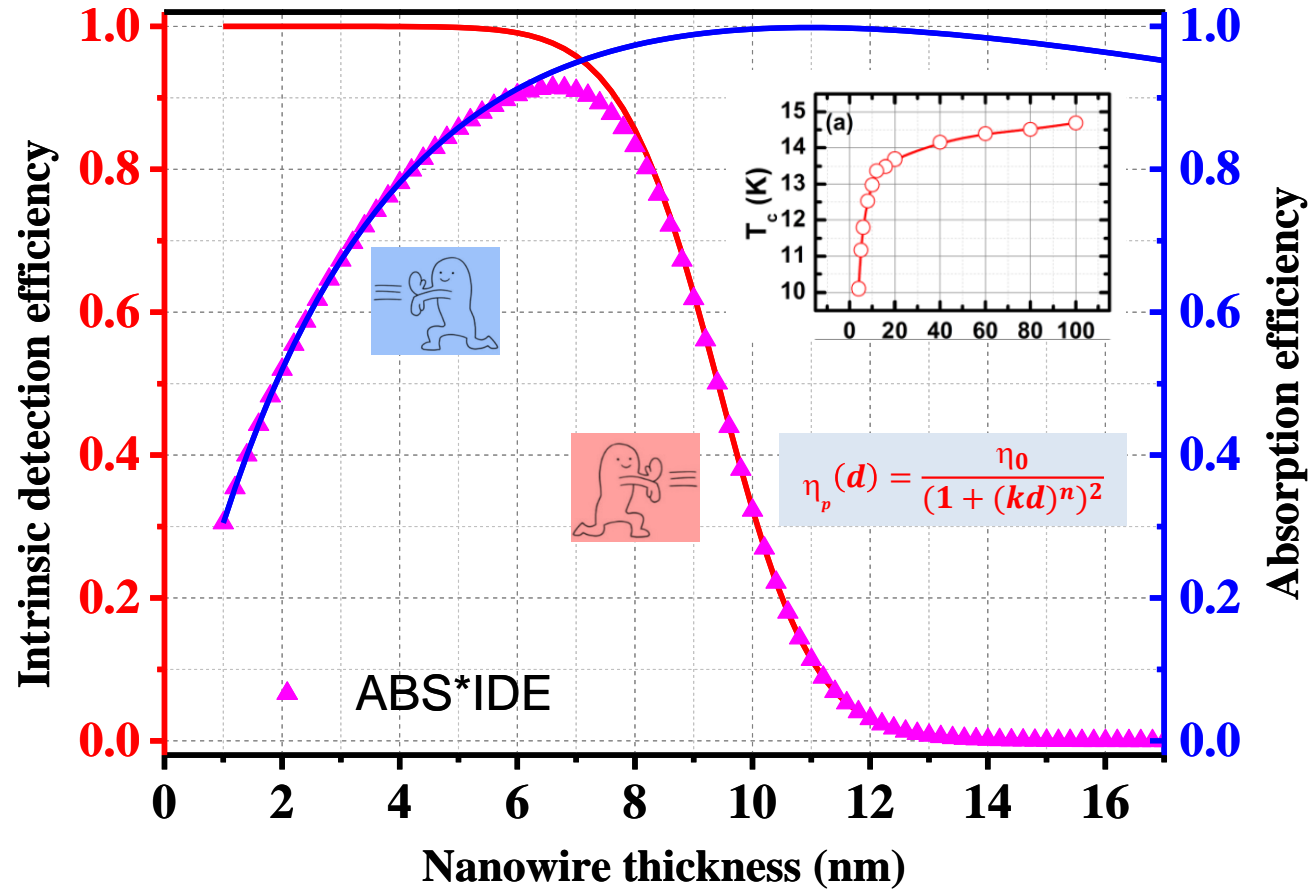
- ✓ Thickness (T_c)
- ✓ linewidth
- ✓ Uniformity
- ✓ Current crowding

Challenges in Design: Entangled factors;

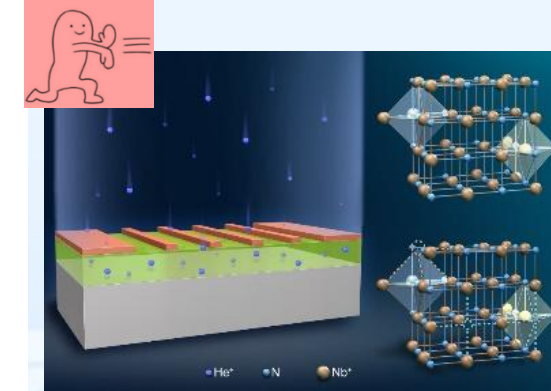
Challenges in Fabrication:

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

Break the trade-off in NbN SSPD

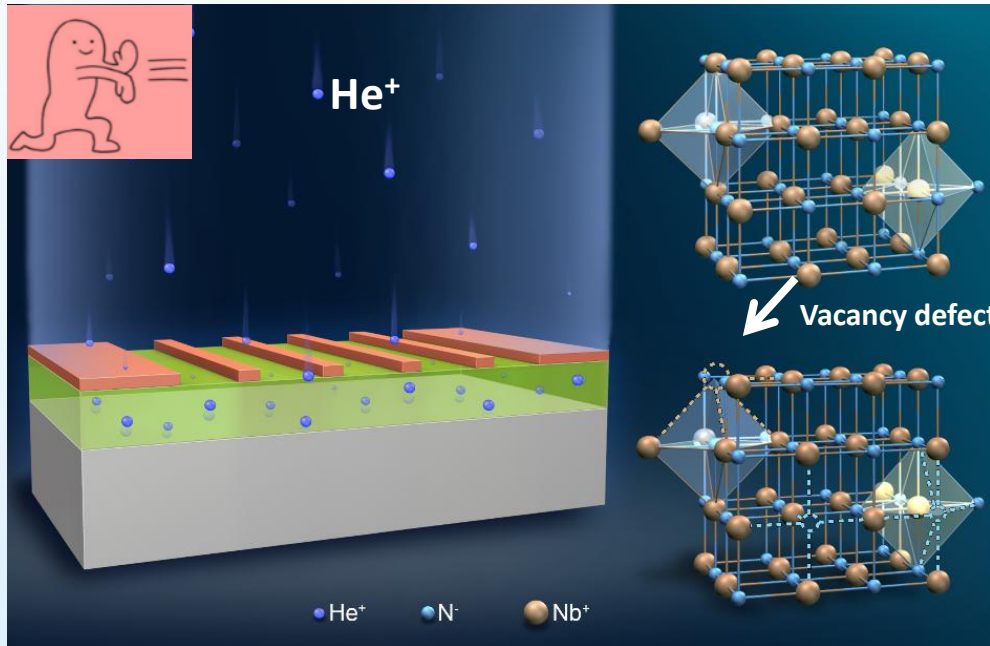


Twin-Layer structure



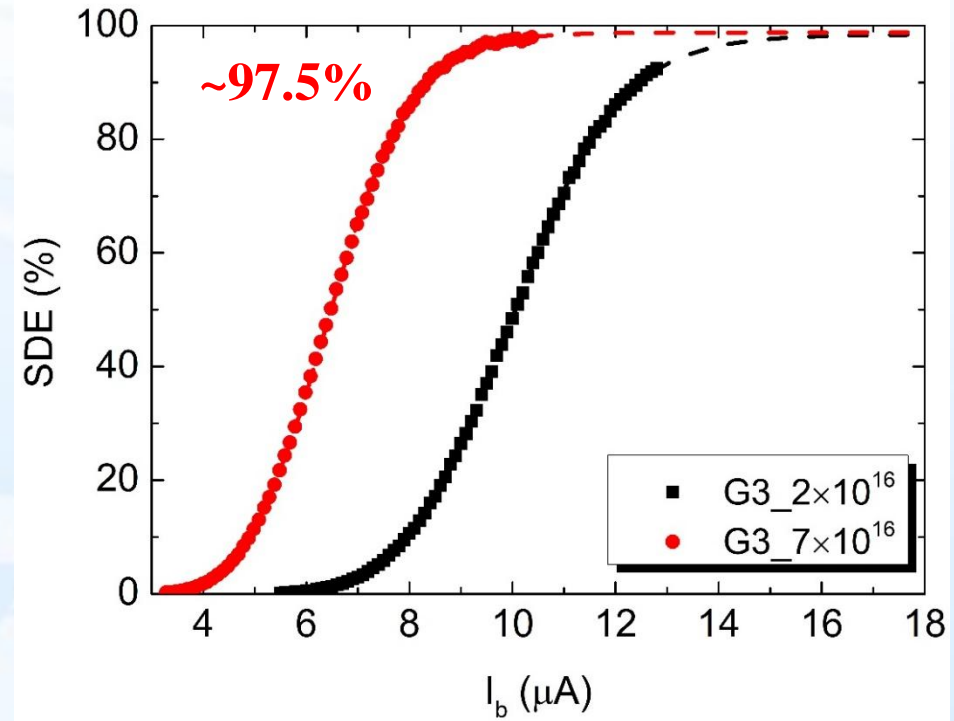
Ion irradiation

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

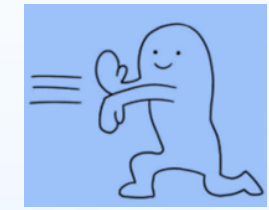
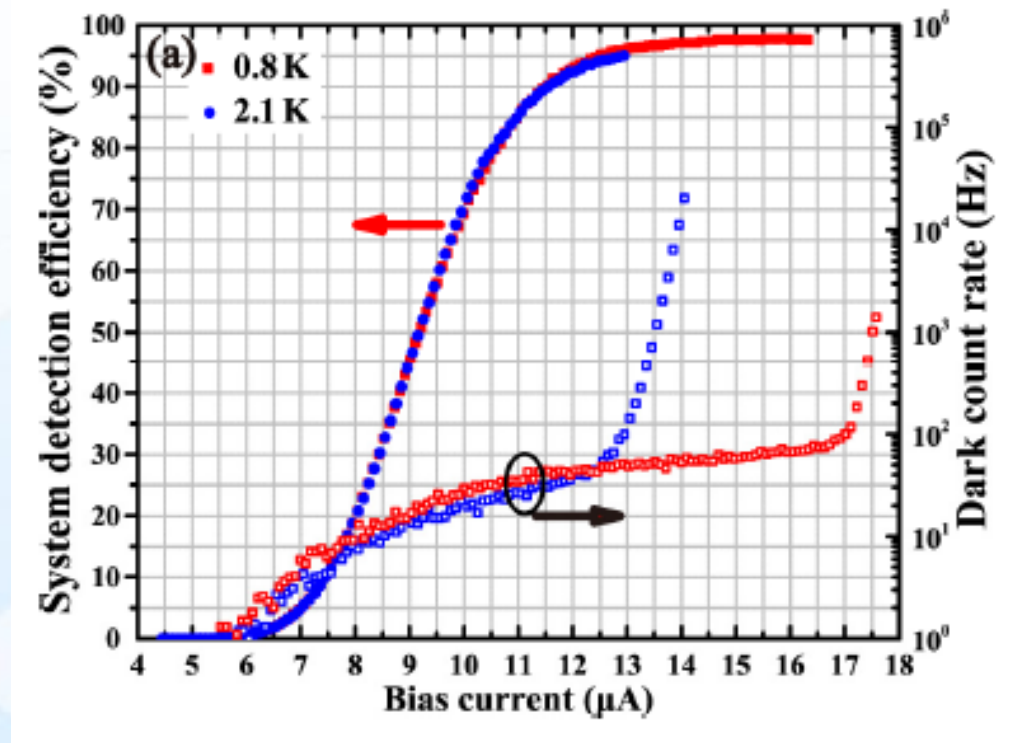
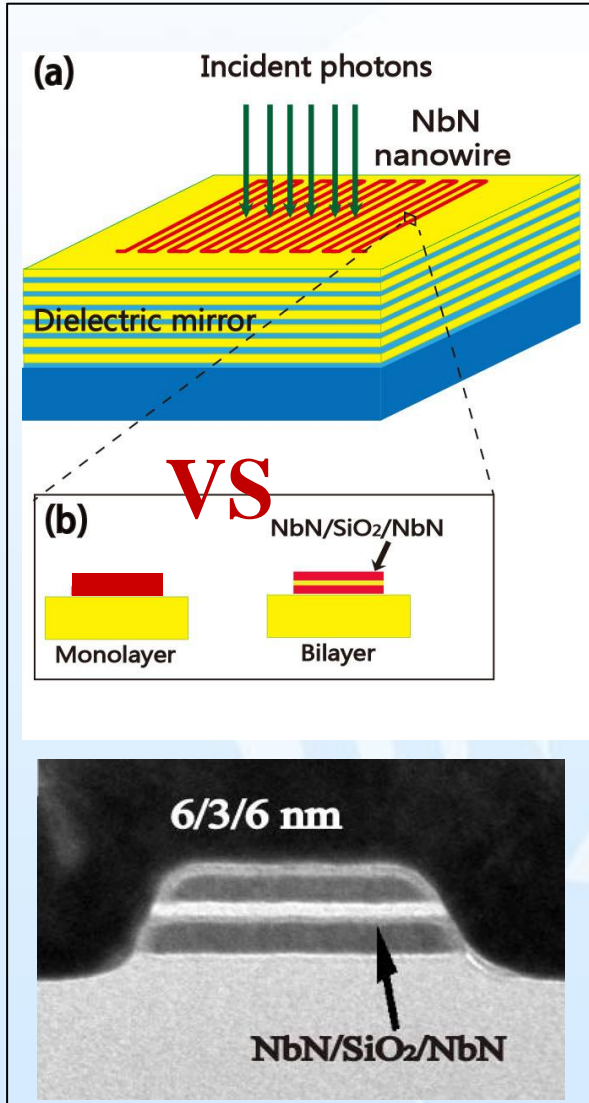


