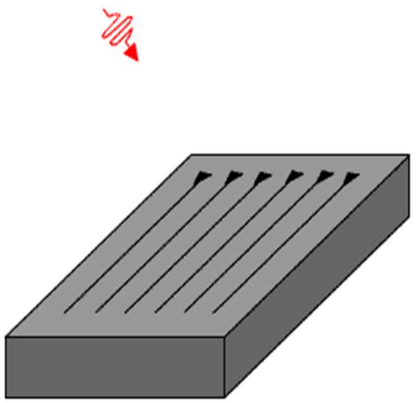
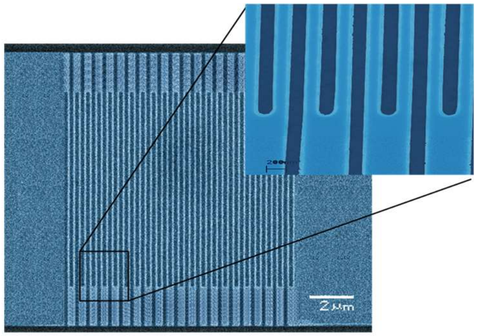
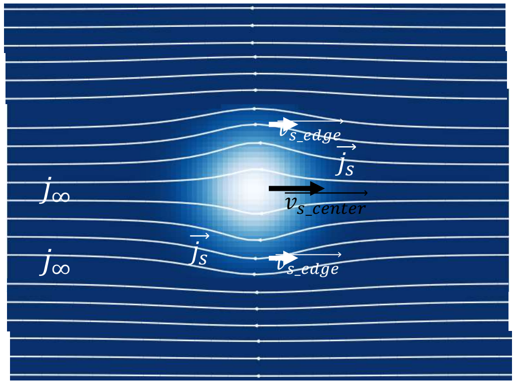
Сверхпроводниковые однофотонные детекторы: физика и применения

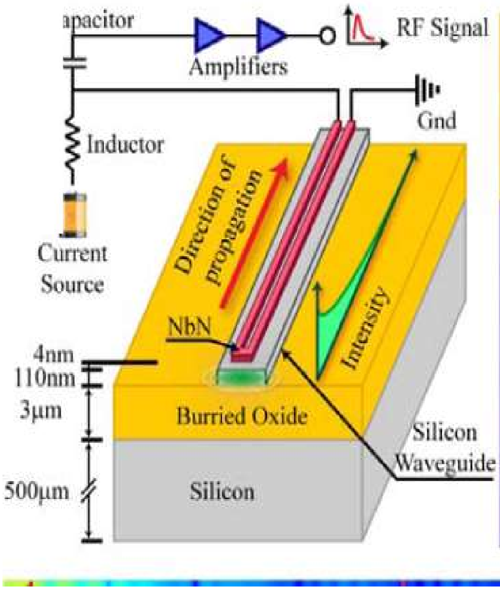
Гольцман Григорий Наумович

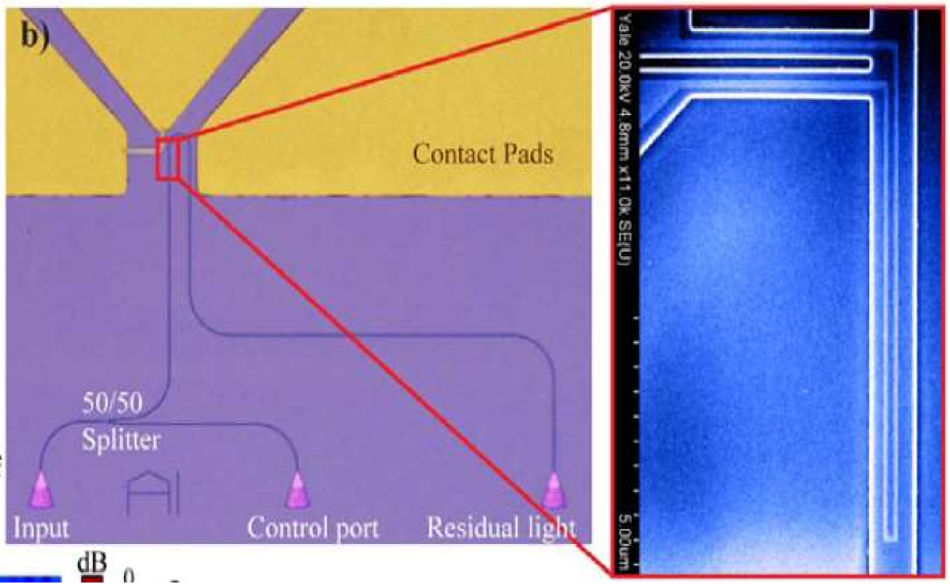
МПГУ, МИЭМ НИУ ВШЭ, ООО Сконтел











Outline:

- Historical introduction: 23 years from the first observation of Superconducting Nanowire Single Photon Detector (SNSPD) response and the first idea of device physics

- Ultrathin superconducting NbN film is our horse material for sensitive and fast detectors

- Superconducting Hot-Electron Bolometer (HEB) mixer is a precursor of a nanowire single photon detector. Application in the terahertz radioastronomy

-Meander-type nanowire structure made from the ultrathin film is still a mandatory element of SNSPD fabrication for single-mode fiber technology

- SNSPD detection mechanism and hot spot size

- The first idea of single-photon response by superconducting **microwire** and the first observation of SMSPD response

- How can a small hot spot turn a wide strip into a resistive state?
- -From SNSPD physics to commercially available devices and systems. Scontel company. First implementation of NbN SNSPD: Silicon CMOS IC Device Debug

- Next breakthrough: SNSPD on the optical waveguide - to the quantum photonic integrating circuits and to quantum computing based on photons

-Conclusions

23 years from the first observation of SNSPD response and the first idea of device physics

Picosecond superconducting single-photon optical detector

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APPLIED PHYSICS LETTERS VOLUME 79, NUMBER 6 6 AUGUST 2001

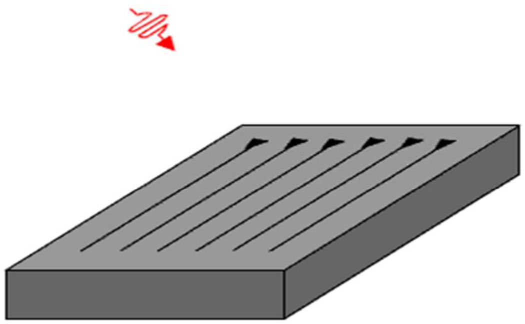

FIG. 1. Schematics of the supercurrent-assisted hotspot formation mechanism in an ultrathin and narrow superconducting strip, kept at temperature far below T_C are shown. The arrows indicate direction of the supercurrent flow.

Quantum detection by current carrying superconducting film

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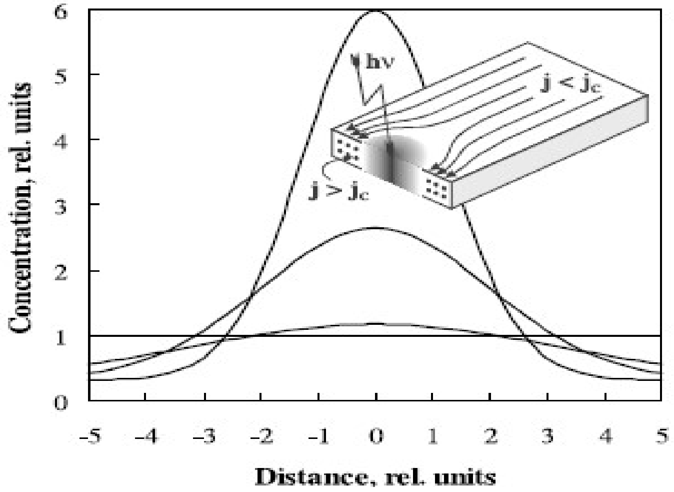
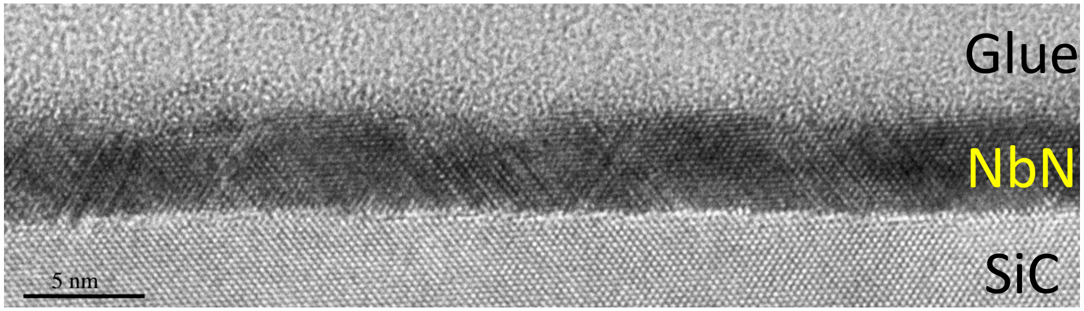


Fig. 1. Concentration of nonequilibrium quasiparticles across the width of the film at different moments after the photon has been absorbed. Time delays are 0.8, 2.0 and 5.0 measured in units of the thermalization time. Distance from the absorption site is shown in units of the thermalization length. Inset illustrates redistribution of supercurrent in the superconducting film with the normal spot – the basis of quantum detection. It shows the cross-section of the film drawn through the point where photon has been absorbed.

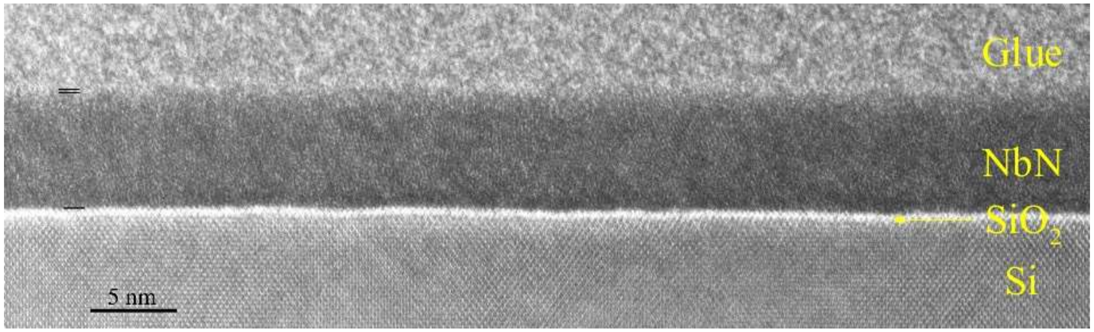
Which superconducting material is better for the detector: High-quality monocrystalline or high-disordered polycrystalline ultrathin films?

NbN on 3C-SiC buffer layer on Si substrate (HREM)



NbN is monocrystalline
a_0 (3C-SiC) =4.36Å
a_0 (NbN) =4.39Å
Thickness is 3.5 – 4.1 nm
Not really flat surface

NbN on Si substrate

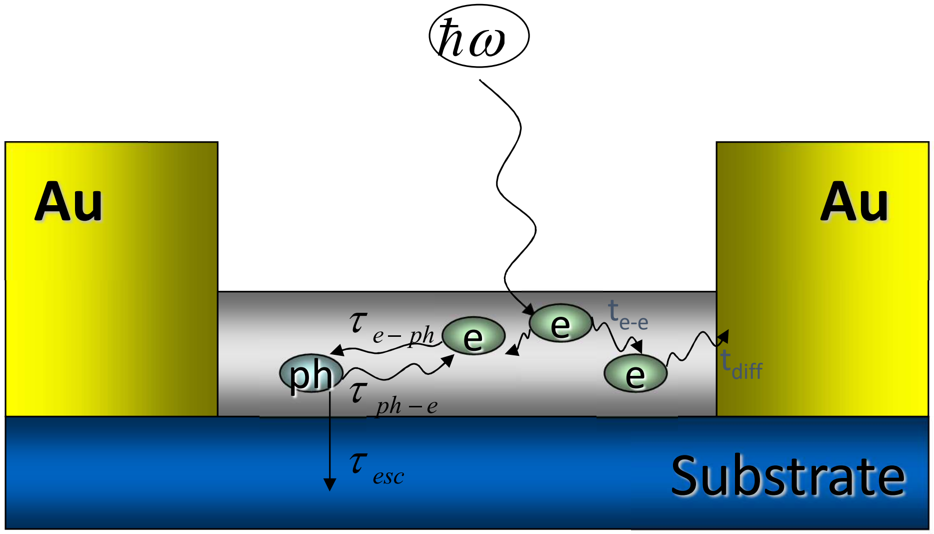


The NbN on Si is polycrystalline.

Transmission electron microscopy of 4 nm thick NbN film deposited on 3C-SiC, Si and Sapphire substrate. Transition temperature $T_c > 10K$, and critical current density $j_c = 10^7 A/cm^2$ allow us to produce planar nanostructures with unique properties.