SDE vs I_b for SNSPDs with He ion irradiation

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 simultaneously
- 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

DILEEP V. REDDY,^{1,2,*} ROBERT R. NEREM,³ SAE WOO NAM,² RICHARD P. MIRIN,² AND VARUN B. VERMA²

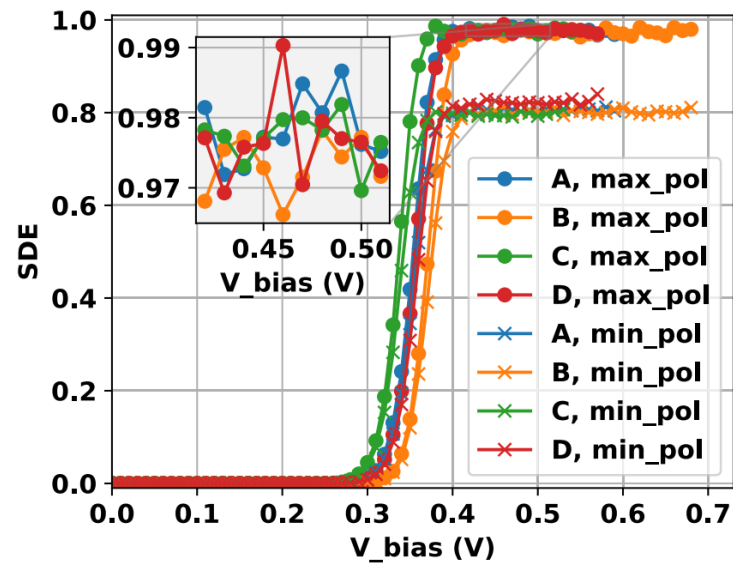
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³Institute for Quantum Science and Technology, University of Calgary, Calgary, Alberta T2N 1N4, Canada

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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

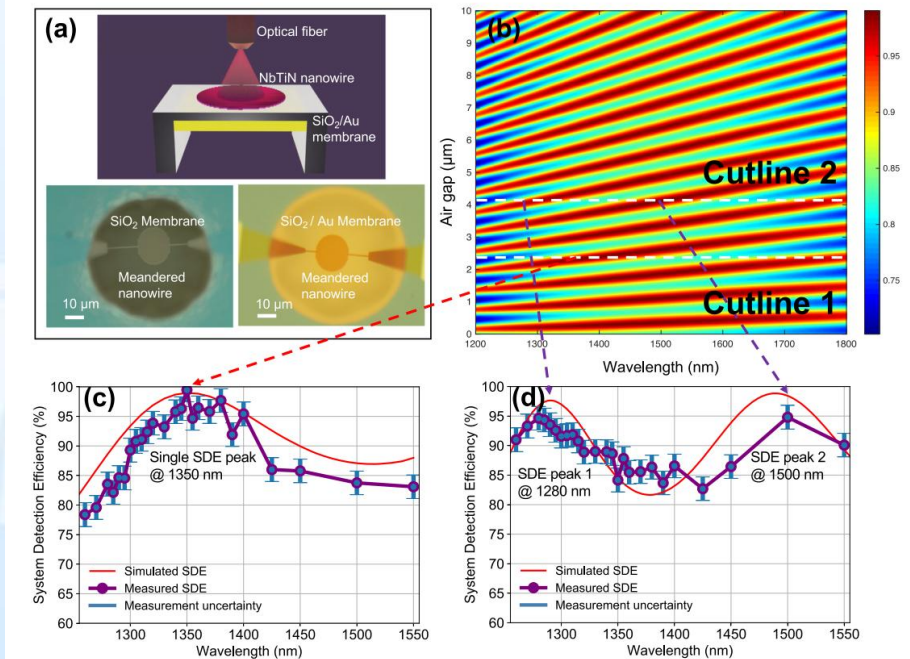
Cite as: APL Photon. 6, 036114 (2021); doi: 10.1063/5.0039772

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Published Online: 30 March 2021



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



SDE99%@1550nm

中国计量科学研究院

测试报告

报告编号 GXgf2024-07093

客户名称 中国科学院上海微系统与信息技术研究所

样品名称 超导纳米线单光子探测器

型号/规格 SSPD / 1550 nm / 3*3mm²

出厂编号 SIMIT - 202405Q2B3 - high2th

生产厂商 中国科学院上海微系统与信息技术研究所

客户地址 上海市长宁区长宁路 865 号

测试日期 2024 年 11 月 23 日

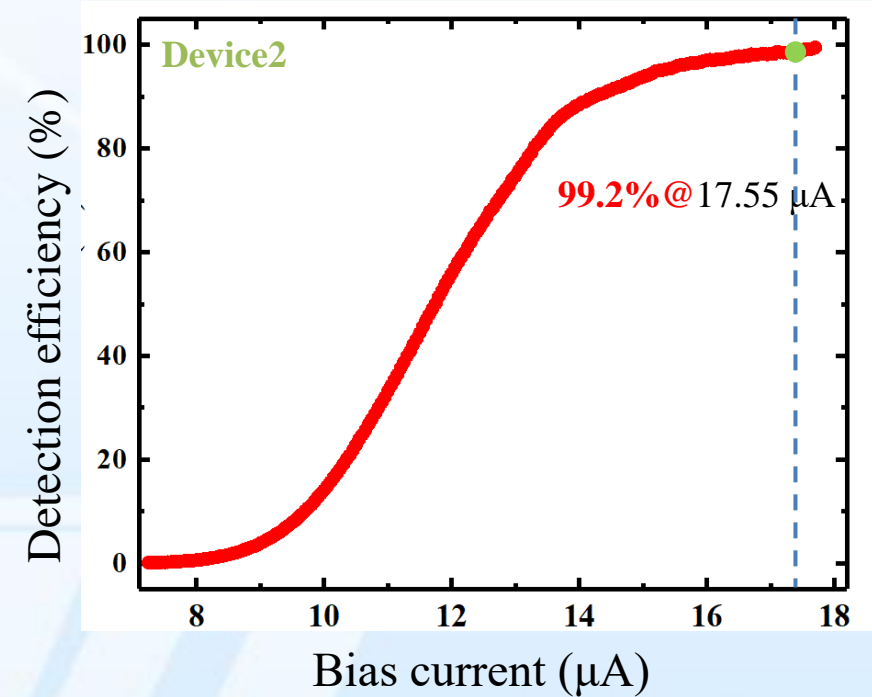
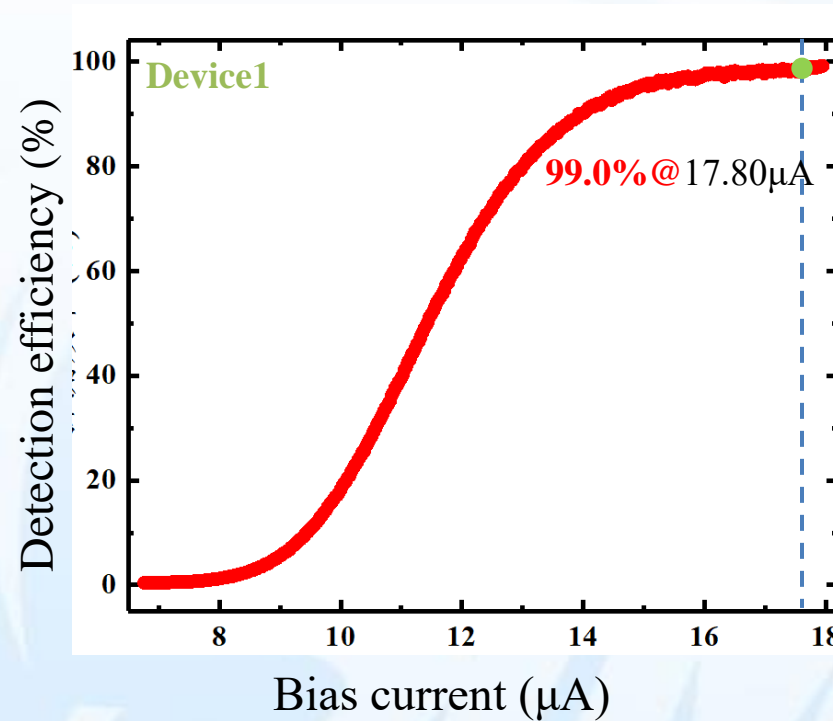
批准人:

地址: 北京北三环东路 18 号 邮编: 100029

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网址: <http://www.nim.ac.cn> 电子邮箱: kehufuwu@nim.ac.cn

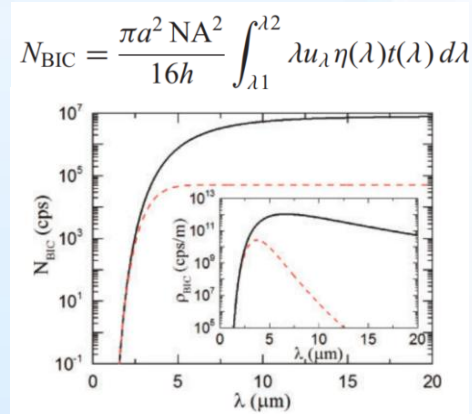
2019-cs-R0520



Uncertainty analysis	Laser power	Polarization	Fiber welding	Wavelength	Photon counting	Uncertainty
Percentage (%)	0.6 (k=2)	0.04 (k=2)	0.1 (k=2)	0.01 (k=2)	0.14 (k=2)	0.89 (k=2)