J.-R. Gao, G. Gol'tsman, B.Voronov, et al, APL (2007)

Superconducting phonon-cooled Hot Electron Bolometer mixer is a precursor of single photon detector

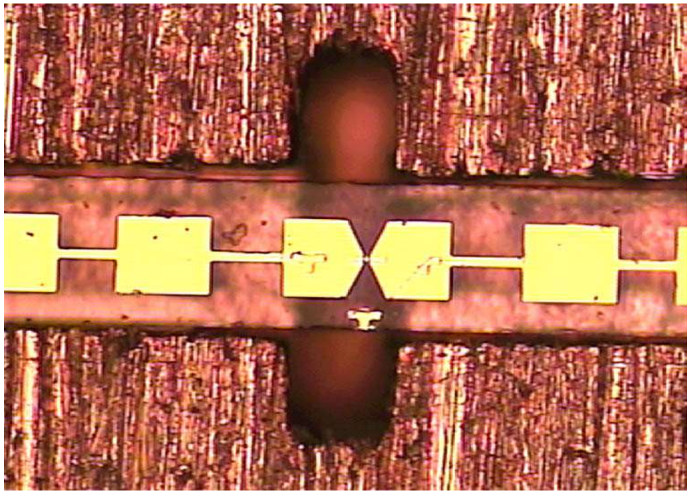


Phonon-cooled HEB mixer – E.M.Gershenzon, G.N.Gol'tsman et al. Sov. Phys. Superconductivity 3,1582,1990
Diffusion-cooled HEB mixer – D.Prober, Appl.Phys.Lett. 62(17), 2119, 1993

MSPU

From waveguide mixer chip to practical receiver up to 1.5 THz and astronomical observations in Chile from an altitude of 5525 meters

Superconducting waveguide hot-electron bolometer (HEB) mixer at 1.5 THz frequency



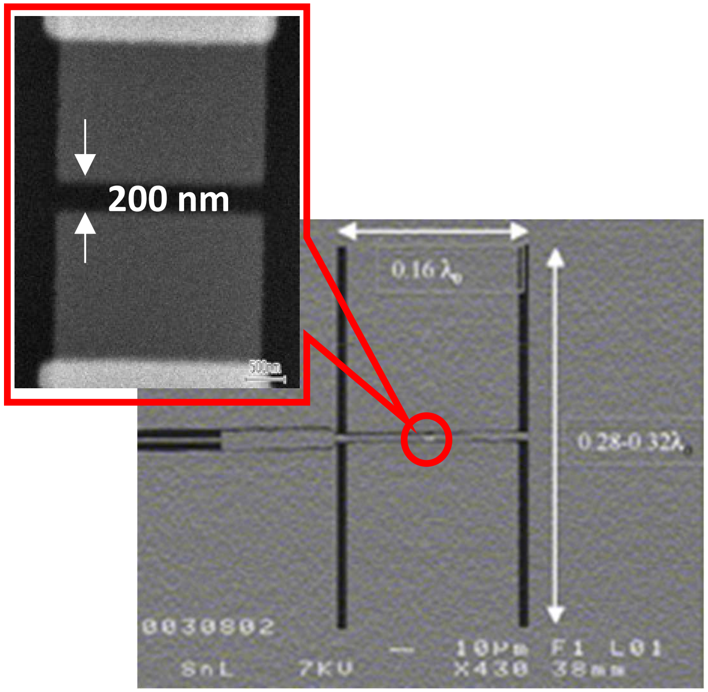
The 1.5 THz chip's sizes are 72 um wide, 1100 um long and 18 um thick

The Receiver Lab Telescope of the **Harvard-Smithsonian Center for Astrophysics is the first ground-based radio telescope designed for operation at frequencies above 1 THz.**

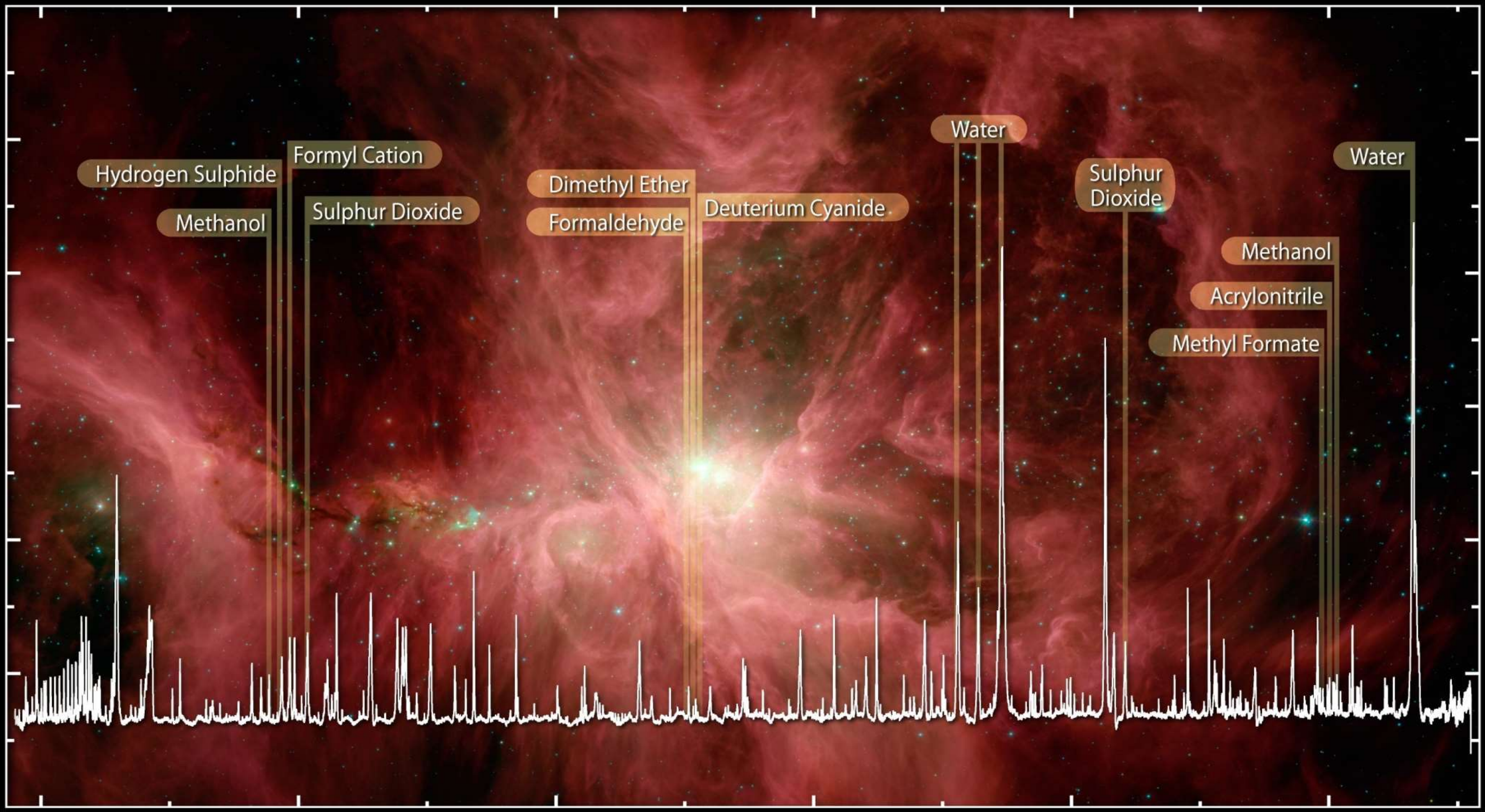
Observations since 2002 from an altitude of 5525 meters in Chile at 0.8-1.5 THz

Superconducting Hot-Electron Bolometer (HEB) mixer is a precursor of single photon detector

Our NbN films are space-qualified



Herschel Space Observatory launched, May 2009
HEB mixers in Bands 6 and 7 of the HIFI instrument: 1.41 THz – 1.91 THz

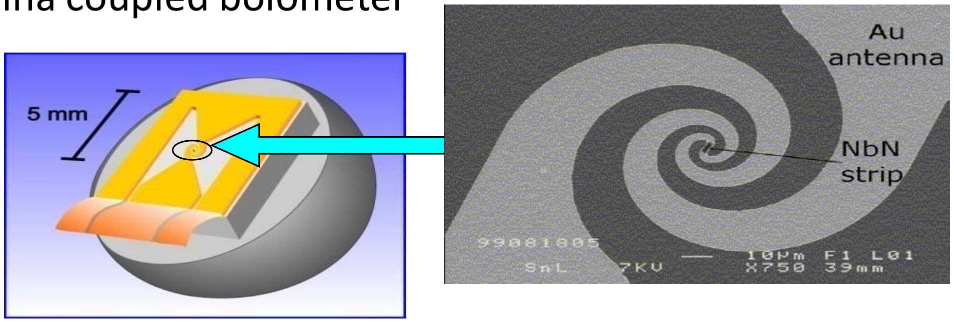


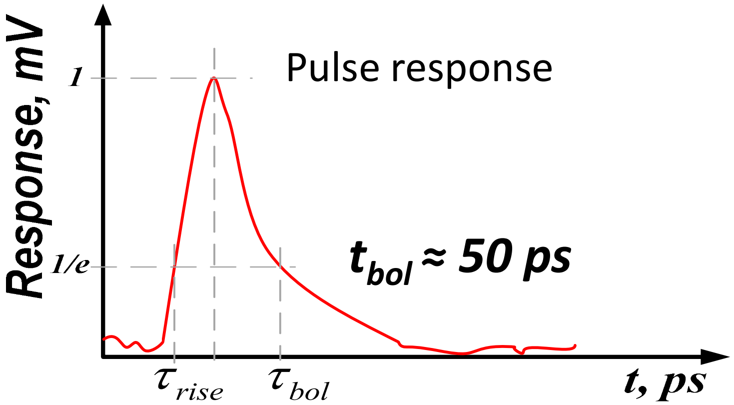
HIFI Spectrum of Water and
Organics in the Orion Nebula

© ESA, HEXOS and the HIFI consortium
E. Bergin

Hot electron bolometers as direct detectors are capable to detect *aJ* pulse energy at GHz rate

Spiral antenna coupled bolometer



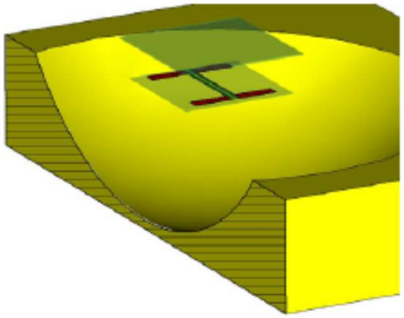


$$NEP \approx 10^{-14}\ W/\sqrt{Hz}$$

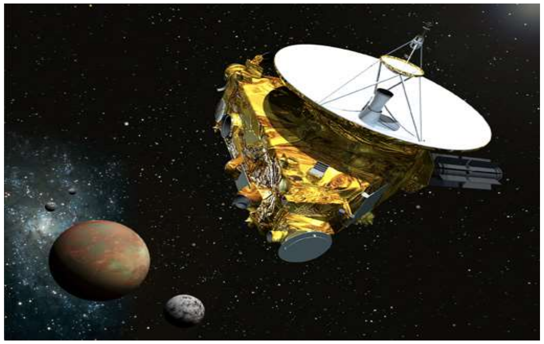
$$W_{pulse} = SNR \times NEP \times \sqrt{\tau_{bol}} \approx 1\ aJ$$

No photon shot noise in THz!

Signal to noise ratio (SNR) ≈ 5 is required for stable link



Double dipole antenna coupled bolometer



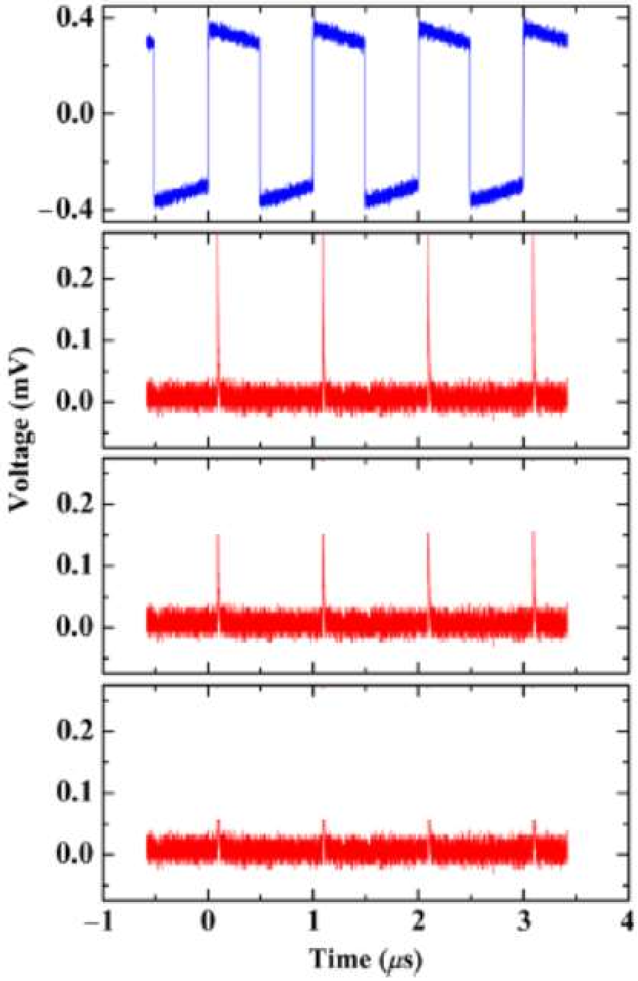
New Horizons: approaching Pluto

(artist's view, was happen in summer 2015)

2.1 m diameter dish antenna to communicate with Earth from 7.5 billion kilometers away