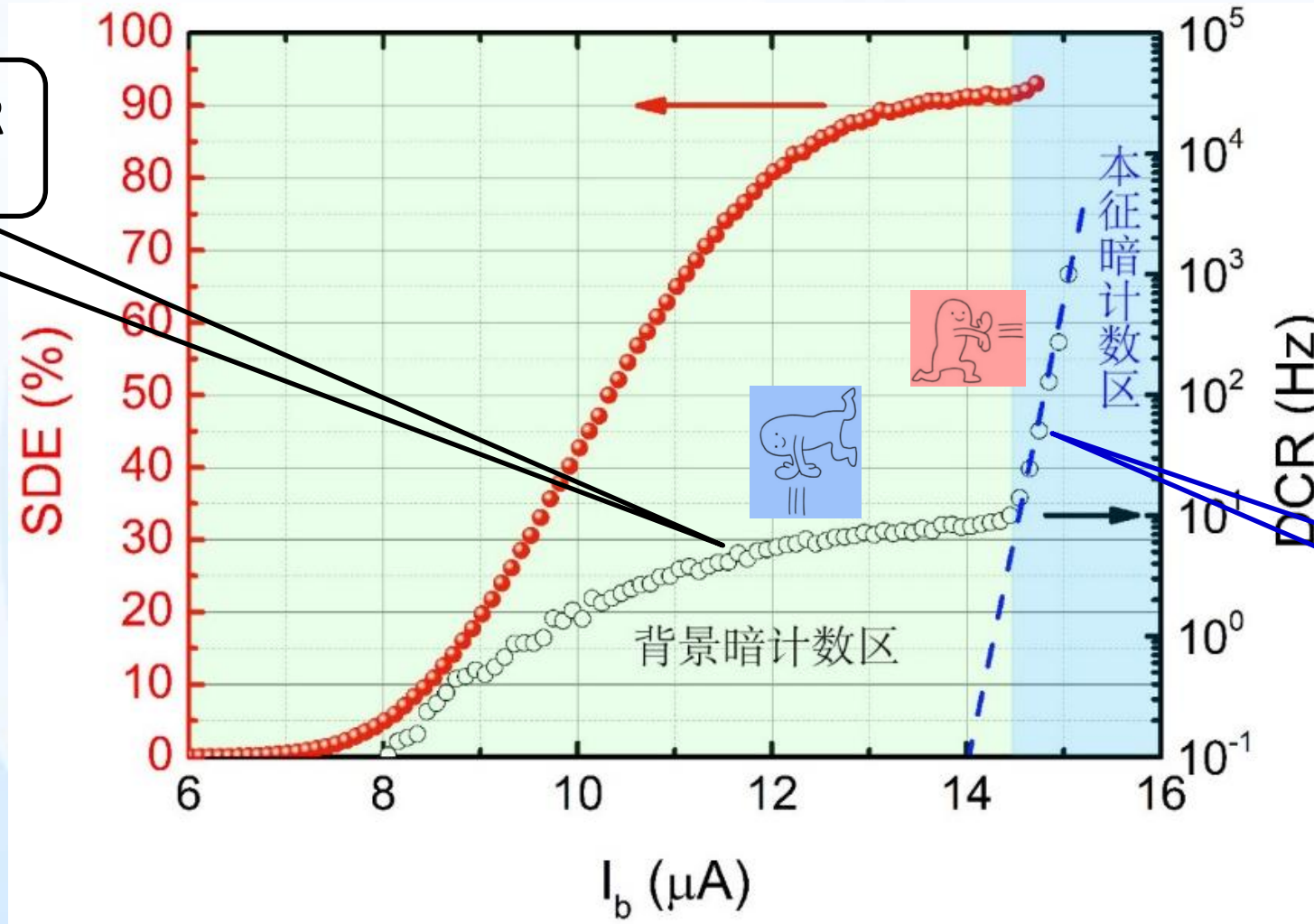
DCR of SSPD

Background DCR
 ~ 10-100 cps



Spectral dependencies of bDCR

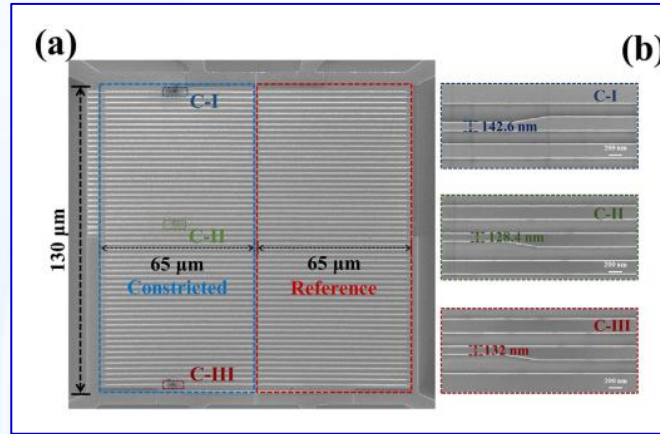
Konstantin, App Phy Exp 8: 022501.
 (2015)



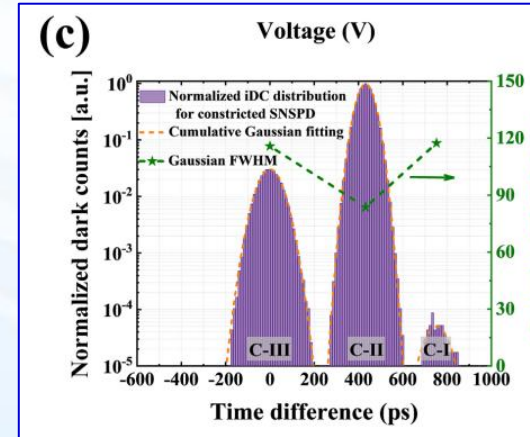
Intrinsic DCR
 I_b sensitive, vortex
 related

Origin of iDCR

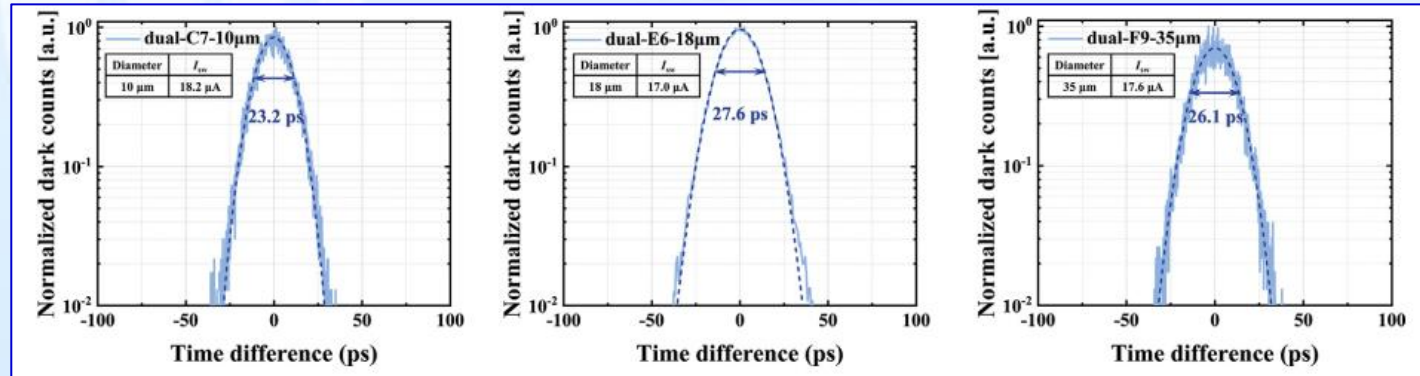
Superconductivity 1: 100006 (2022)



DUT with artificial defects



iDCR in time domain

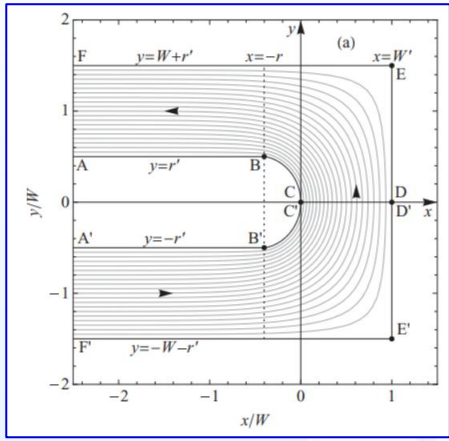


iDCR of Conventional SSPDs in time domain

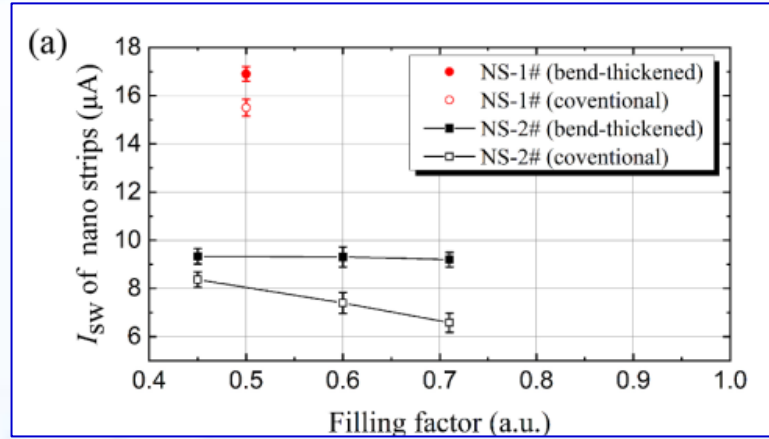
Conclusion: iDCR of typical SSPDs is contributed by the **single (weakest) defect/constriction**



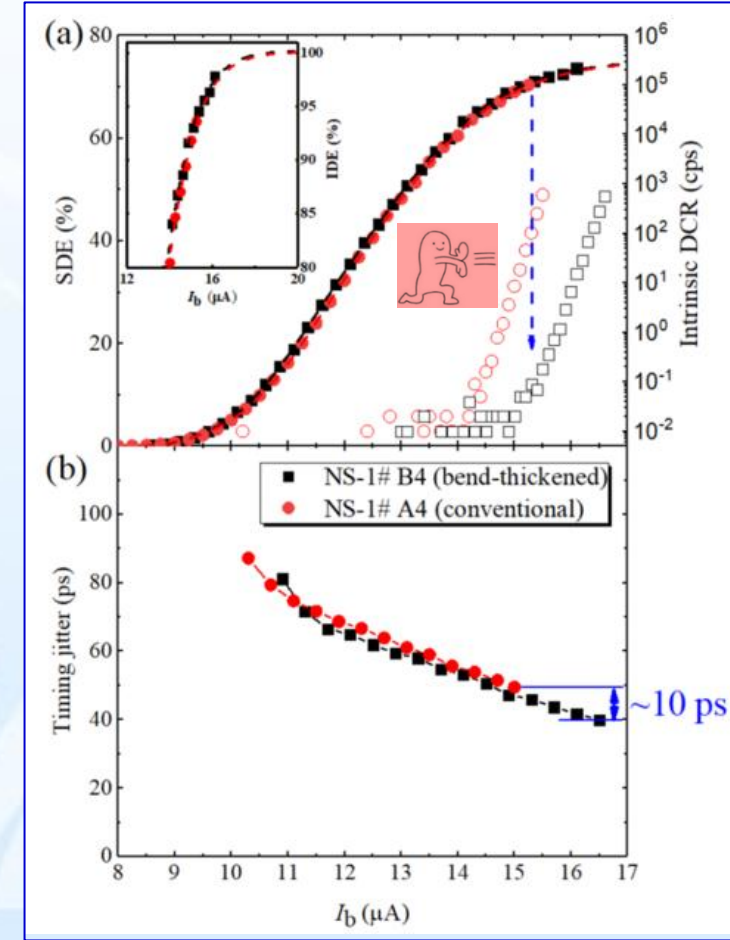
Fight with current crowding effect



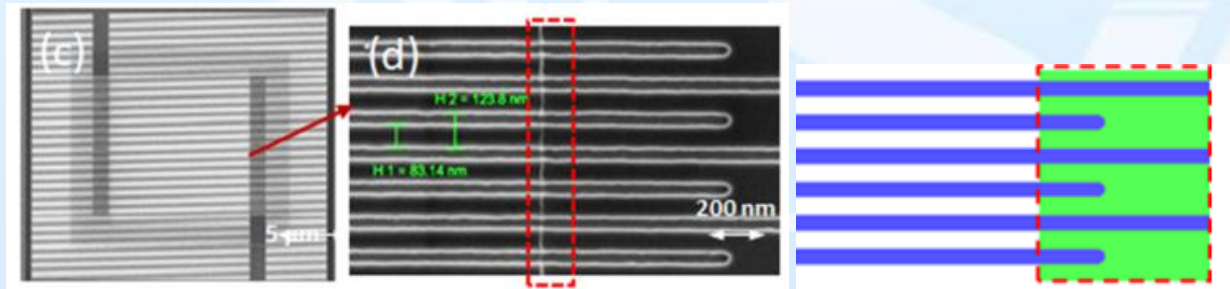
Crowding effect in bending area
 J. R. Clem and K. K. Berggren.
 PRB 84 174510 . (2011)



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



Maximum SDE ↑ , DCR & TJ ↓

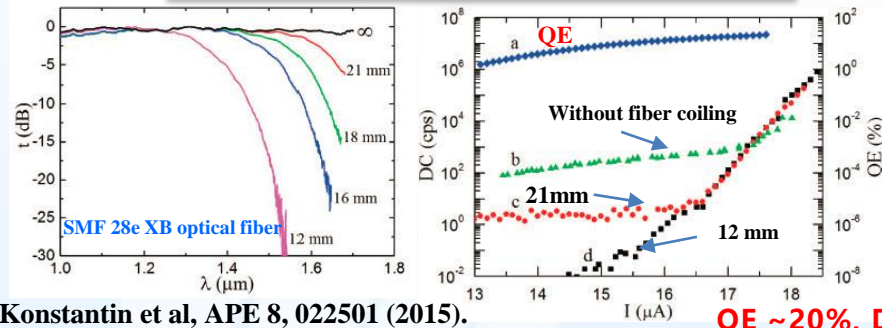


SSPDs with thicker bending area



Suppress background DCR

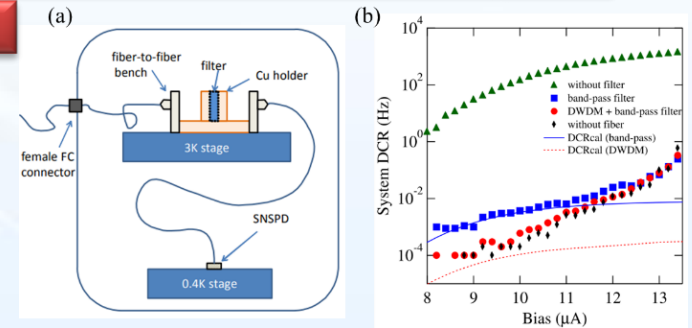
coiled fiber as a short-pass filter



Konstantin et al, APE 8, 022501 (2015). **QE ~20%, DCR ~4 cps**

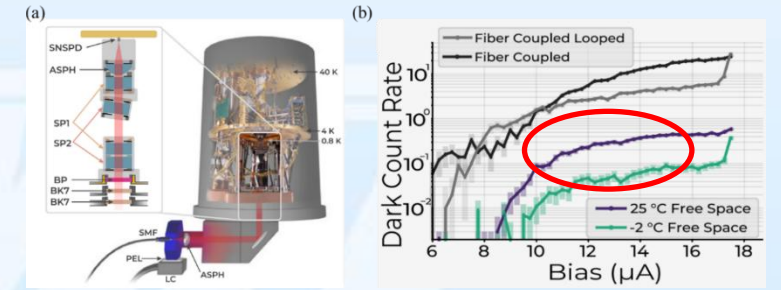
bandpass filter bench (bulk filter)

fiber-to-fiber



SDE ~2.3%, DCR ~10⁻³ cps
 Shibata et al, Opt. Lett., 40, 3428 (2015).