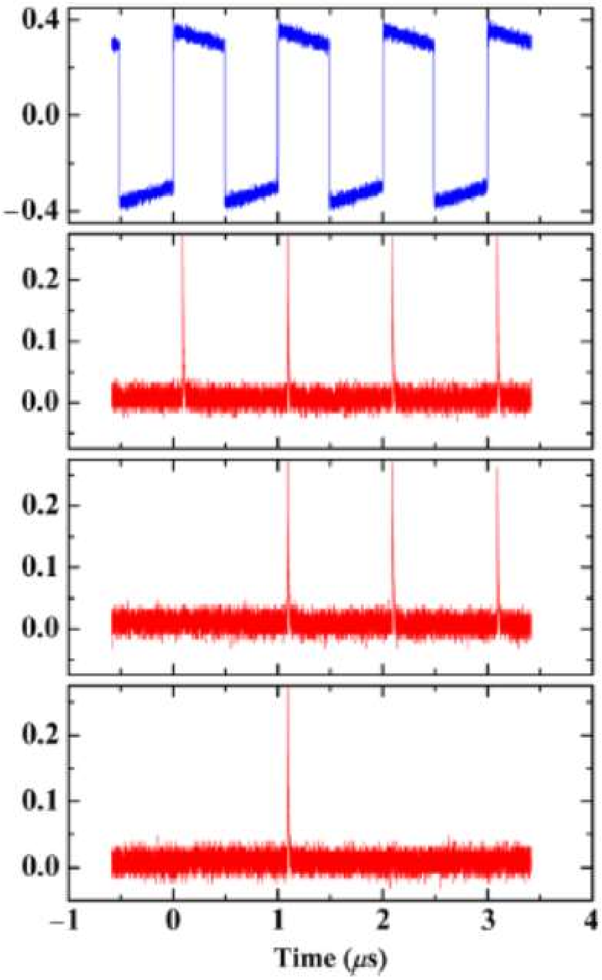
Credit: Johns Hopkins University Applied Physics Laboratory/Southwest Research Institute (JHUAPL/SwRI)

Bolometric mode
(terahertz pulses)



Attenuation

Single-photon detection mode
(optical pulses)

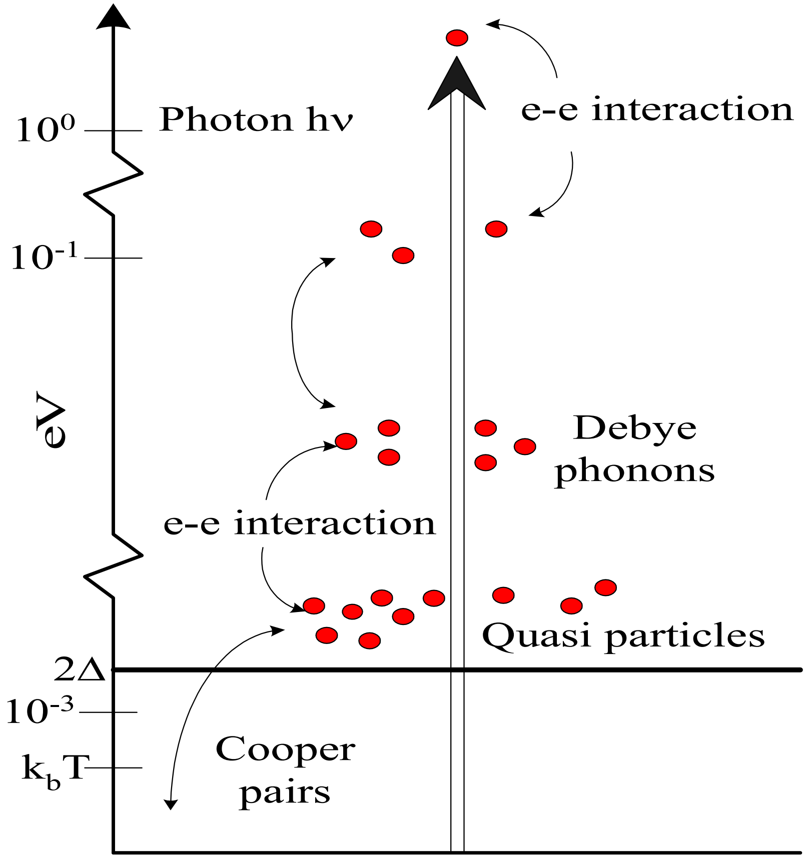


Real-time waveform record showing clock pulses from the laser (the top blue curve) and pulses detected by the bridge at different attenuation levels of the power from the laser (the red curves, with power decreasing from top to bottom).

In bolometric mode With the increase of attenuation of the power, an amplitude of response decreases.

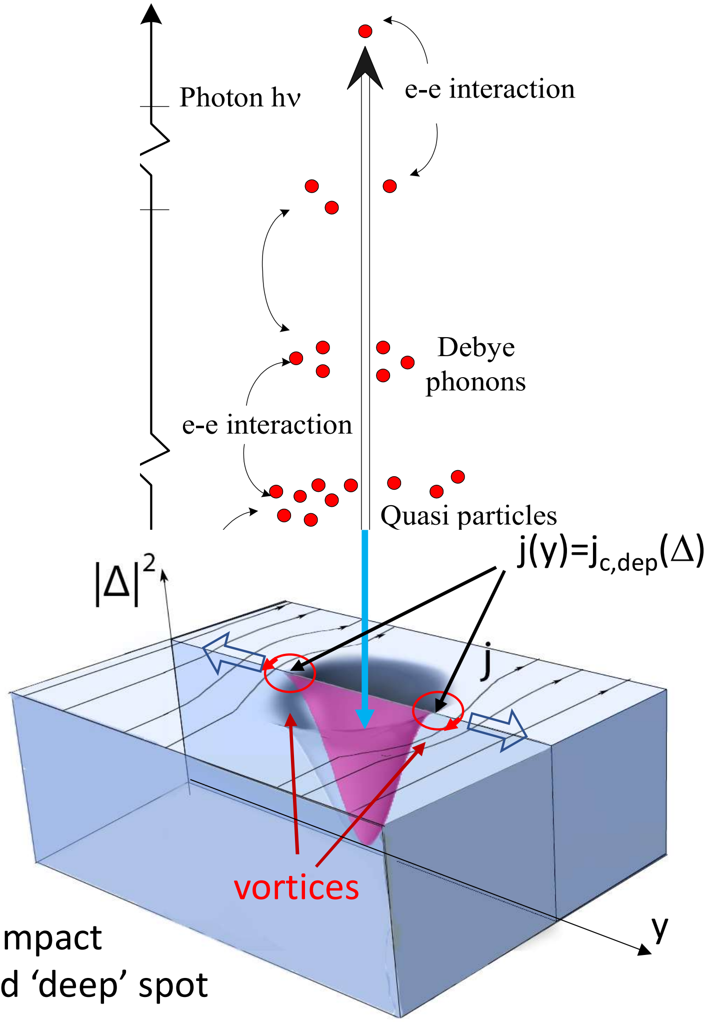
In single-photon detection mode with the increase attenuation of the power, the number of detected pulses decreases.

Energy Relaxation Process in an optically excited superconducting thin film



Schematic description of relaxation process in an optically excited superconducting thin film.

SNSPD detection mechanism and hot spot size



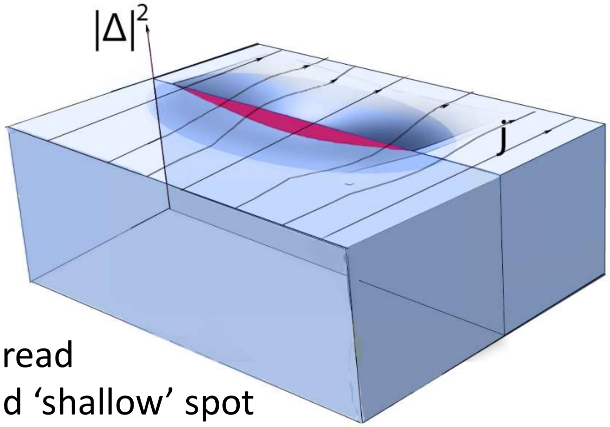
Compact
and ‘deep’ spot

<u>The same</u> integral suppression
of superconductivity, $\int dxdy\delta\left|\Delta\left(x,y\right)\right|^{2}$

can result in <u>different</u> size
and ‘depth’ of hot spot

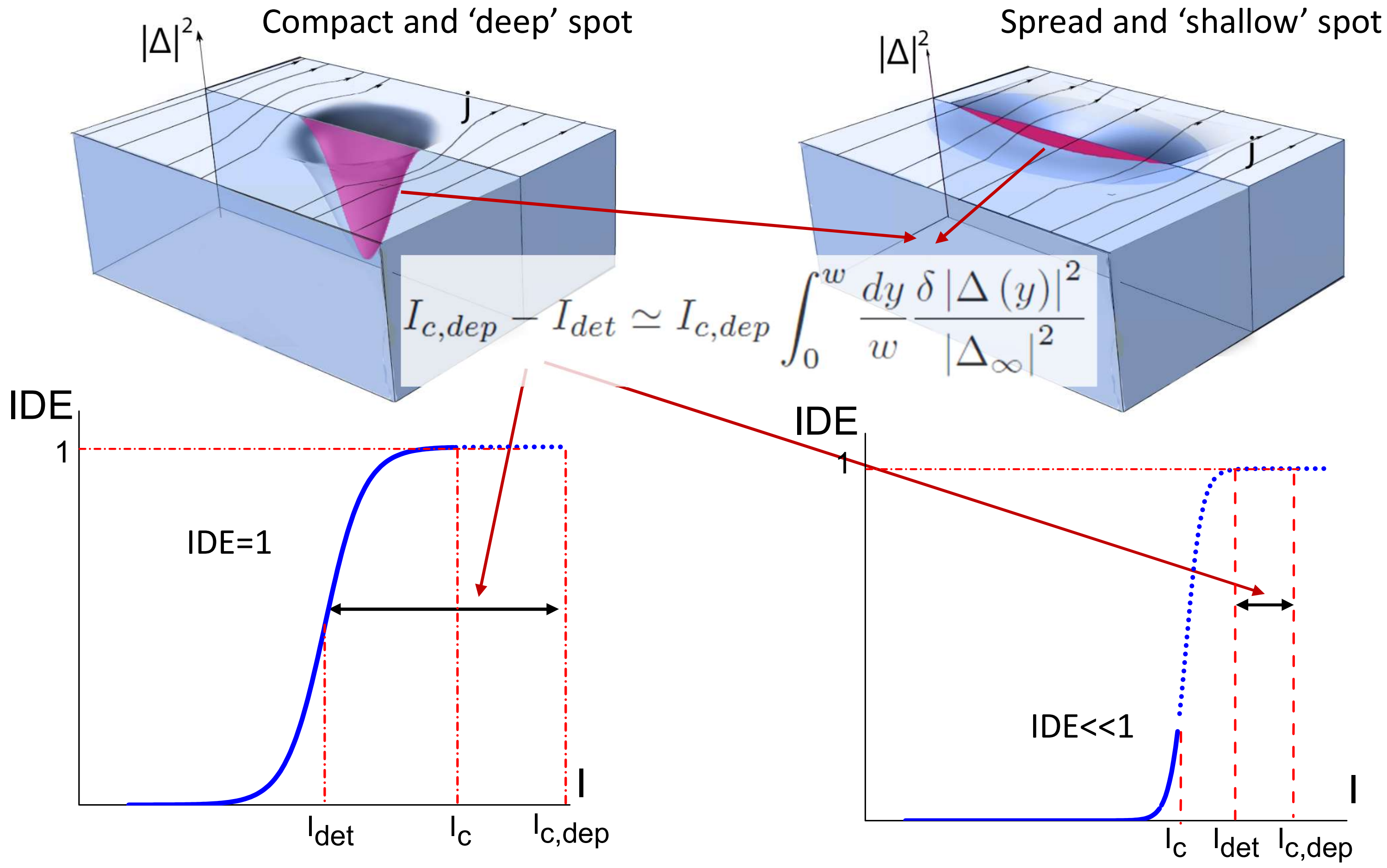
$$d \simeq 4\sqrt{D_{eff}\tau_{th}} \quad \delta\left|\Delta\right|^{2} \propto \frac{1}{D_{eff}\tau_{th}}$$

because they depend on
material parameters



Spread
and ‘shallow’ spot

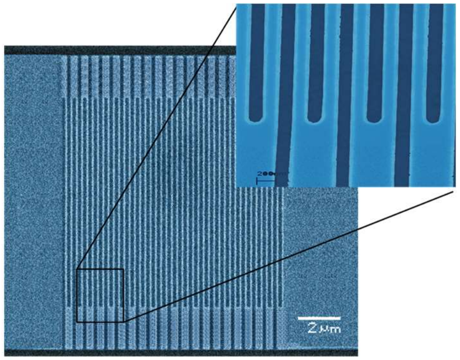
Size of hot spot does matter! (At least to detect mid-IR photons)



$$I_{c,dep} - I_{det} \simeq I_{c,dep} \int_0^w \frac{dy}{w} \frac{\delta \left|\Delta(y)\right|^2}{\left|\Delta_\infty\right|^2}$$

Efficient detection of mid-IR photons needs knowledge of actual size (and depth) of hot spot!

Meander-type nanowire structure made from the ultrathin film is still a mandatory element of SNSPD fabrication for single-mode fiber technology



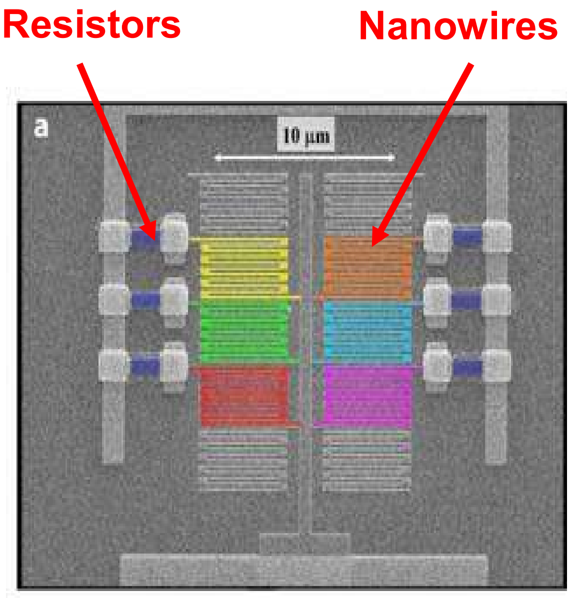
Fabrication:
- DC magnetron sputtering of NbN film on silicon +SO_2 substrate
- E-beam lithography with reactive ion etching

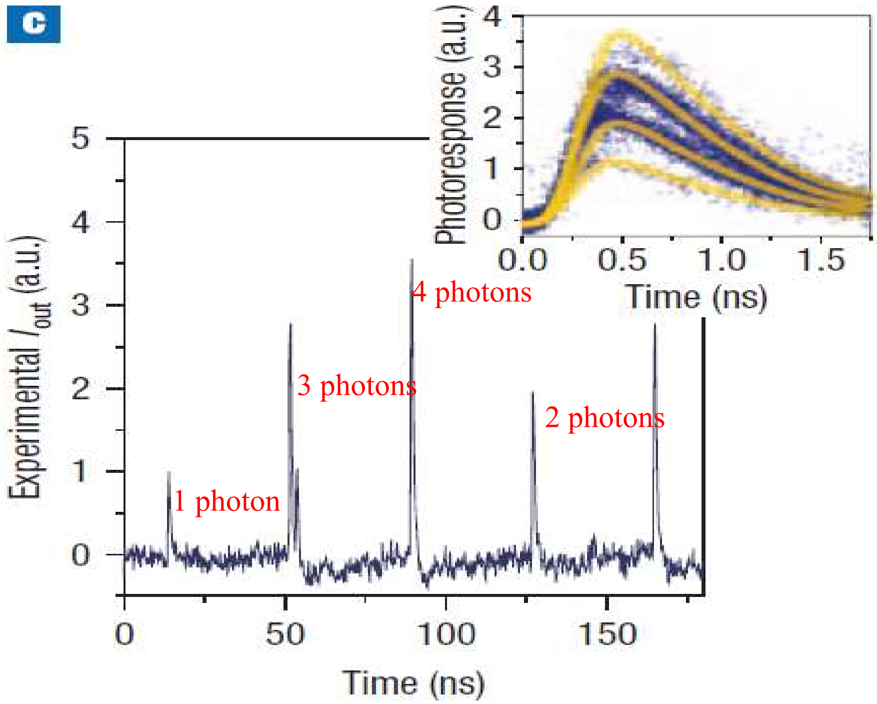
What we did those days:
- increase filling factor (presently about 60%)
- to reduce strip width from 100 nm to 50 nm or even less

Korneev A. *et al*, *Appl. Phys. Lett.* 84 (2004)

First photon-number resolving SNSPD (PNR-SNSPD)

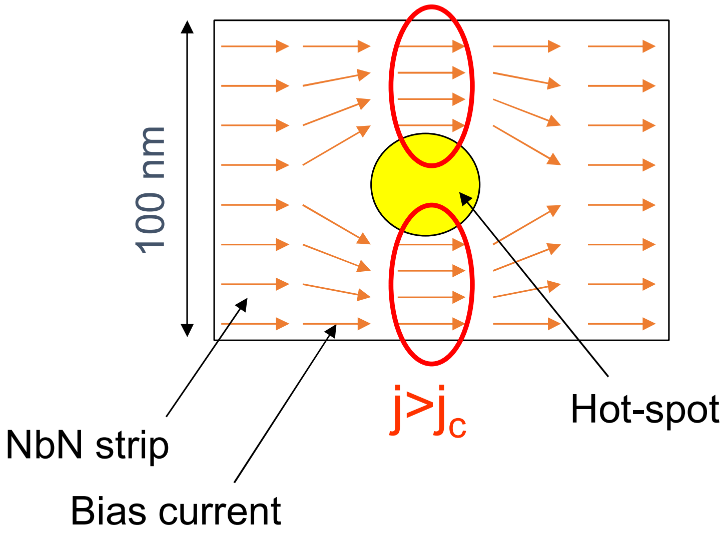
Photoresponse pulse voltage is proportional to the number of simultaneously absorbed photons

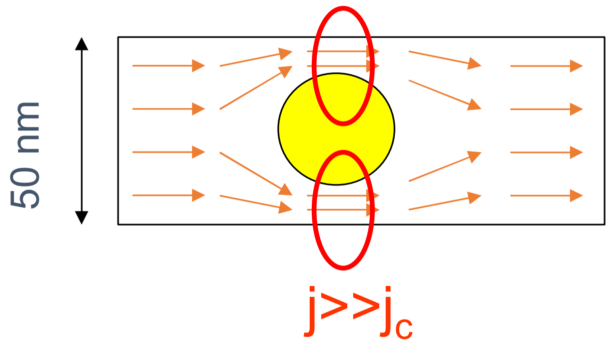




A. Divochiy, F. Marsili, D. Bitauld, A. Gaggero, R. Leoni, F. Mattioli, A. Korneev, V. Seleznev, N. Kaurova, O. Minaeva, G. Goltsman, K. G. Lagoudakis, M. Benkhaoul, F. Levy, and A. Fiore, Nature Photonics, vol. 2, pp 302–306, 2008

One of the possible approach to push SNSPD technology to the Far-Infrared range is to switch to narrow stripe





The first idea of single-photon response by superconducting microstrip and it’s first observation

PHYSICAL REVIEW B **85**, 024509 (2012)

Photon detection by current-carrying superconducting film: A time-dependent Ginzburg-Landau approach

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(Received 3 October 2011; revised manuscript received 23 December 2011; published 5 January 2012)

PHYSICAL REVIEW APPLIED **7**, 034014 (2017)

Single-Photon Detection by a Dirty Current-Carrying Superconducting Strip Based on the Kinetic-Equation Approach

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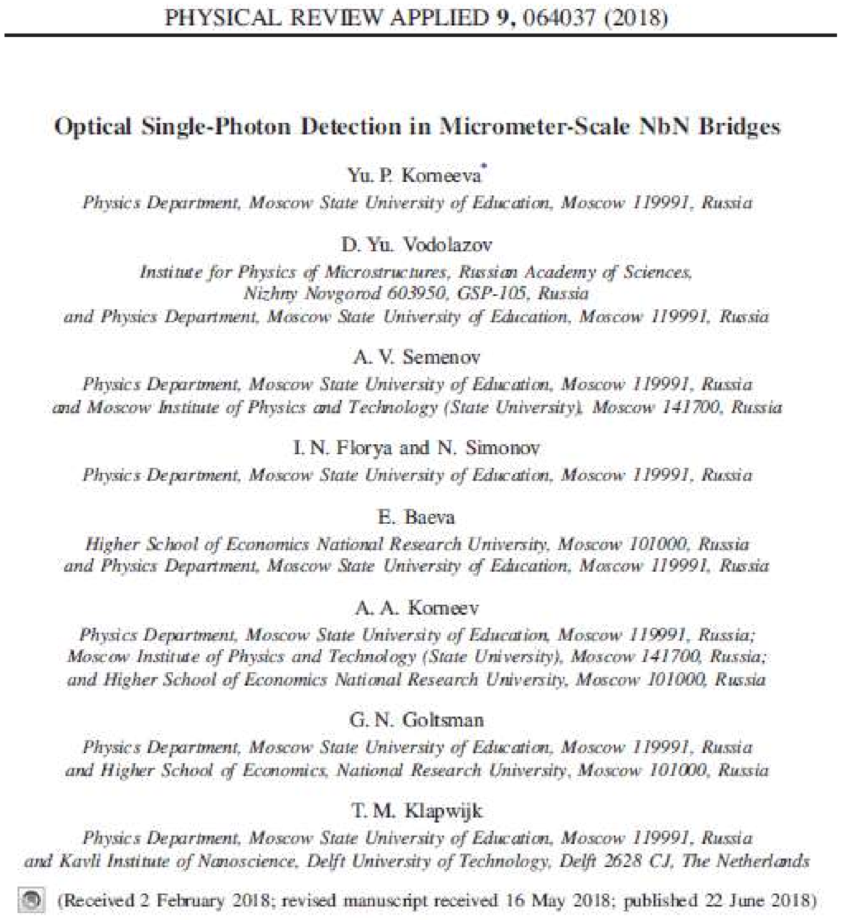
(Received 14 December 2016; revised manuscript received 30 January 2017; published 23 March 2017)

We predict that even a several-micron-wide dirty superconducting bridge is able to detect a single near-infrared or optical photon if its critical current exceeds 70% of the depairing current.



PHYSICAL REVIEW APPLIED **9**, 064037 (2018)

Optical Single-Photon Detection in Micrometer-Scale NbN Bridges

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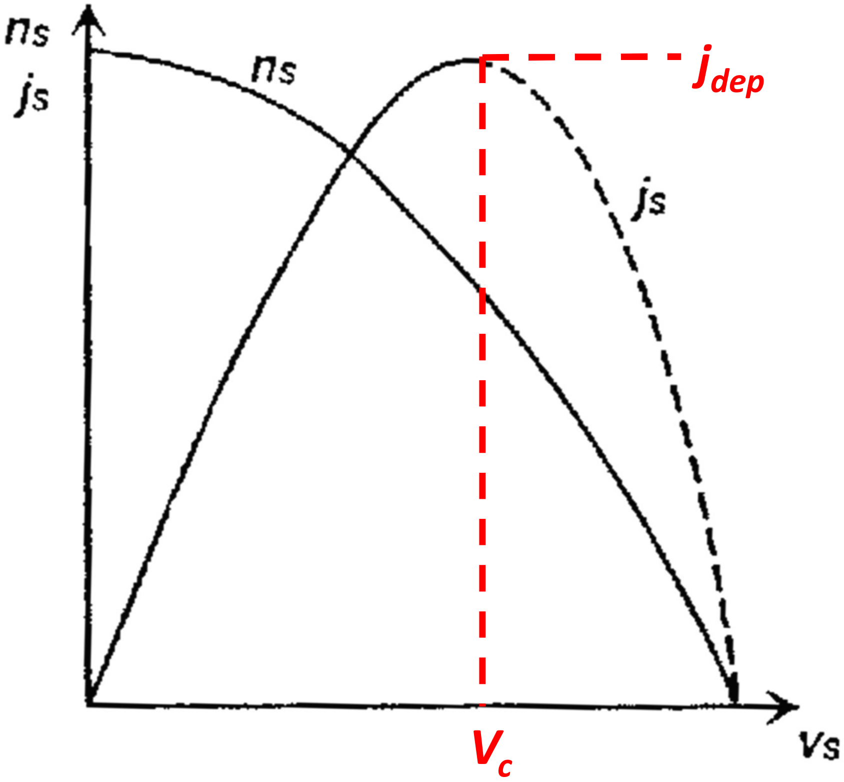
What is the depairing current?



$j_s = 2en_sv_s$ n_s - concentration of Cooper pairs

v_s - supervelosity

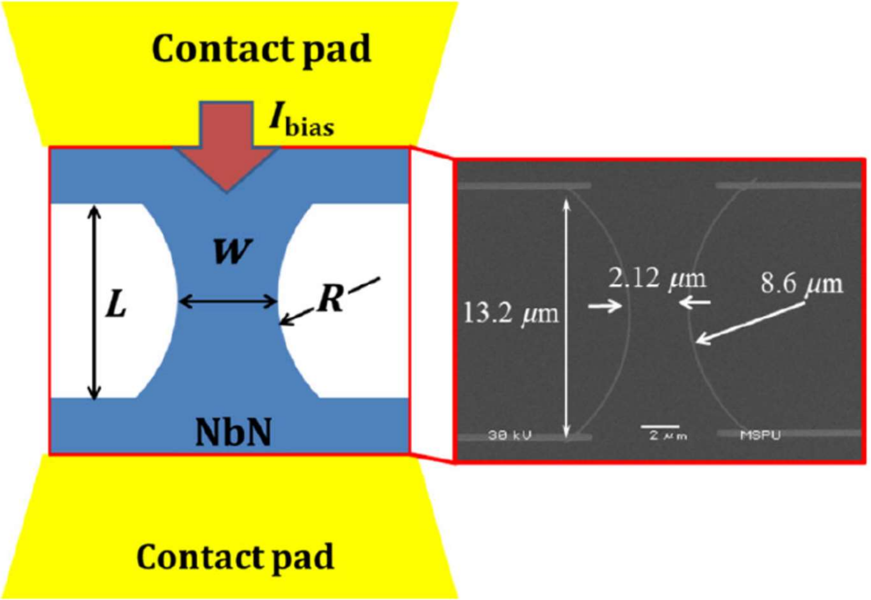
$n_s(v_s)$ falls with the increase of v_s