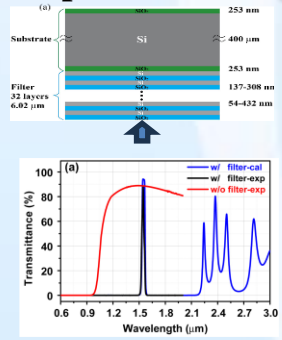
free-space



SDE~72%, DCR ~0.1 cps
 Mueller et al, Optica, 8, 1586 (2021).

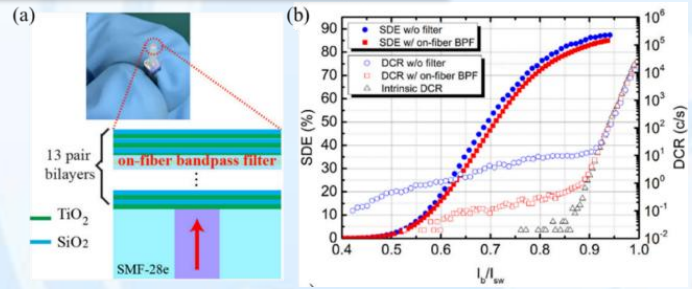
integrated bandpass filter

on-chip filter



SDE ~56%, DCR ~1 cps
 Opt. Express 22, 16267 (2014).

on-fiber filter



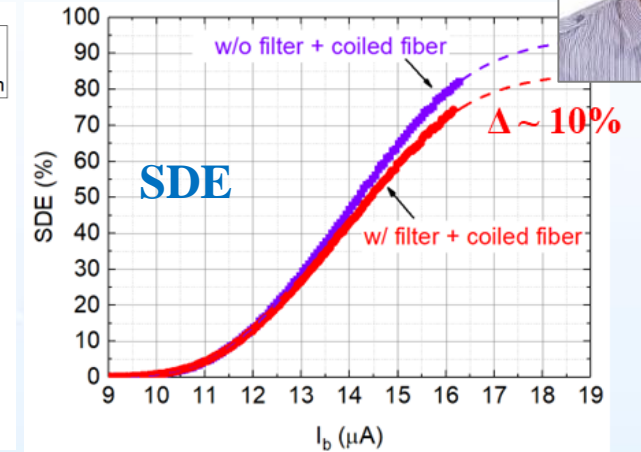
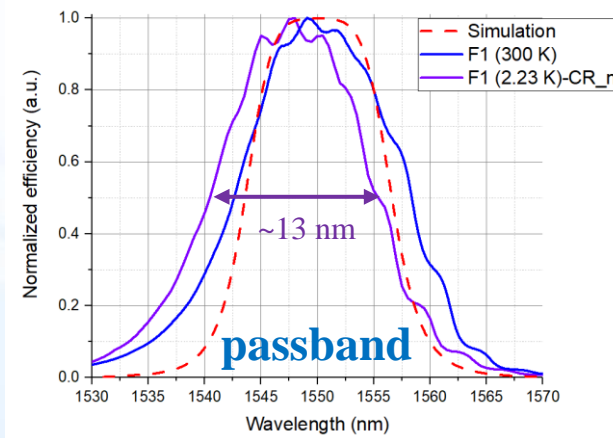
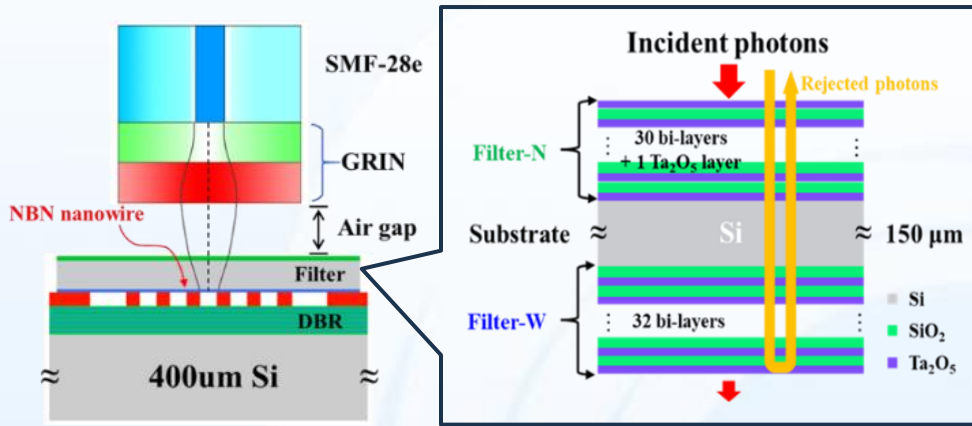
SDE ~80%, DCR ~0.5 cps
 SUST, 31 035012 (2018).

Patents issued in USA, JP and CN

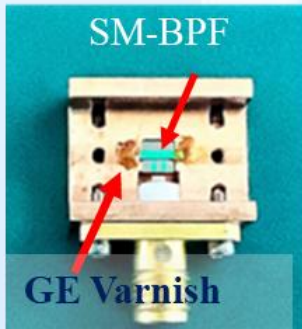
Challenging: cryogenic optical filter with low insert loss, wide stopbands, and narrow passbands



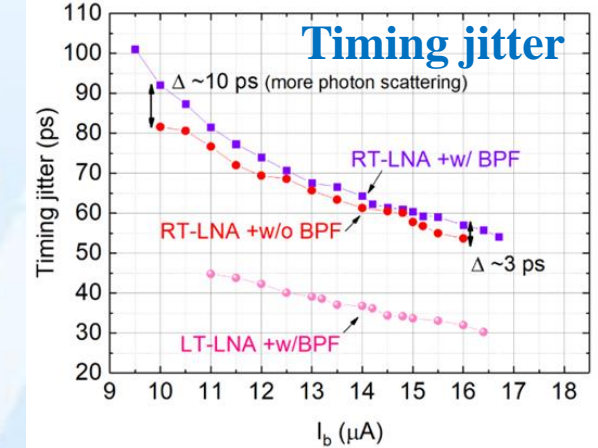
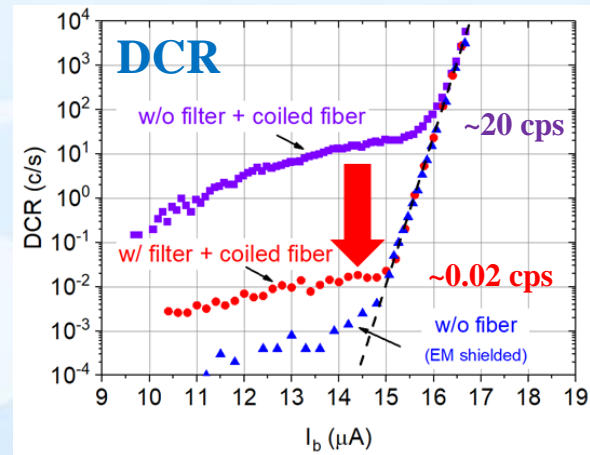
SSPDs with low DCR or high SNR



Surface-Mount bandpass filter (SM-BPF)



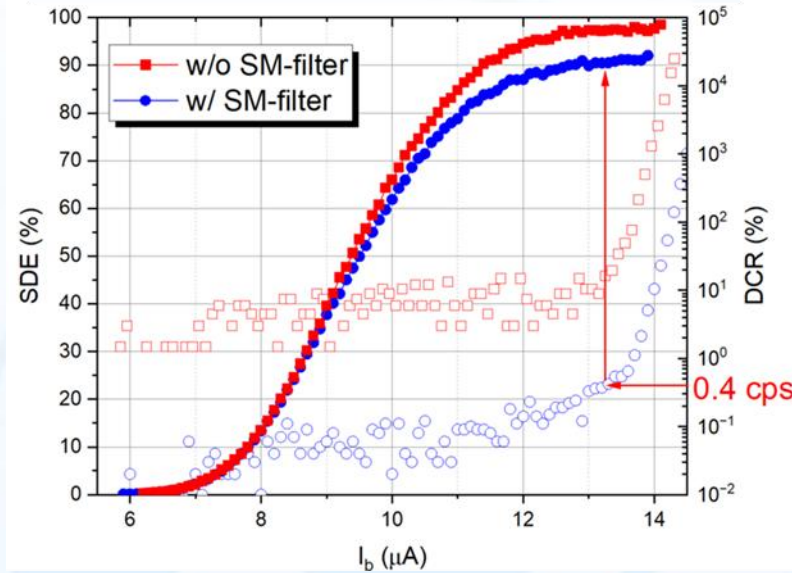
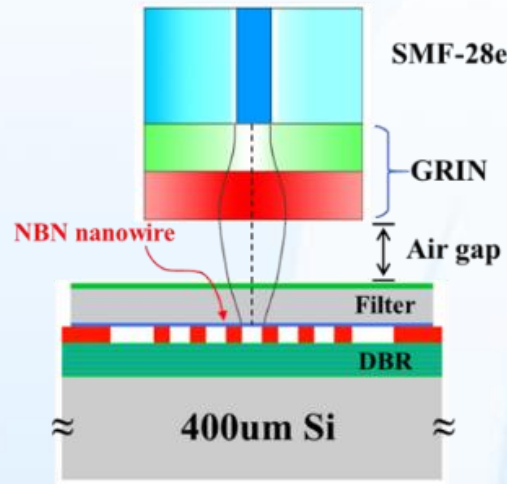
- compact packaging
- Promising mass production
- **independent optimization**
- stopband up to 2.2 μm



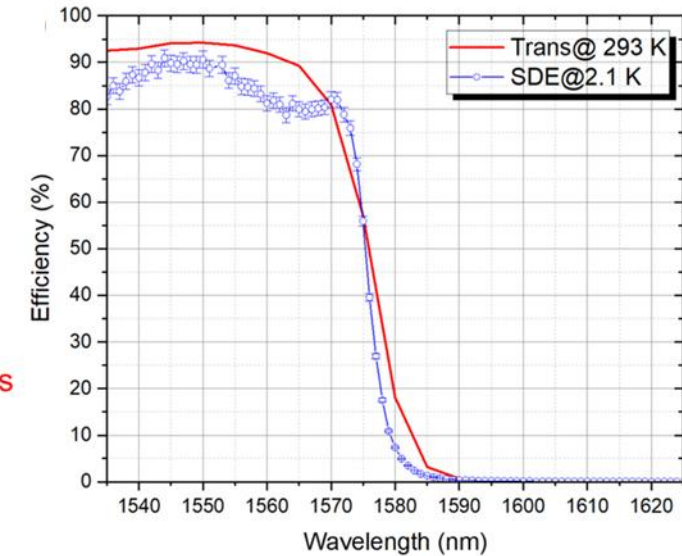
- SDE $\sim 60\%$, DCR ~ 0.02 cps, TJ ~ 34 ps (40K cryo-LNA) @ 15 μA
- Figure of merits (FOM) = $\text{SDE}/(\text{DCR} \cdot \text{TJ}) \sim 8.8 \times 10^{11}$