⬇

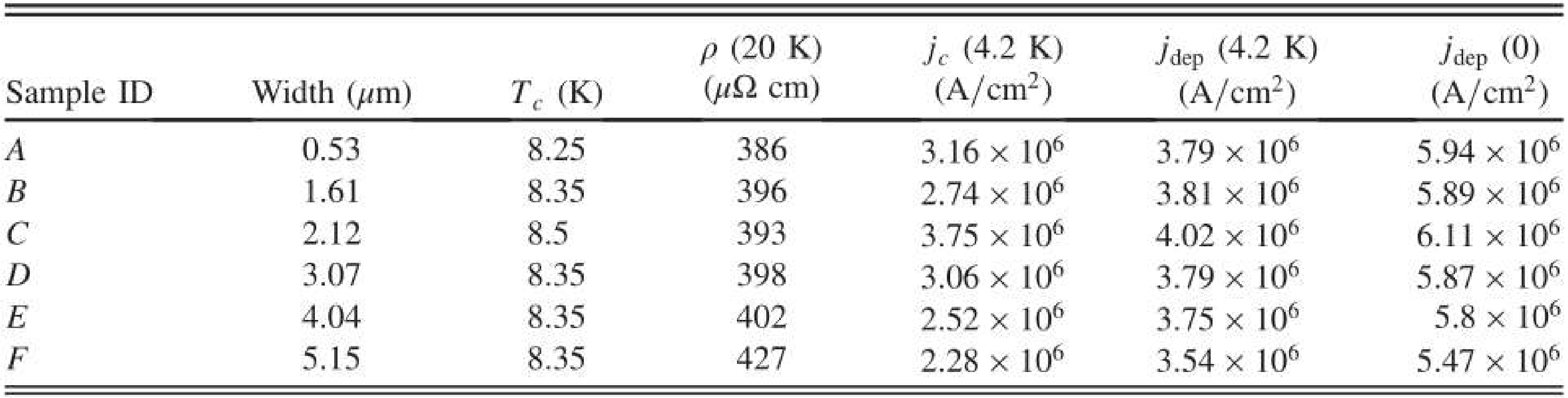
$j_s(v_s)$ has maximum at some $v_s = v_c$

$$\boxed{j_s(v_c) \equiv j_{dep}}$$

Typical sample for the first experiment is planar constriction-type microbridge

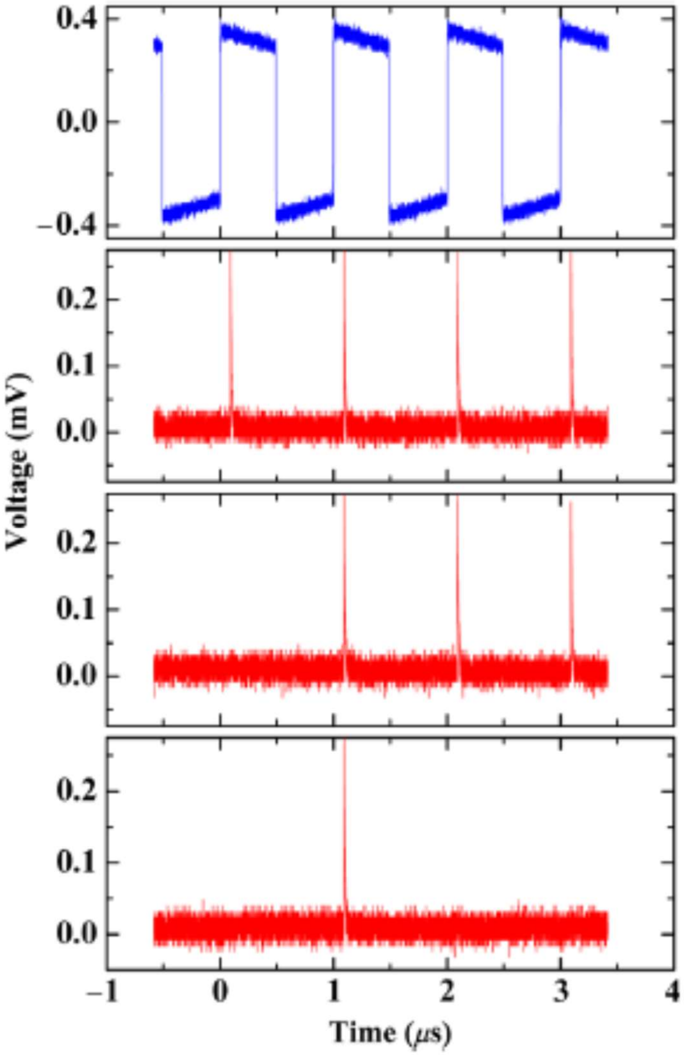


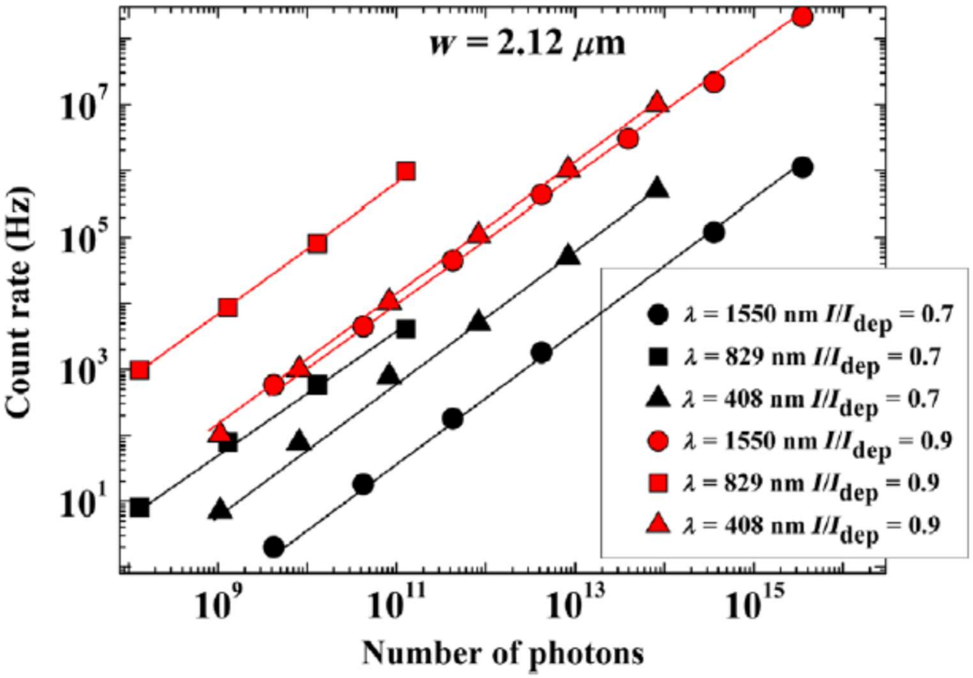
Drawing of a typical NbN constriction-type bridge with a scanning-electron-microscope (SEM) image of one of the bridges with indicated dimensions (sample C in Table I). The contacts on top of the NbN film are made of gold (Au). All bridges have edges designed as a segment of a circle with the radius 8.6 µm.



Sample ID	Width (μm)	T_c (K)	ρ (20 K) ($\mu\Omega$ cm)	j_c (4.2 K) (A/cm^2)	j_{dep} (4.2 K) (A/cm^2)	j_{dep} (0) (A/cm^2)
A	0.53	8.25	386	3.16×10^6	3.79×10^6	5.94×10^6
B	1.61	8.35	396	2.74×10^6	3.81×10^6	5.89×10^6
C	2.12	8.5	393	3.75×10^6	4.02×10^6	6.11×10^6
D	3.07	8.35	398	3.06×10^6	3.79×10^6	5.87×10^6
E	4.04	8.35	402	2.52×10^6	3.75×10^6	5.8×10^6
F	5.15	8.35	427	2.28×10^6	3.54×10^6	5.47×10^6

Count rate versus the number of photons in a laser pulse for different wavelengths





Real-time waveform record showing clock pulses from the laser (the top blue curve) and photon pulses detected by the bridge at different attenuation levels of the power from the laser (the red curves, with power decreasing from top to bottom). With the increase of attenuation of the power, the number of detected pulses decreases.

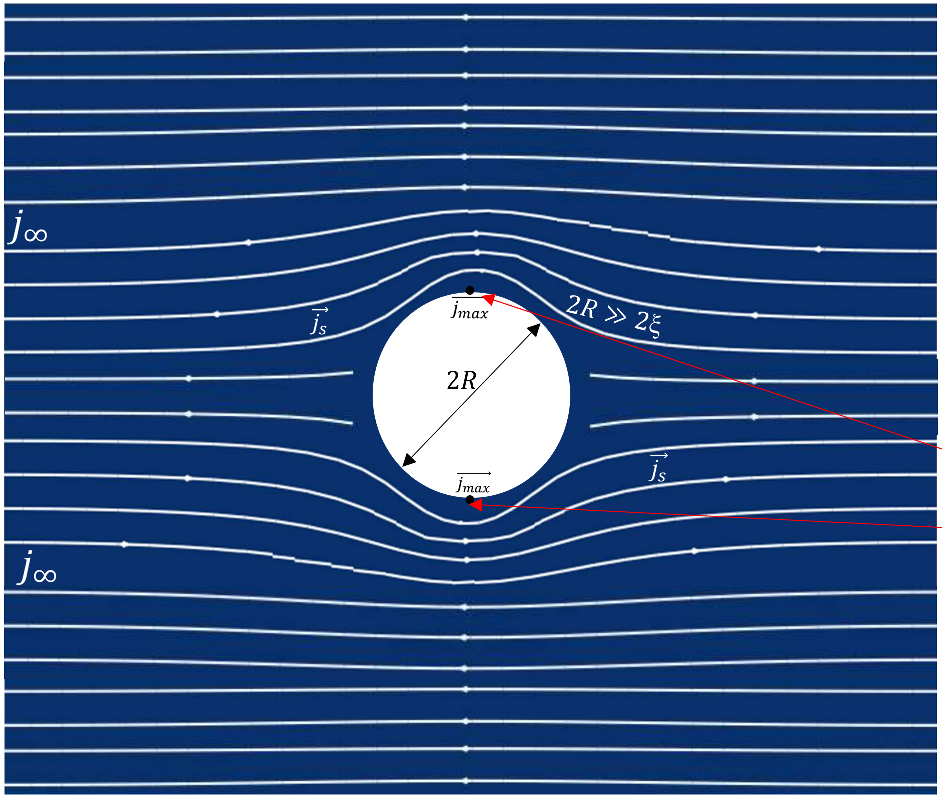
How can a small hot spot turn a wide strip into a resistive state?

The key issue is the redistribution of supercurrent density near the hot spot

Can be described by $\vec{j_s} = 2en_s\vec{v_s}$ and $\nabla\vec{j_s} = 0$, where $2m\vec{v_s} = \nabla\varphi$

n_s - concentration of Cooper pairs

v_s - supervelocity ϕ – superconducting phase



1. A fully normal hot spot with sharp edge

n_s=n_∞ outside and n_s=0 inside the hot spot

Assuming for simplicity that n_s=const(j_s), one has the Laplace equation for φ outside the spot

$$\nabla^2\varphi = 0$$

This is analogous to the problem of normal current flowing around a circular hole in a film, with the known solution. In particular,

$$j_{max} = 2j_\infty$$

at these side points of the spot

If it turns out that j_{max}>j_{dep}, i.e.

$$j_\infty > j_{dep}/2 \quad , \quad I_b > I_{dep}/2$$

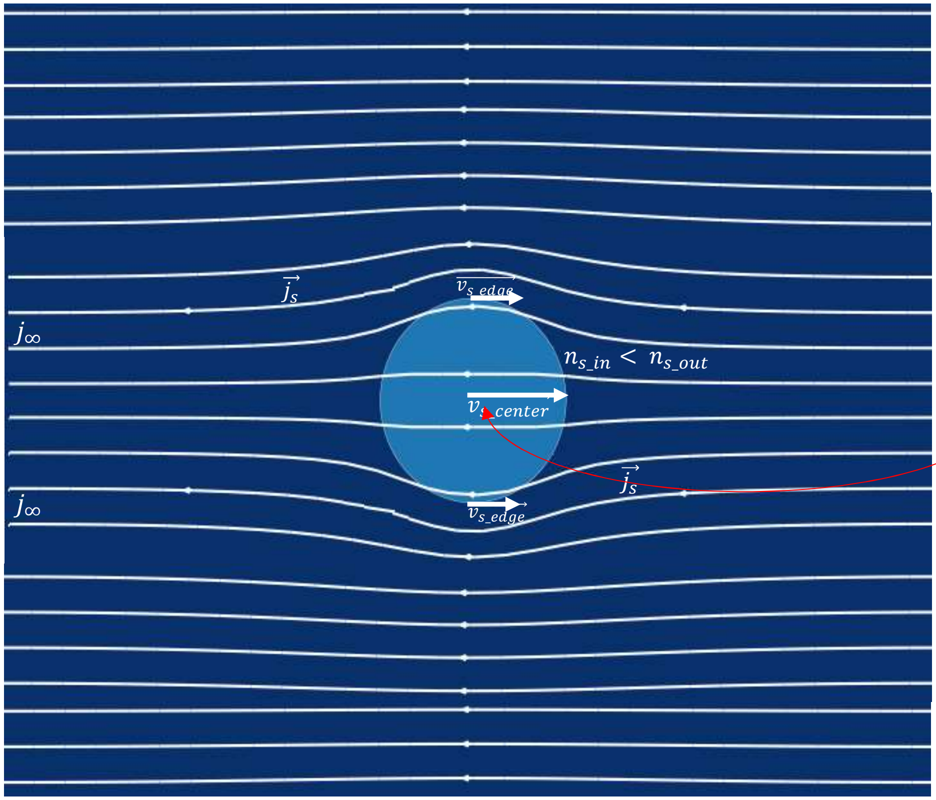
then vortices start to nucleate at these points and resistance emerges

How can a small hot spot turn a wide strip into a resistive state?