SM-BPF with a high transmittance



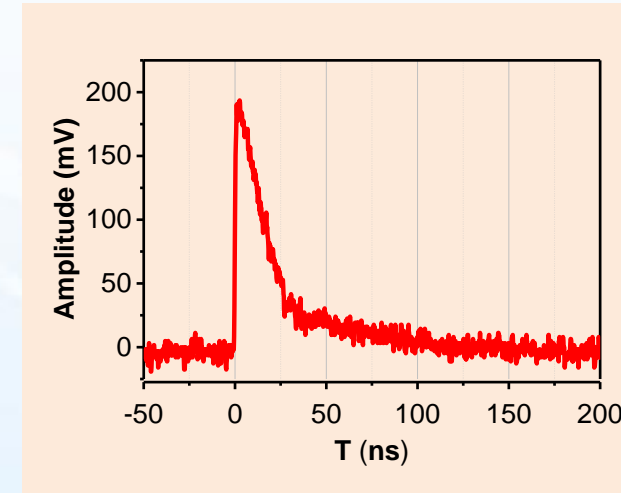
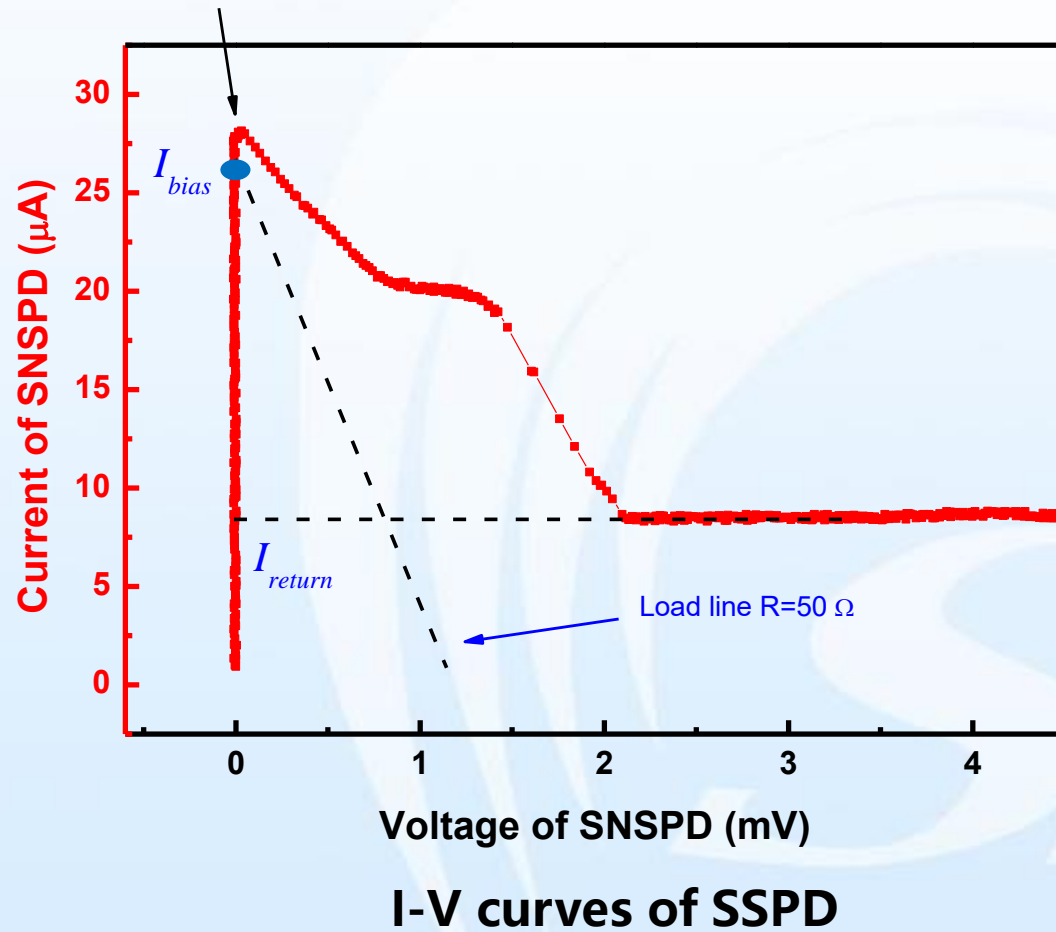
SDE and DCR vs bias current with and without SM-BPF



Room temperature transmission spectrum vs SDE wavelength dependence

- a SM-BPF with **~94%** transmittance packaged with a SSPD featuring **~98%** SDE at 1550 nm
- SDE **~90.5%**@ 0.4 cps

PNR of SSPDs



Single photon response in time domain

Amplitude

$$V_{pulse} = \frac{R_n}{R_n + Z_0} \cdot I_b \cdot Z_0 \cdot G$$

Rising Edge

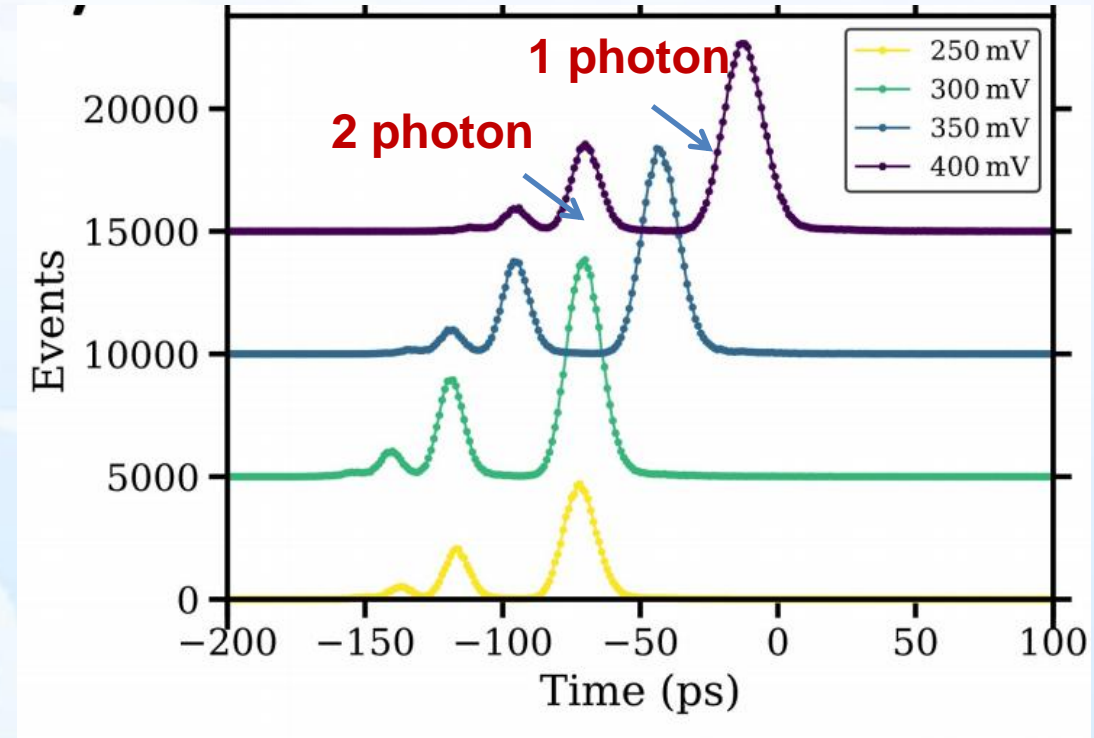
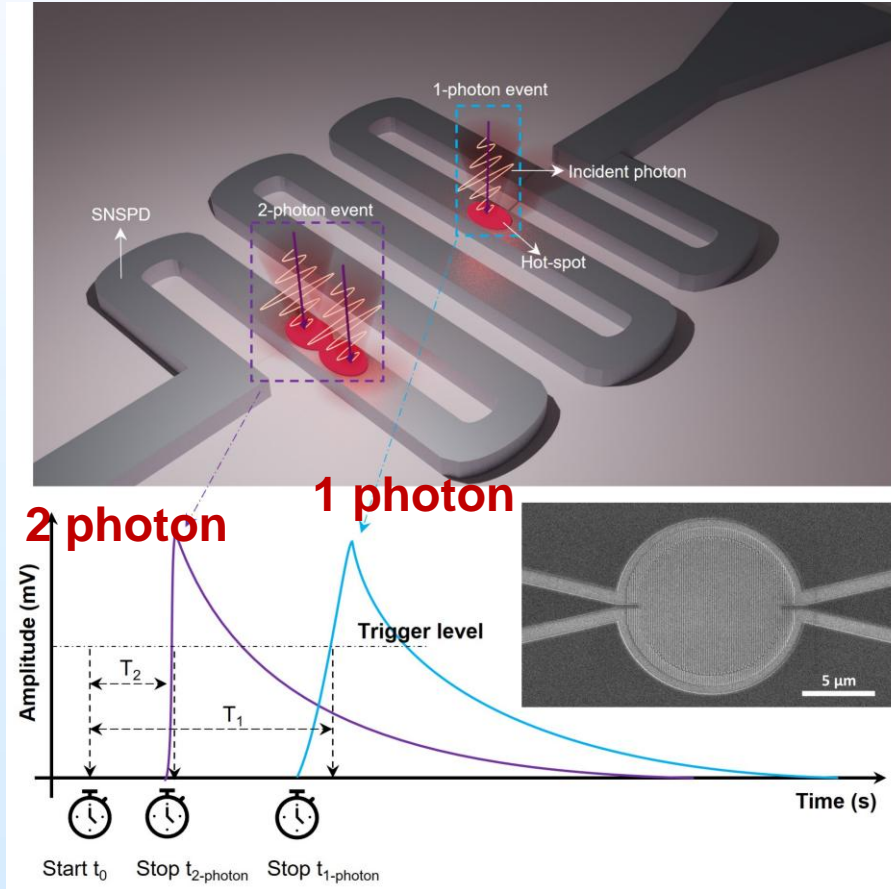
$$\tau_{rise} = \frac{L_k}{R_n + Z_0}$$

Falling Edge

$$\tau_{fall} = \frac{L_k}{Z_0}$$

Conclusion: SSPD is a switch, which do not have PNR

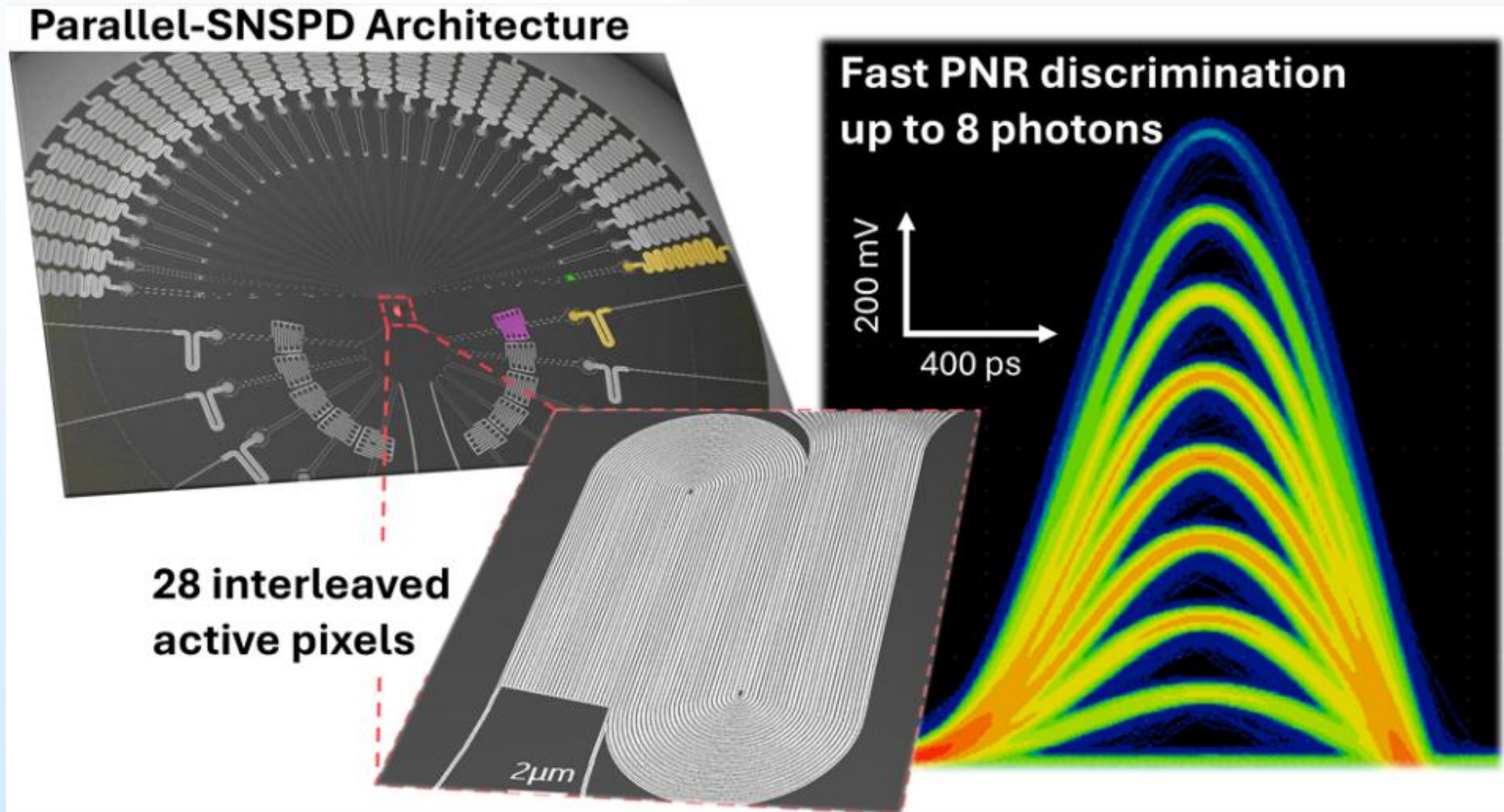
- Recently, with improved measurement resolution, conventional SSPD has been found to resolve photon numbers with **the arrival time** or **rising edge of the response pulse**.



TCSPC measurement

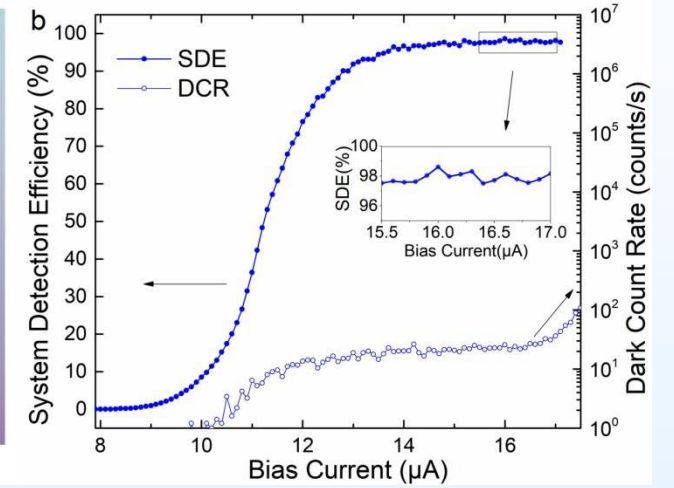
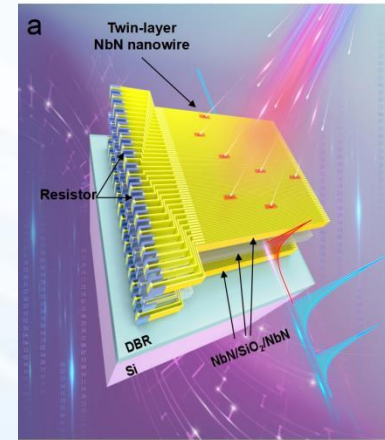
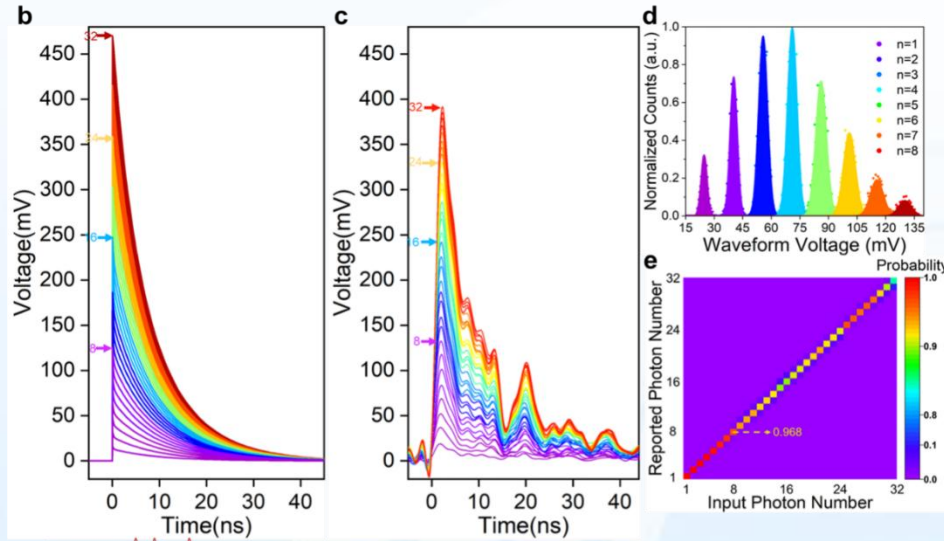
- The measurement is similar to the timing jitter measurement

Fast parallel SSPD with PNR of up to 8

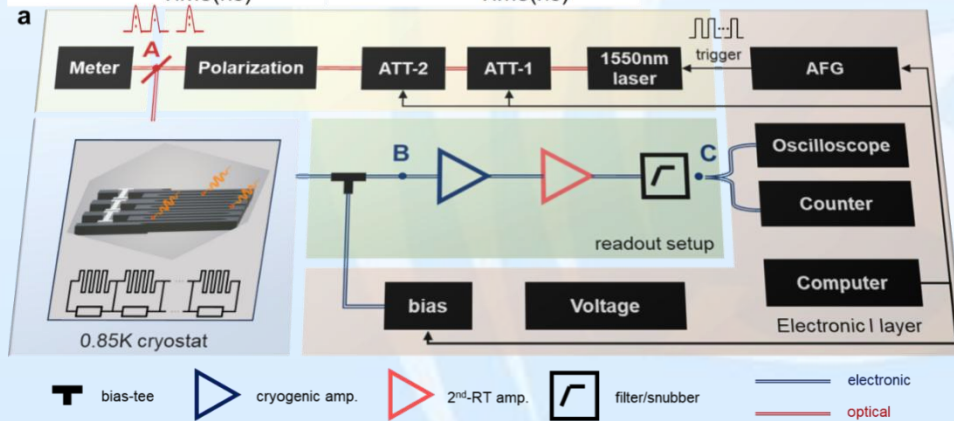


ID Quantique, ACS Photonics 2025, 12, 320

SSPD with PNR ~ 32



SSPD with high efficiency and PNR (SDE ~ 98%, PNR ~ 32)



PNR with Resistive-shunted SSPDs

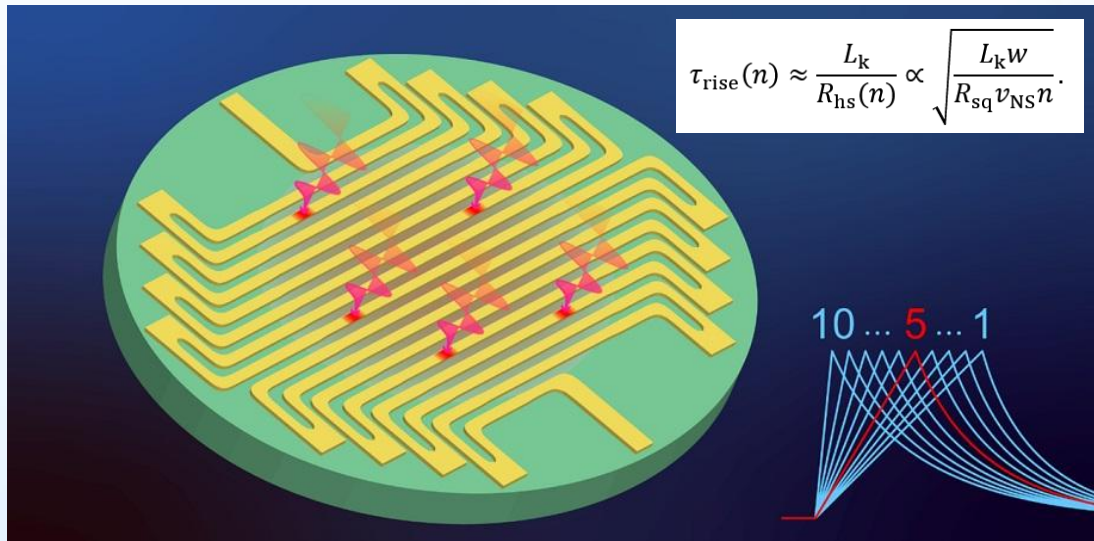
P	Input photons m						
	0	1	2	3	4	5	6
0	1.000	0.025	0.043	0.053	0.074	0.085	0.090
1		0.975	0.082	0.079	0.125	0.132	0.118
2			0.874	0.135	0.191	0.195	0.167
3				0.734	0.205	0.132	0.111
4					0.405	0.186	0.136
5						0.271	0.164
6							0.215

Fidelity of Multi-photon

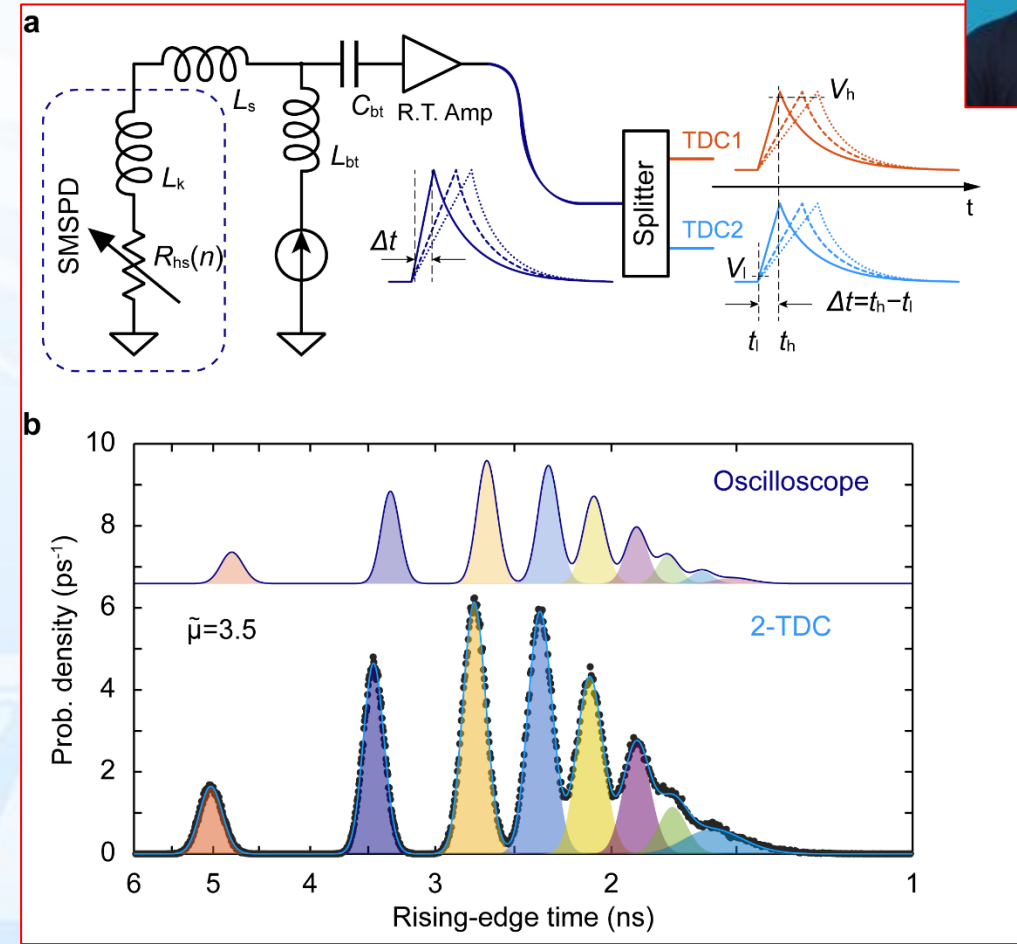
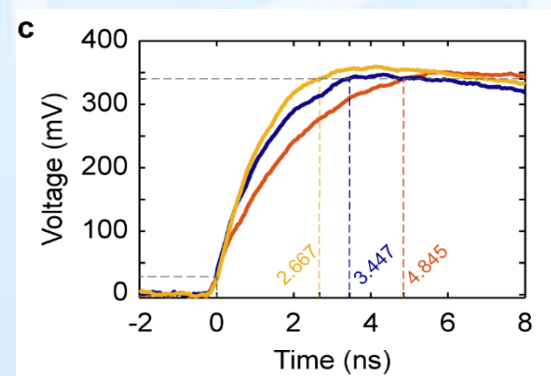
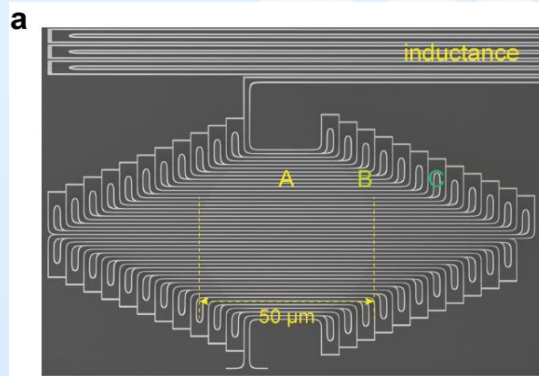
- ✓ **Single channel readout;**
- ✓ **High efficiency (98%);**
- ✓ **Low noise (20 cps)**
- ✓ **High PNR (32)**
- ✓ **High Fidelity**



Microstrip SSPD with PNR ~ 10



Schematics (top) and experimental results (bottom)