The key issue is the redistribution of supercurrent density near the hot spot

Can be described by $\vec{j_s} = 2en_s\vec{v_s}$ and $\nabla\vec{j_s} = 0$, where $2m\vec{v_s} = \nabla\varphi$

n_s - concentration of Cooper pairs
v_s - supervelocity ϕ – superconducting phase



2. Hot spot with suppressed n_s and sharp edge

$n_s=n_\infty$ outside and $n_s=n_{in}$ inside the hot spot

Assuming for simplicity that n_s=const(j_s), one still has the Laplace equation for φ outside and inside the spot

$$\nabla^2\varphi = 0$$

Now, it is more instructive to look at v_s

$$v_{max} = 2v_\infty$$

at the center of the spot

If it turns out that $v_{max}>v_{dep}$,(n_{in}), which corresponds to

$$I_b > \left(\frac{n_{in}}{n_\infty}\right)^{1/2} \frac{1}{2}\left(1+\frac{n_{in}}{n_\infty}\right) I_{dep}$$

The factor is between ½ and 1

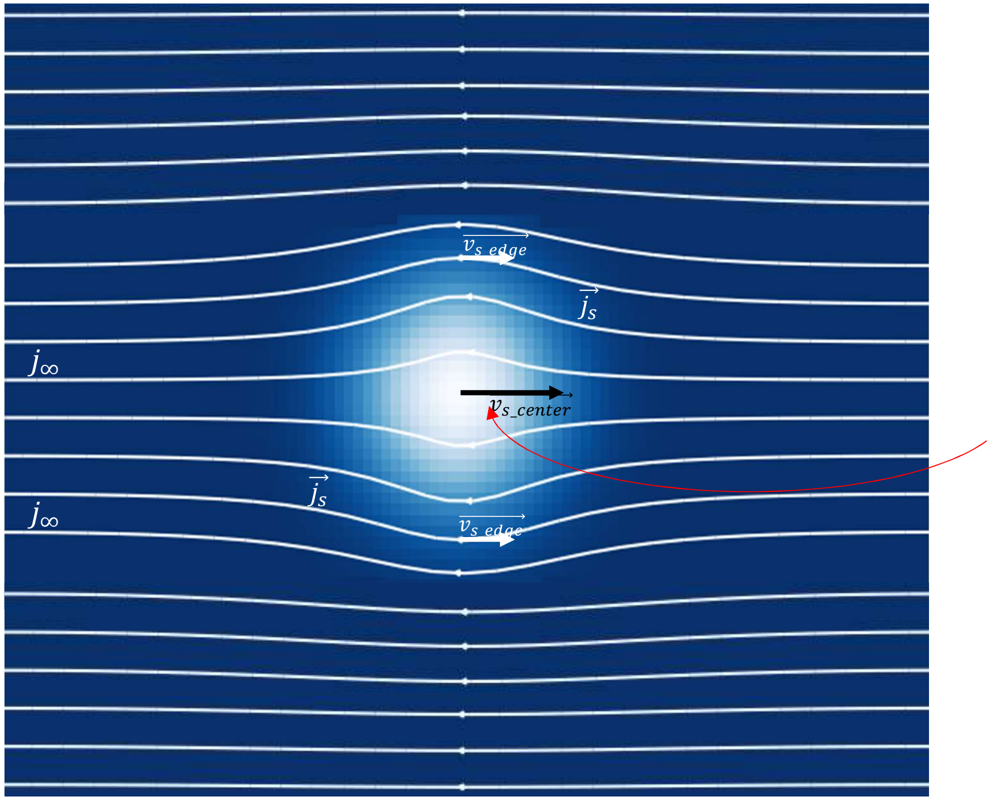
then pairs of vortices start to nucleate at the center of the spot and resistance emerges

How can a small hot spot turn a wide strip into a resistive state?

The key issue is the redistribution of supercurrent density near the hot spot

Can be described by $\overrightarrow{j_s} = 2en_s\overrightarrow{v_s}$ and $\nabla\overrightarrow{j_s} = 0$, where $2m\overrightarrow{v_s} = \nabla\varphi$

n_s - concentration of Cooper pairs
v_s - supervelocity ϕ – superconducting phase



3. Real hot spot with a gradually changed n_s inside

Assumption n_s=const(j_s) now scan be lift off, $n_s=n_s(v_s)$
Instead of Laplace equation for φ one has

$$\nabla\,(n_s\nabla\varphi) = 0$$

But still,

$$v_{max} > v_\infty$$

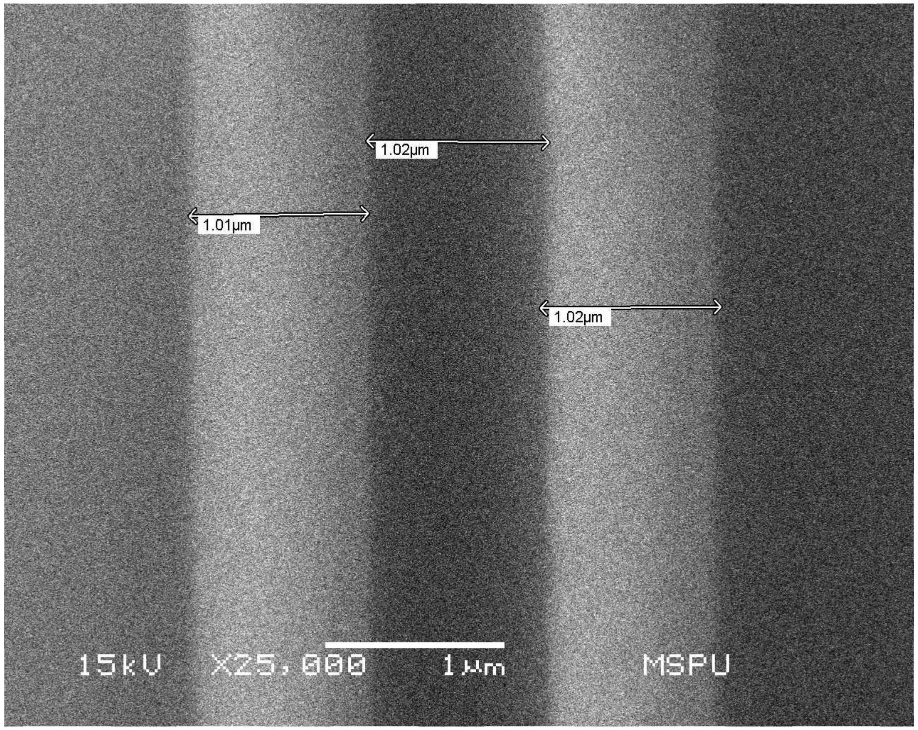
is reached at the center of the spot
If it turns out that $v_{max}>v_{dep},(n_{center})$, which corresponds to

$$I_b \geq 0.7I_{dep}$$

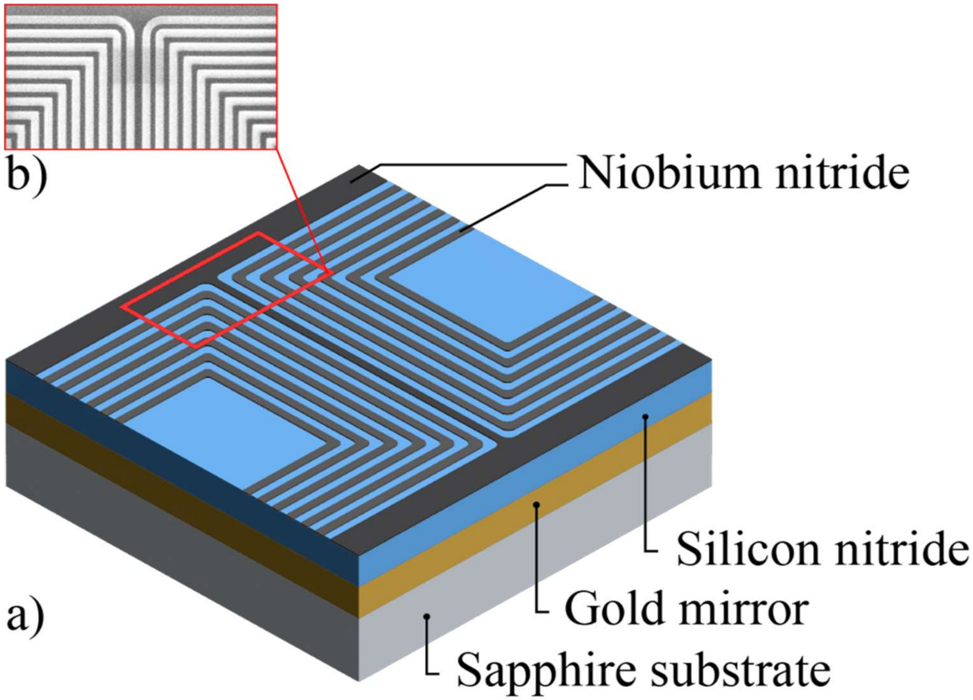
Vodolazov, 2017; in agreement with Korneeva, 2018

then pairs of vortices start to nucleate at this point and resistance emerges

SMSPD as 1 µm wide and 75 µm long strip

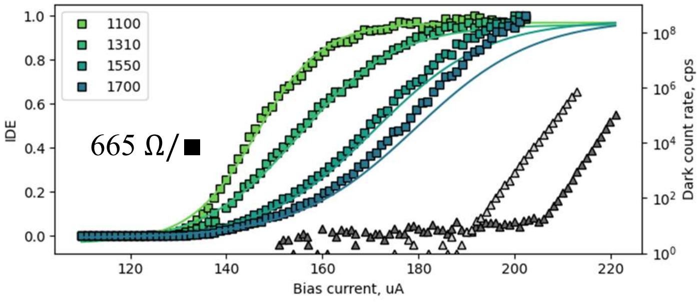


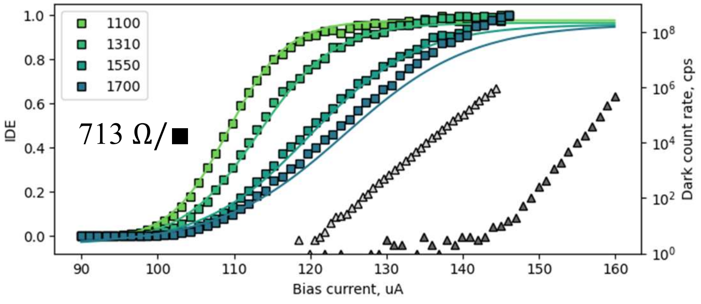
SEM image of the microstrip detector

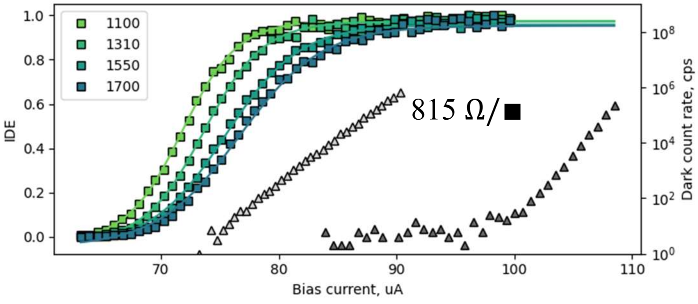


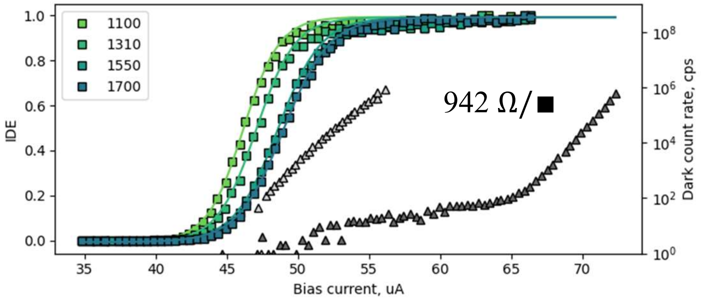
a) Layer structure of studied devices. Light grey patterns represent dose-stabilization structures, while dark grey area represents the microstrip (the only current carrying part of the device).
b) Scanning electron microscope image of the microstrip along with fabricated dose stabilization structures.

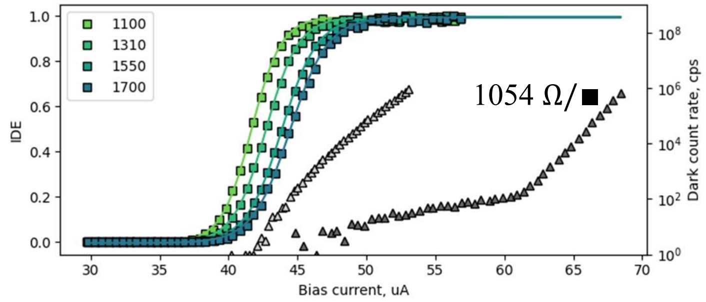
Internal Quantum Efficiency vs bias current for different sheet resistance and wavelengths for 1 μm wide and 75 μm long strips

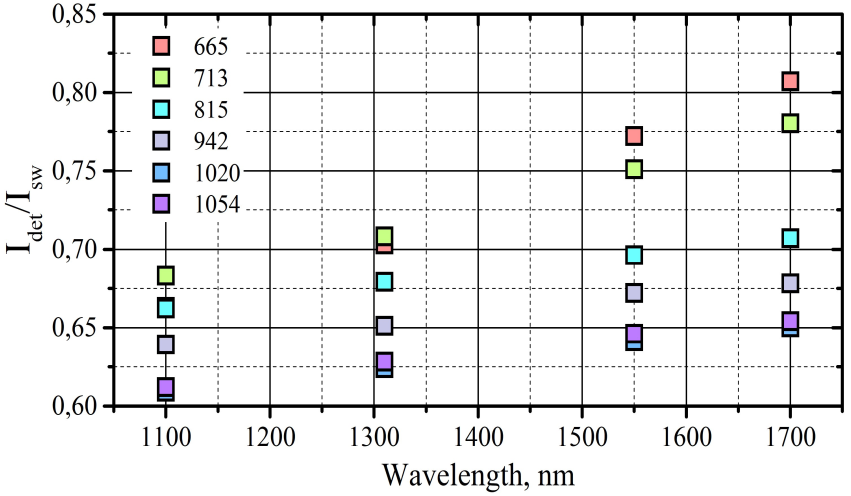












Values of detection current, divided by switching current, for different wavelengths and film thickness