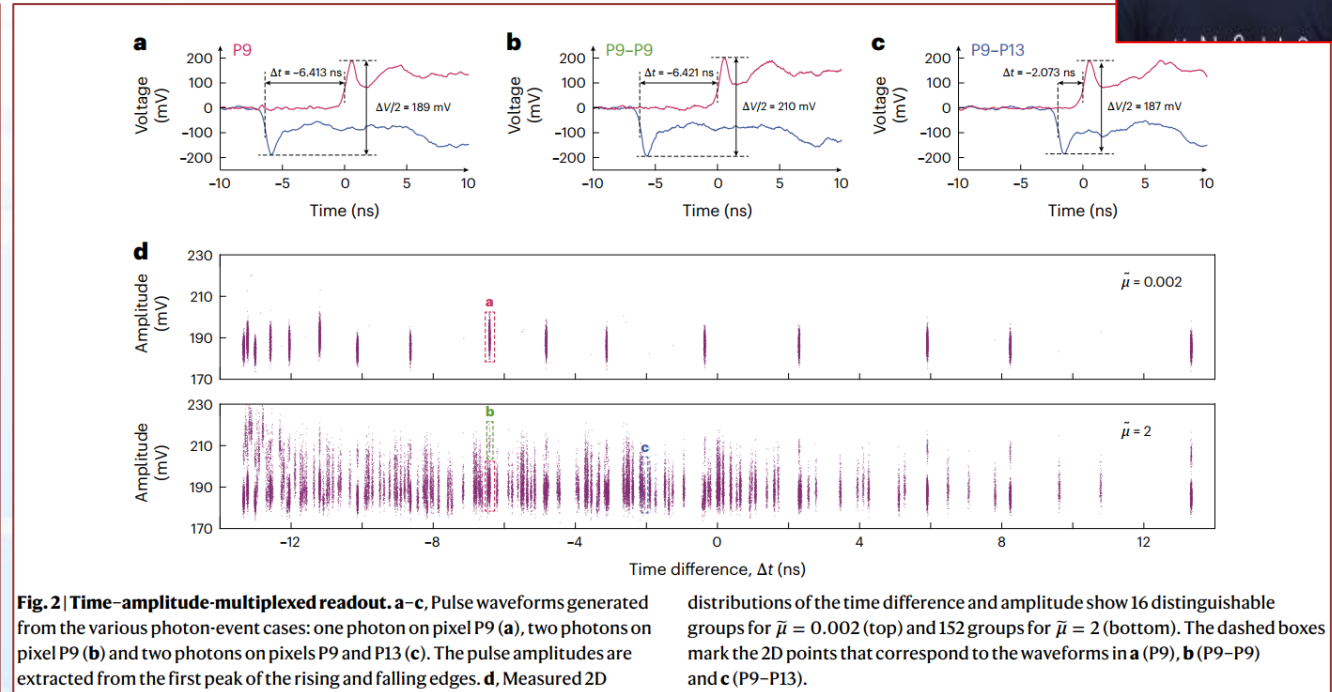
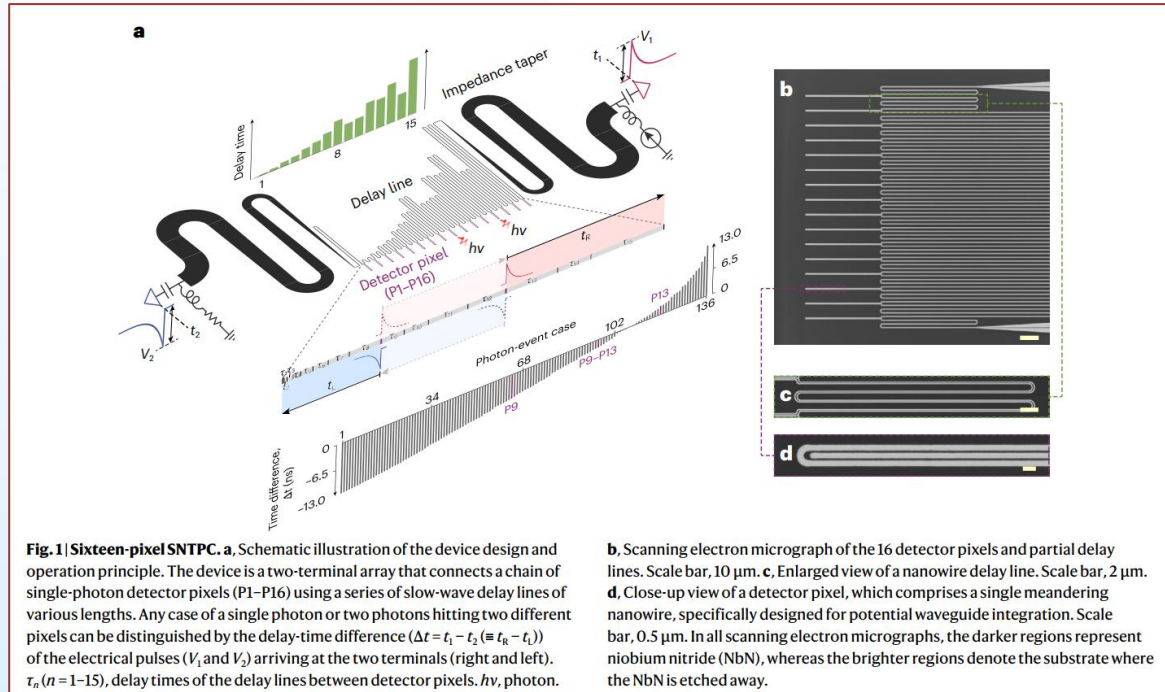
PNR up to 10 photons

With using microstrip and increase L to **tune the slope of rising edge** for different incident photons and **improve SNR**

Advanced Photonics 6: 016004. (2024)



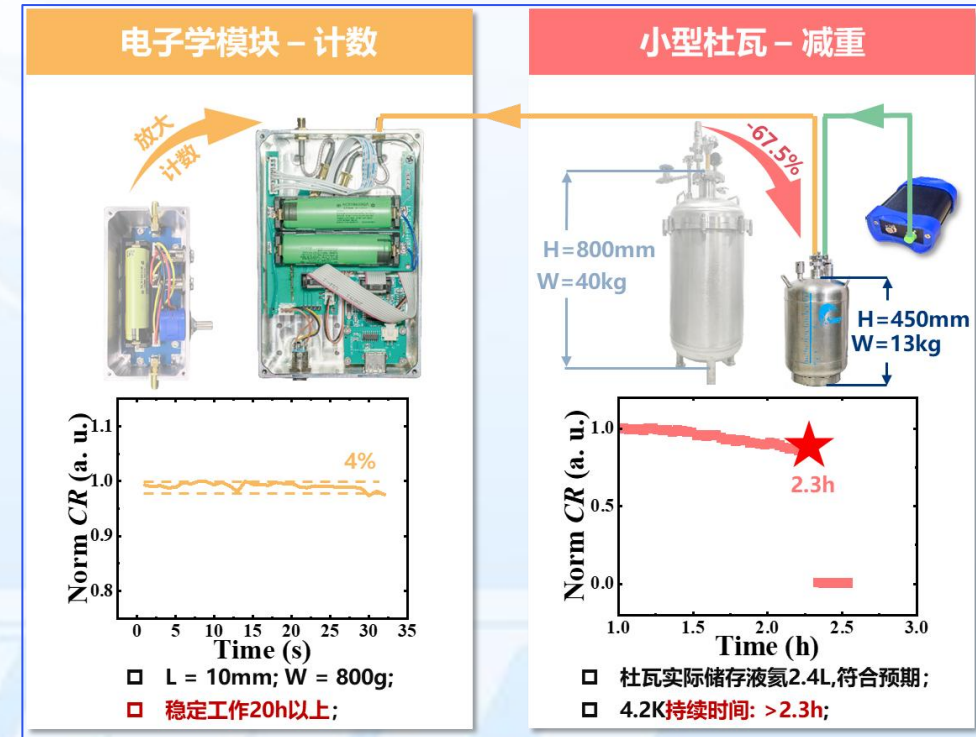
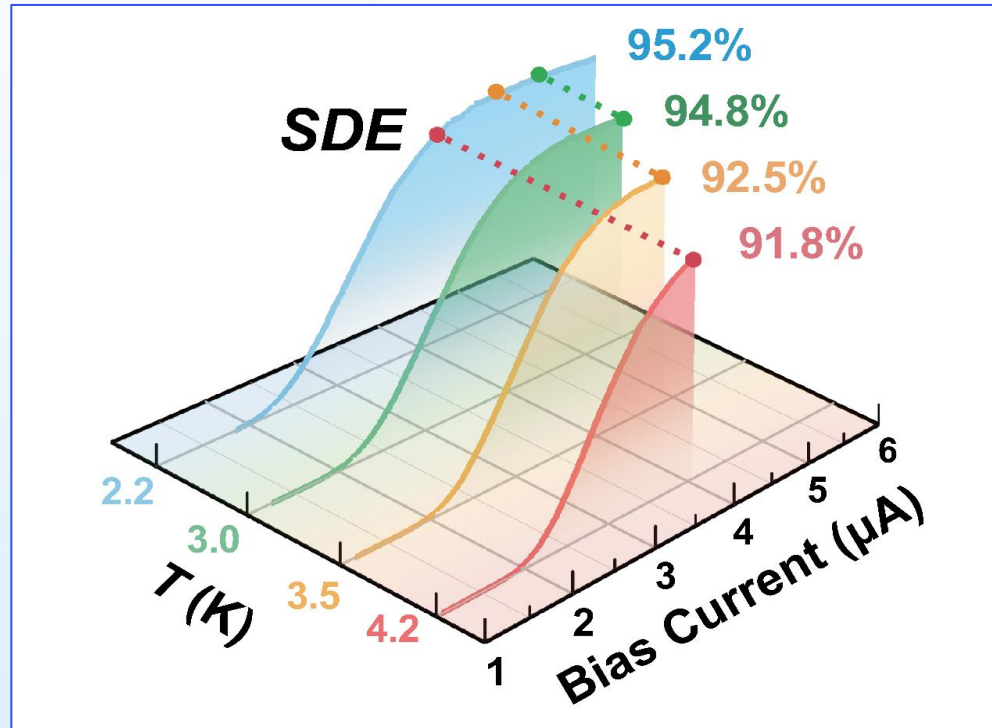
Two-photon coincidence counter



Two-terminal two-photon coincidence counter using SSPDs with customized delay-time series, which resolves all 152 potential single- and two-photon events in a 16-pixel configuration, with combinatorial time logic and amplitude multiplexing.

Kong et al, Nature Photonics, 19: 407 (2025)

SSPD@4.2K, Drone-based SSPD



Material optimization \rightarrow T from 2.2K to 4.2K

Operation in LHe

Drone-based SSPD system w/ SDE>90% @ 1550 nm

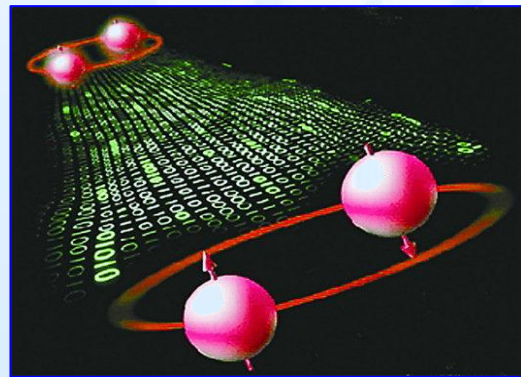
Optics Express 31: 30650 (2023) ; AP Nexus 4: 026003. (2025)

Content

- Background & Introduction
- SSPD with high performance
- Applications
- Summary

Quantum Information

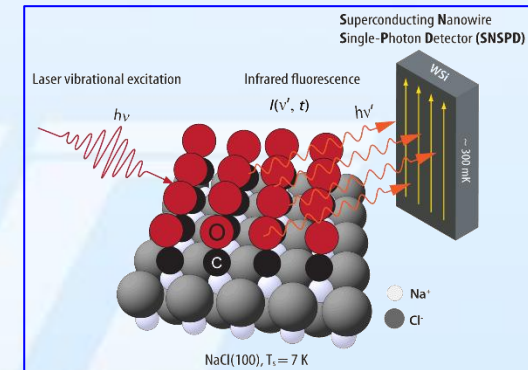
Quantum Communication



Quantum Computation



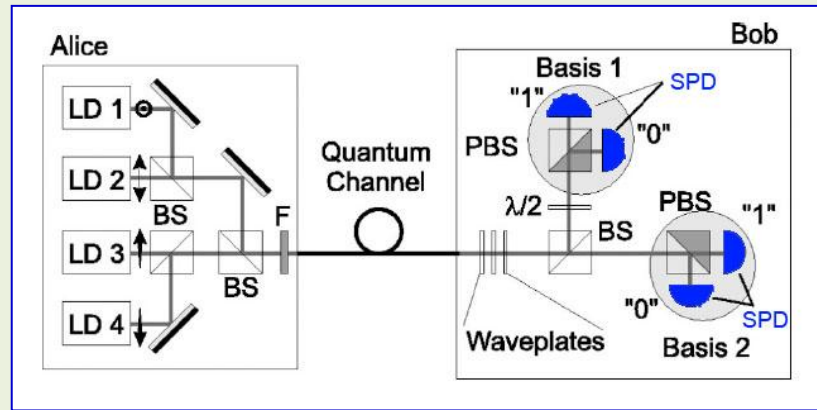
Quantum Metrology



SSPD plays indispensable role in QIP

Requirements from QI

QKD

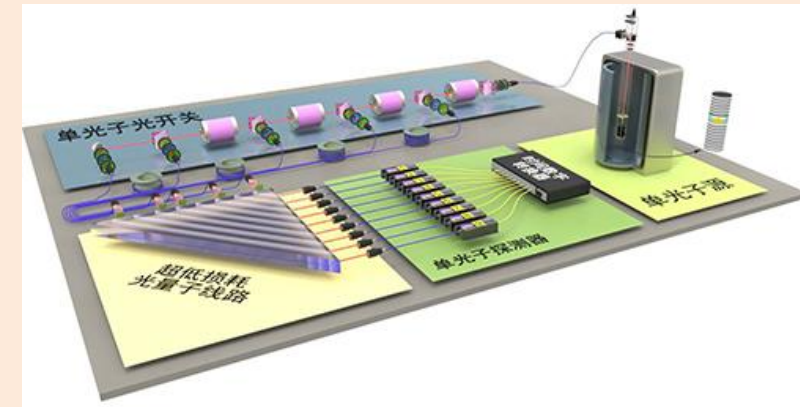


$$\begin{cases} K_u \text{ (final secure key rate)} \propto f \cdot \mu \cdot L \cdot DE \\ ER \propto R_{dc} / K_u \end{cases}$$

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

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

USTC 2014:
200 km MDI-QKD

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

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

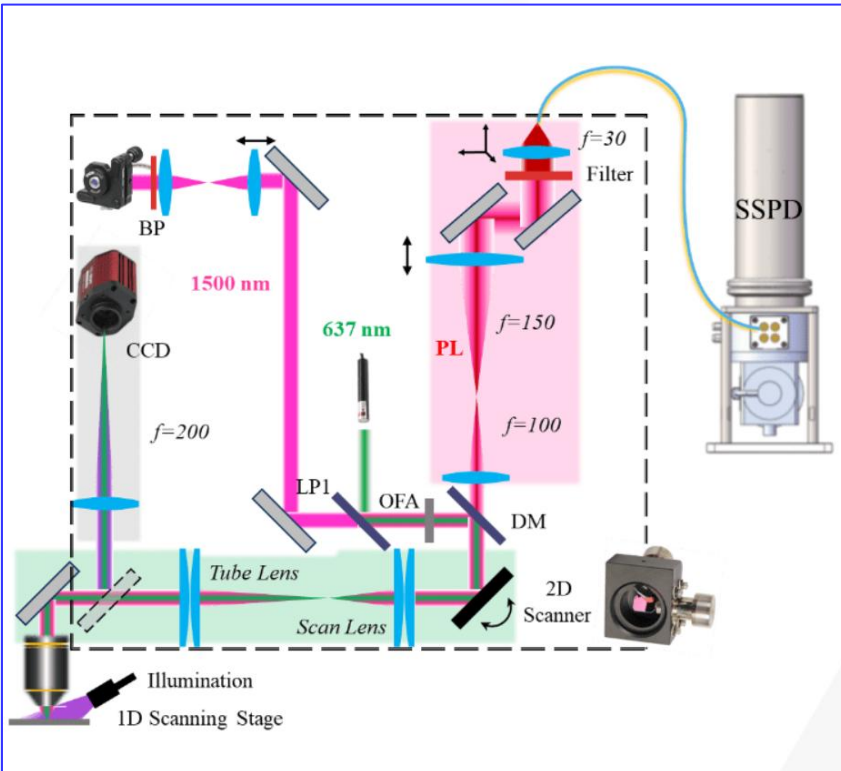
2023: TF-QKD over 1000 km
using **SSPDs w/ ultralow DCR**

2023: TF-QKD w/ 110 Mbps (10 km)
using **SSPDs w/ high speed**

- ❑ PRL 130: 210801 (2023)
- ❑ Nature Photon 17: 416 (2023)

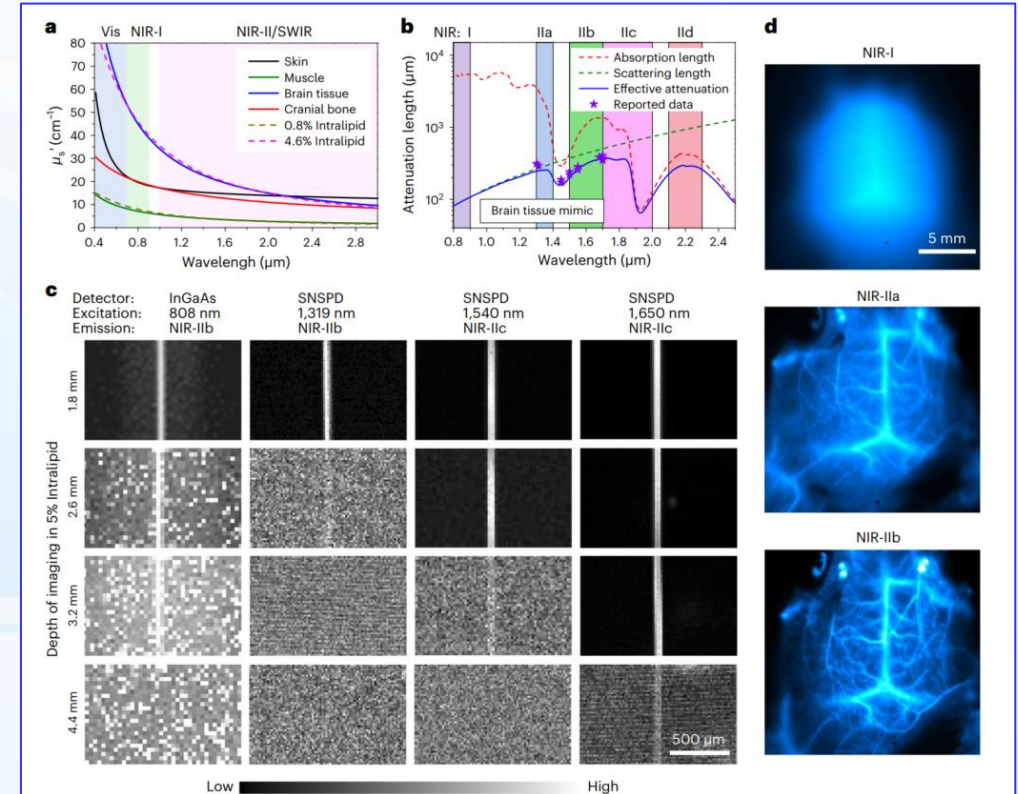
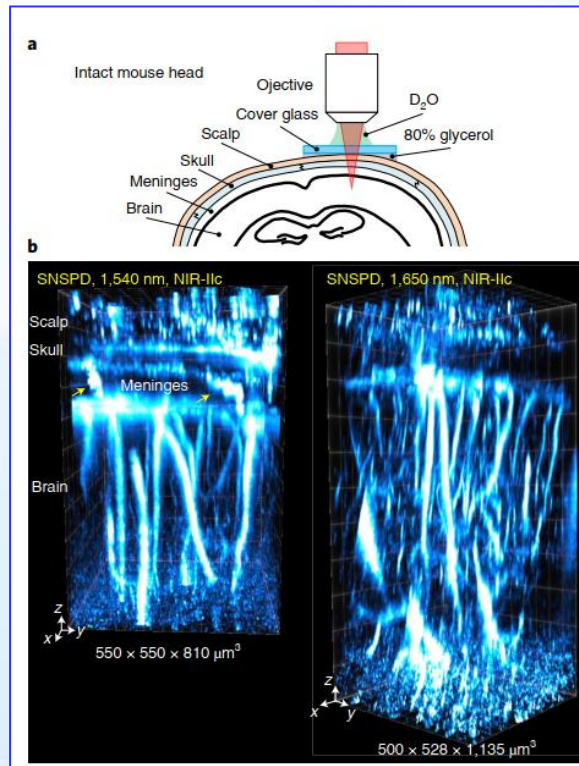
SSPDs had advanced QKD effectively

SSPDs for fluorescence imaging



Confocal microscopy using SSPD

- ❑ NIR with Wavelength over 2 μm ;
- ❑ Quantum limit sensitivity;
- ❑ Large penetration depth for biological imaging

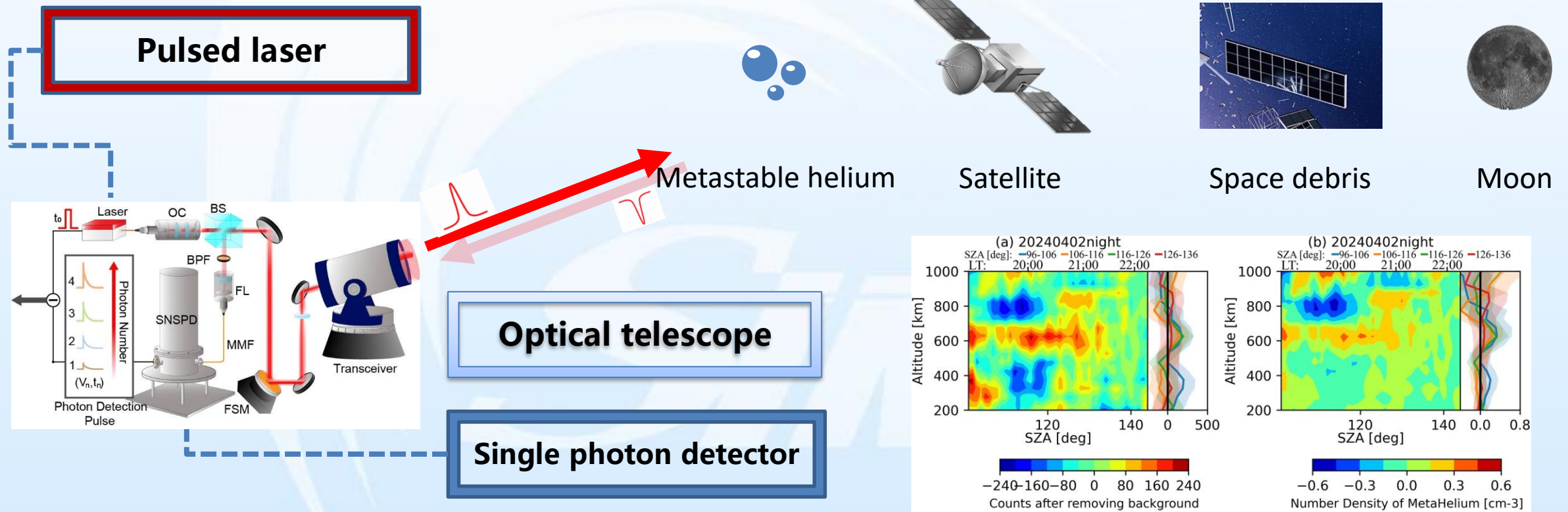


Non-invasive in vivo confocal microscopy in NIR-II

Nature Photonics. (2024), HJ Dai @ Stanford Univ
<https://doi.org/10.1038/s41566-024-01391-5>

SSPDs for remote sensing

Nanjing University applied his high-speed SSPDs with a large detection area to **detect metastable helium in space, range satellite and moon-to-earth.**



Space Weather, 2024, e2024SW003977.

Courtesy of Prof. Labao Zhang



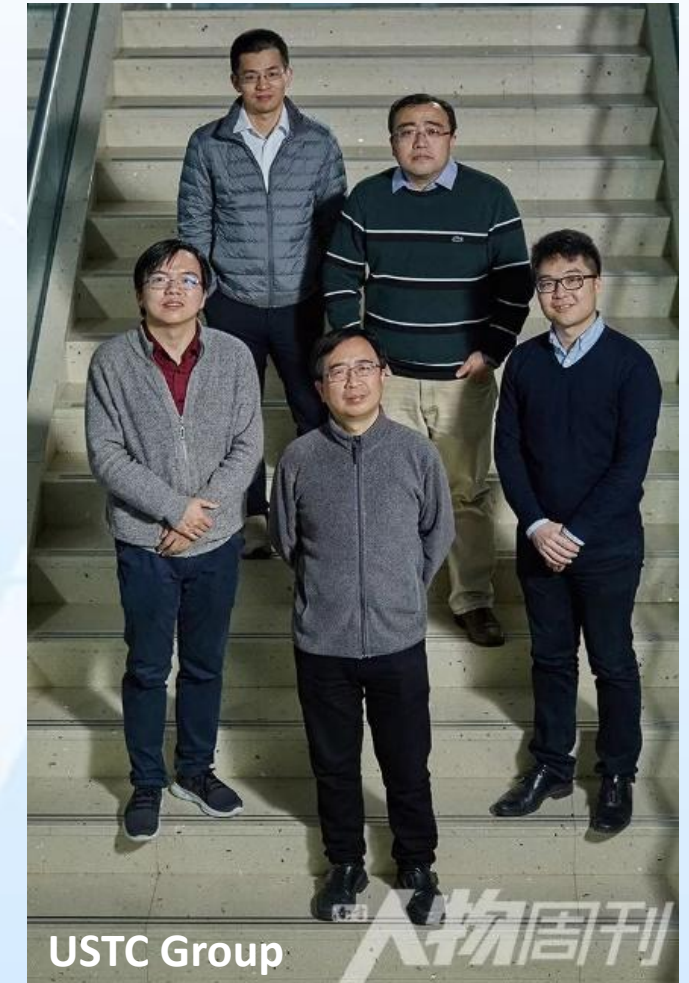
Niche market



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

Conclusion

- ❑ SSPDs outperform semiconducting counterparts
- ❑ Many applications of SSPDs for QIP
- ❑ Niche market available for SSPDs



Superconducting Electronics Facility (SELF)



We are looking for young talents to join SIMIT-CAS

Contact: lxyou@mail.sim.ac.cn