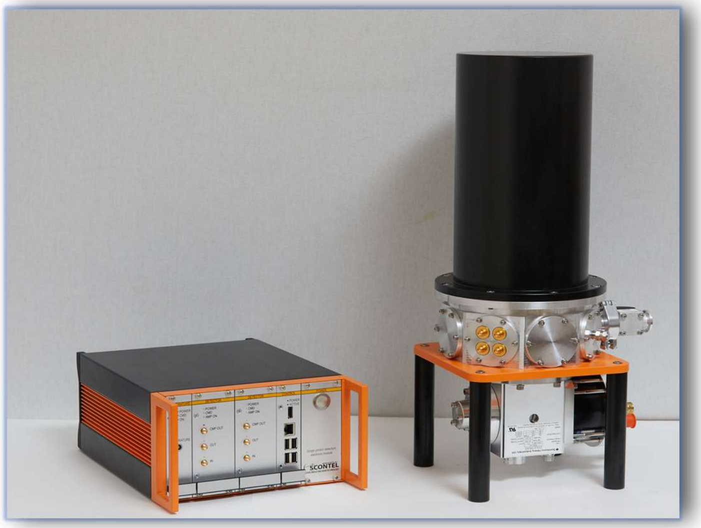
Commercially available Single Photon Detectors on the global market

Photomultipliers (PMT)

Single-photon avalanche photodiodes (SPAD)

Superconducting Single-Photon Detector (SSPD)

The company "Superconducting Nanotechnologies" Scontel was founded in 2004 for the commercialization of science-intensive developments



The first 50 customers of Scontel company (there are now more than 500 of them)

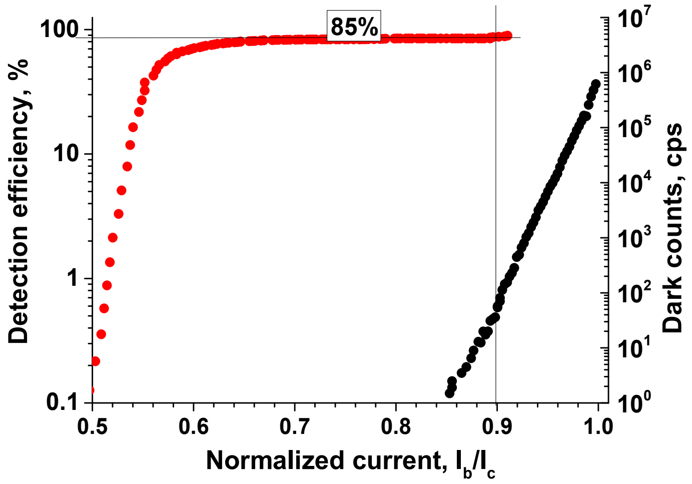
1. Rochester institute of technology
2. Technische Universität München
3. Stockholm university
4. Institüt für Halbleiteroptik und Funktionelle
5. Physikalisch-Technische Bundesanstalt
6. JPL. California institute of technology
7. University of California Los Angeles
8. University of Linz
9. Eindhoven University of Technology
10. University at Buffalo.
11. Institut de Photonique Quantiques
12. Chalmers university of technology
13. CNRS. Centre National de la Recherche Scientifique
14. Thales
15. Universite de Geneve
16. Scuola Normale Superiore
17. Cardiff University
18. Swiss Federal Institute of Technology, Zurich
19. Institute of Semiconductor and Solid State Physics
20. University College Cork
21. Walter Schottky Institute
22. The Racah Institute of Physics
23. Universitи Libre de Bruxelles
24. University of Magdeburg
25. Millitary University of Technology, Poland
26. Technische Universitat Berlin
27. Yale University
28. NTT. New Tera Technology
29.Delft University of Technology
30.Insight Product Company
31. QMC Instruments Ltd
32. Universiteit Leiden
33. Observatoire de Paris LERMA
34. Optoelectronics Industry Development Association
35. Institut Physikalische Hochtechnologie e.V.
36. Pierre & Marie Curie University (UPMC)
37. Max Plank Institute
38. Nanjing University
39. Ben-Gurion University of the Negev
40. Universita degli studi di Pavia
41. Pirelli
42. Institute Technologii Drewna
43. Purple Mountain Observatory, CAS
44. RTI Cryomagnetic System
45. ShangHai Institute of Microsystem
and Information Technology
46. Netherland Institute for Space Research
47. Tokyo Instruments, INC
48. University of Oulu
49. University of Waterloo
50. Universitat Wien

MSPU

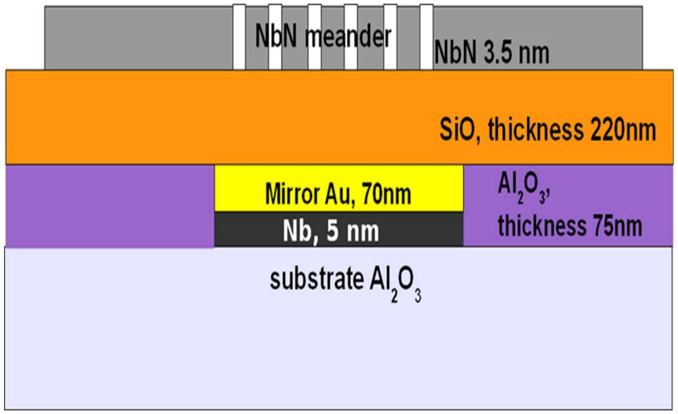
Practical single-photon receivers based on SNSPD

WWW.SCONTEL.RU
SCONTEL
SUPERCONDUCTING NANOTECHNOLOGY

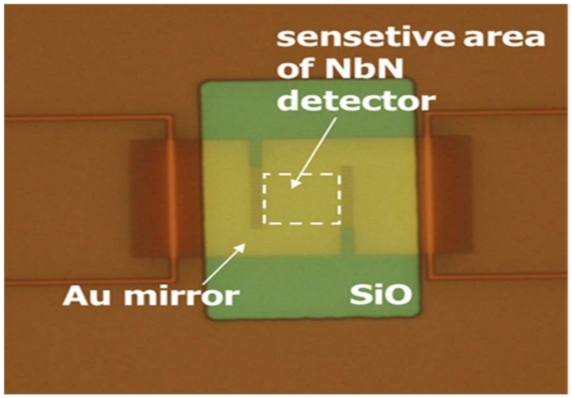
Now: Quantum efficiency 90% at 1550nm, jitter 20ps, max. counting rate 100 MHz and dark count rate 1s^{-1}



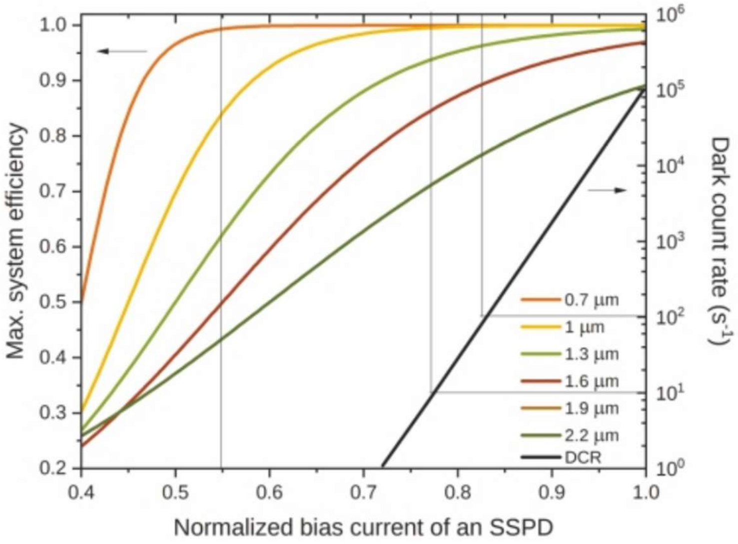
Cavity-integrated SSPD

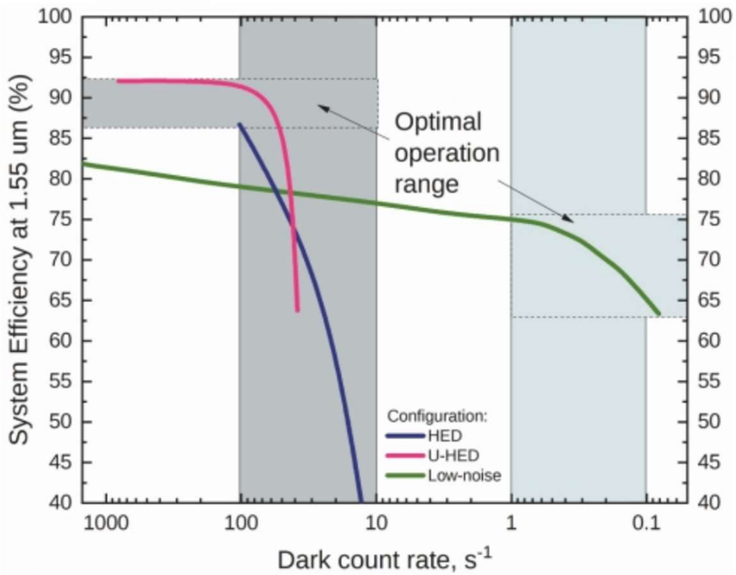


Spectral range	Quantum efficiency (referred to optical input)
0.7 – 1.3 μm	85 %
1.3 – 1.6 μm	80 %
1.6 – 2.3 μm	50 %



Типичные характеристики SSPD





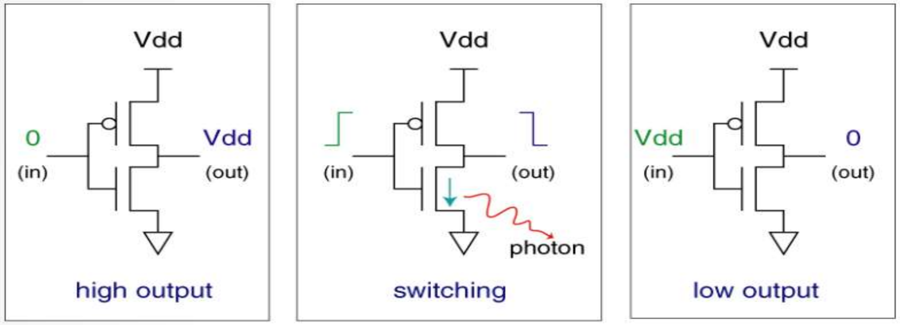
Преимущества:

+ Широкий диапазон длин волн: от 0.3 мкм до 3 мкм
+ Высокая чувствительность: квантовая эффективность 90%
+ Низкое мертвое время: 10 наносекунд
+ Высокая максимальная скорость счета: до 100 МГц
+ Высокое временное разрешение: до 20 пикосекунд
+ Низкий темновой счет: до 1 ложного отсчета в 10 секунд
+ Способность различать число фотонов в импульсе

Недостатки:

- Охлаждение до 4 К в специальном холодильнике
- Габариты приемной системы
- Энергопотребление
- Цена

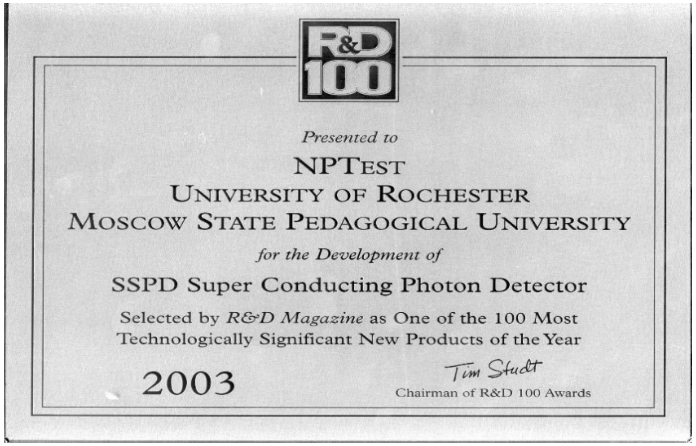
First application of NbN SNSPD: Silicon CMOS IC Device Debug



Applications:

- Electronic industry, specification, designing, verification and microchip manufacturing
- microelectronics: as a detection system of non-document parts of a microchip.

Normally operating nMOS transistor emits near IR photons (0.9-1.4um) when current passes through the channel. Time-correlated photon emission detection measures transistor switching time.



R&D 100

Presented to

NPTEST
UNIVERSITY OF ROCHESTER
MOSCOW STATE PEDAGOGICAL UNIVERSITY

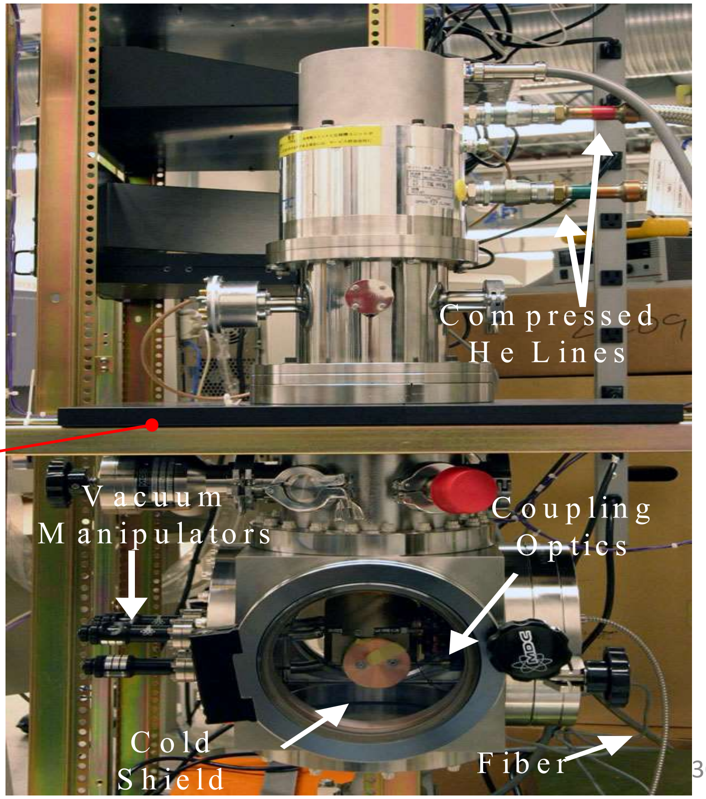
for the Development of

SSPD Super Conducting Photon Detector

Selected by *R&D Magazine* as One of the 100 Most Technologically Significant New Products of the Year

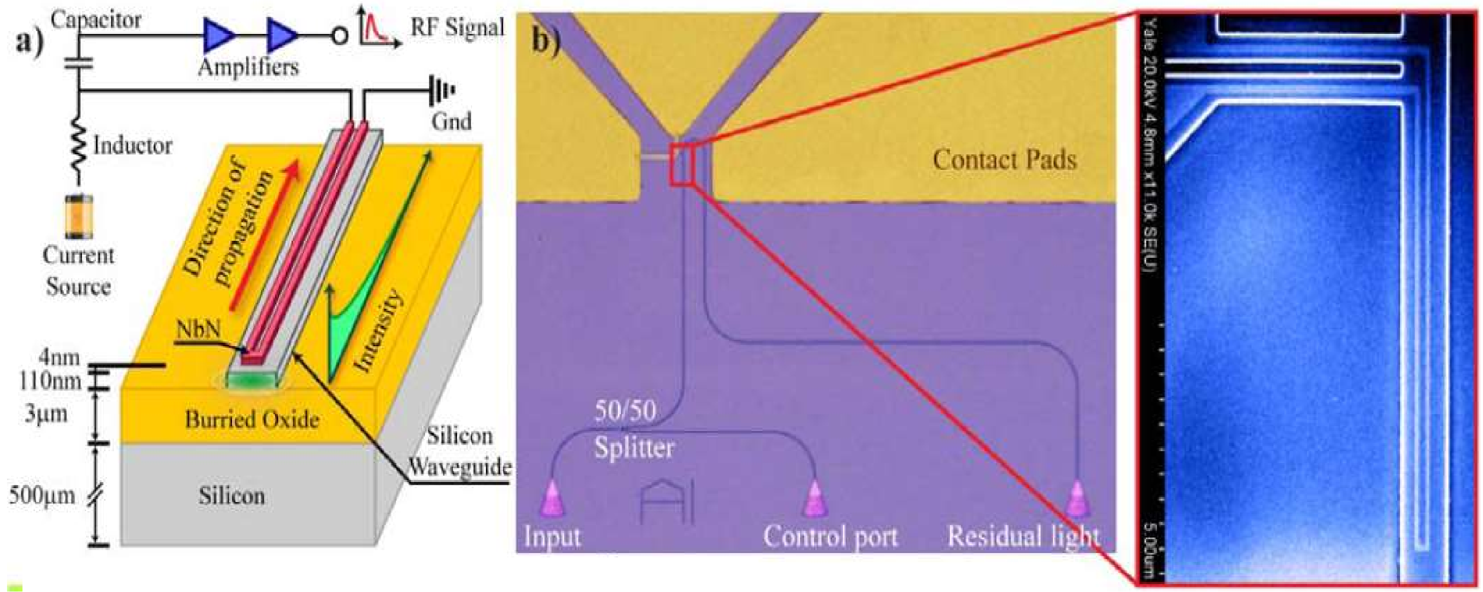
2003

Tim Studt
Chairman of R&D 100 Awards



High Speed Travelling Wave Single-Photon Detectors With Near-Unity Quantum Efficiency

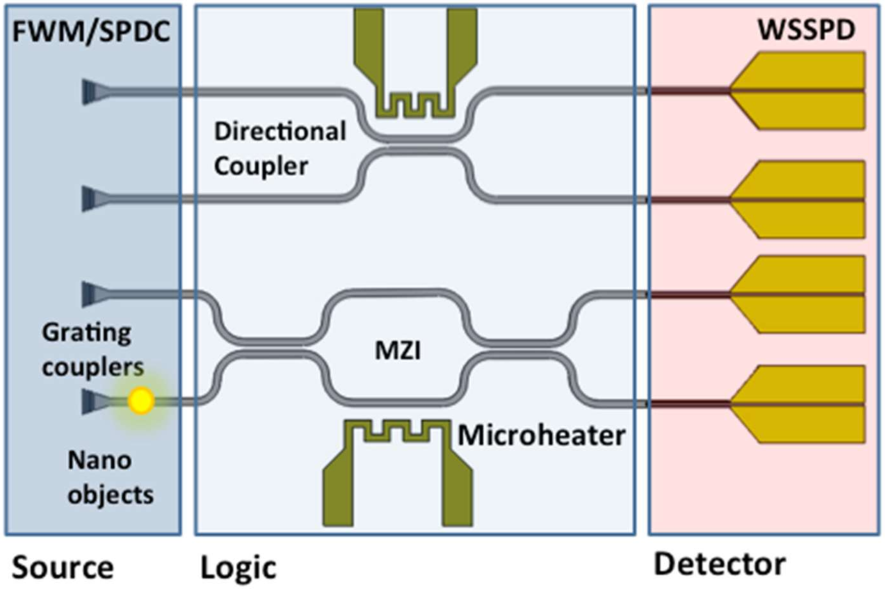
W. Pernice, C. Schuck, O. Minaeva, M. Li, G. Goltsman, A. Sergienko, H. Tang,
Nature Communications, 3, 1325 (2012)



a) Principle of the travelling wave SSPD: a sub-wavelength absorbing NbN nanowire is patterned atop a silicon waveguide to detect single photons; Max. QE= 91%

b) Optical micrograph of a fabricated device showing the optical input circuitry, RF contact pads and the SSPD; Inset: zoom into the detector region with an SEM image showing the detector regime. The control and residual ports are used for calibration purposes.

Silicon Nitride on Si - Single-photon platform for the realization of integrated SNSPD



Why on-chip photonics?

- ✓ The ability to integrate a huge number of optical components in a small area,
- ✓ Superposition of quantum states can be easily represented, encrypted, transmitted and detected
- ✓ Easy to manipulate (Linear Optics Quantum computation(LOQC), using only linear optical elements: beam splitters, phase shifters and mirrors)
- ✓ Low power consumption

Why silicon nitride?

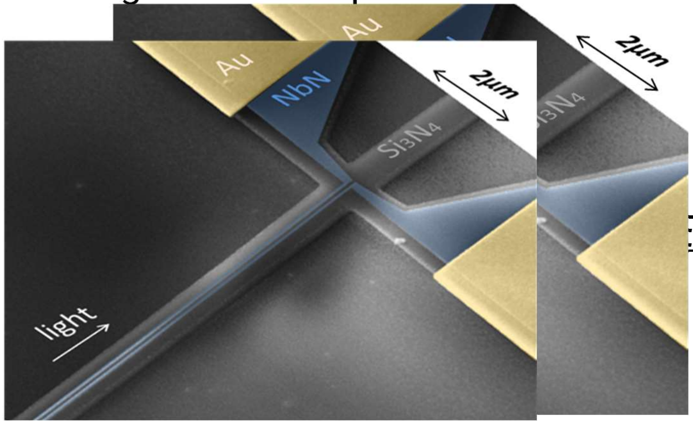
- ✓ Wide band gap → small absorption in visible and in IR range
- ✓ High refractive index
- ✓ Good mechanical properties
- ✓ Possibility to create SPS due to nonlinearity
- ✓ Compatibility with NbN thin film deposition process

Why WSNSPD?

- ✓ Compact design
- ✓ High detection efficiency
- ✓ Low timing jitter
- ✓ Low dead time
- ✓ No gating needed
- ✓ No afterpulsing

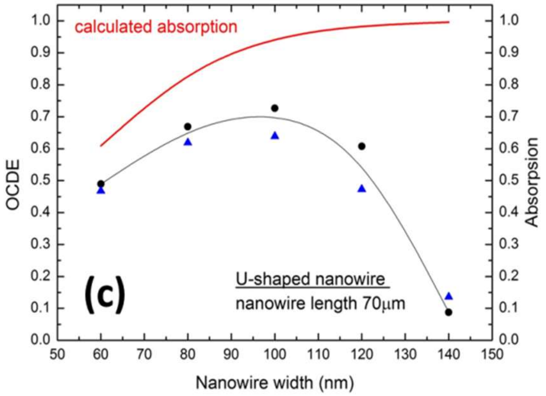
On-chip detection efficiency (OCDE) vs nanowire width

SEM Image of a U-shaped nanowire

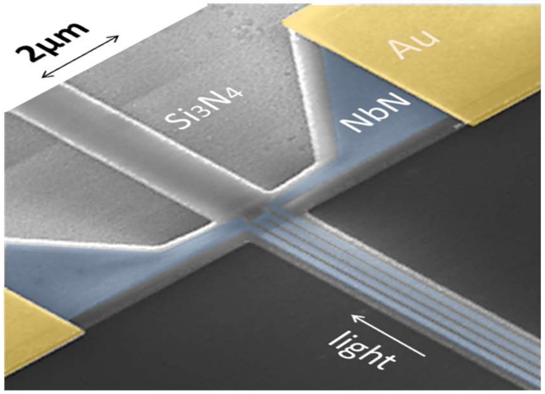


*E=A*IQE*

OCDE vs NbN nanowire width (U-shaped)

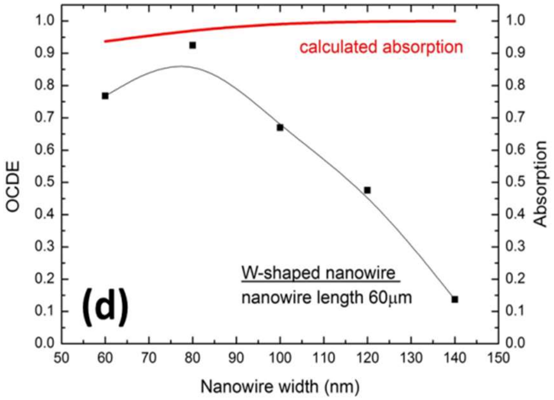


SEM Image of a W-shaped nanowire



OCDE≈IQE

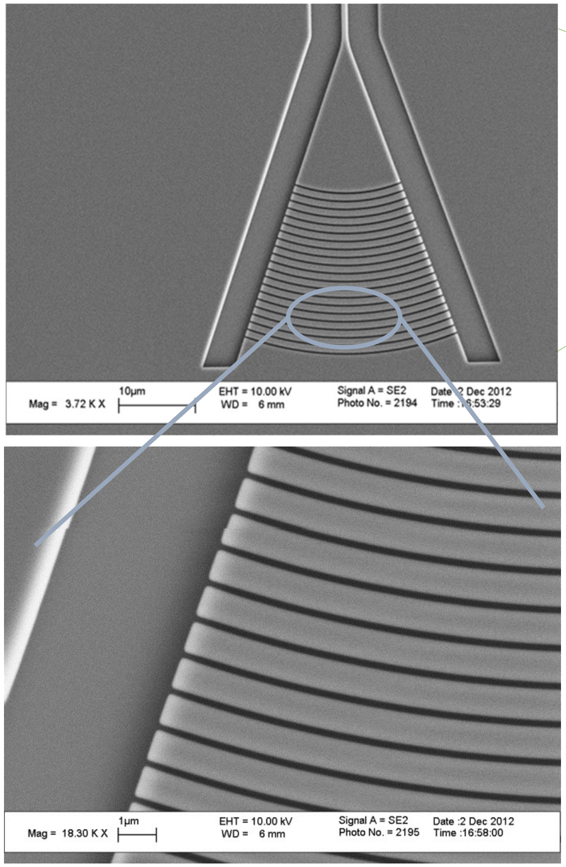
OCDE vs NbN nanowire width (W-shaped)

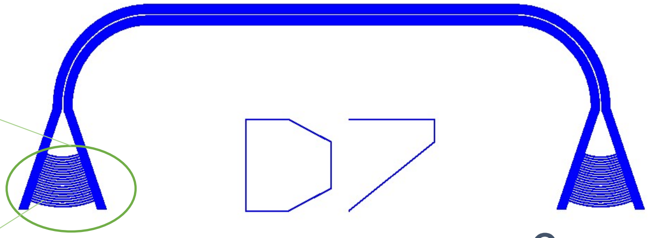


Focusing grating coupler optimization

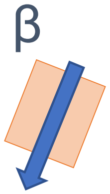
SEM image of (FGC)

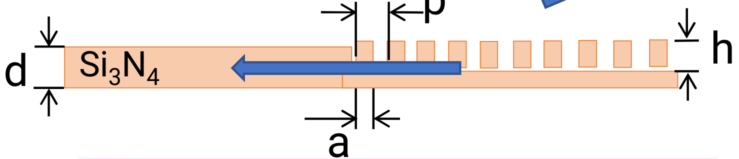
Image of a device prepared in Cadeance (Acrobat)

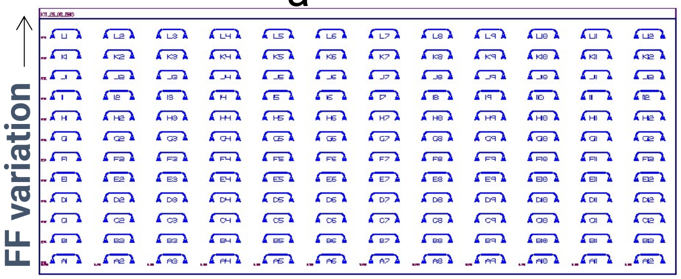




Parameters
d = 330nm, 450nm
ff = a/p (50-90%), height= h/d=0,5-1

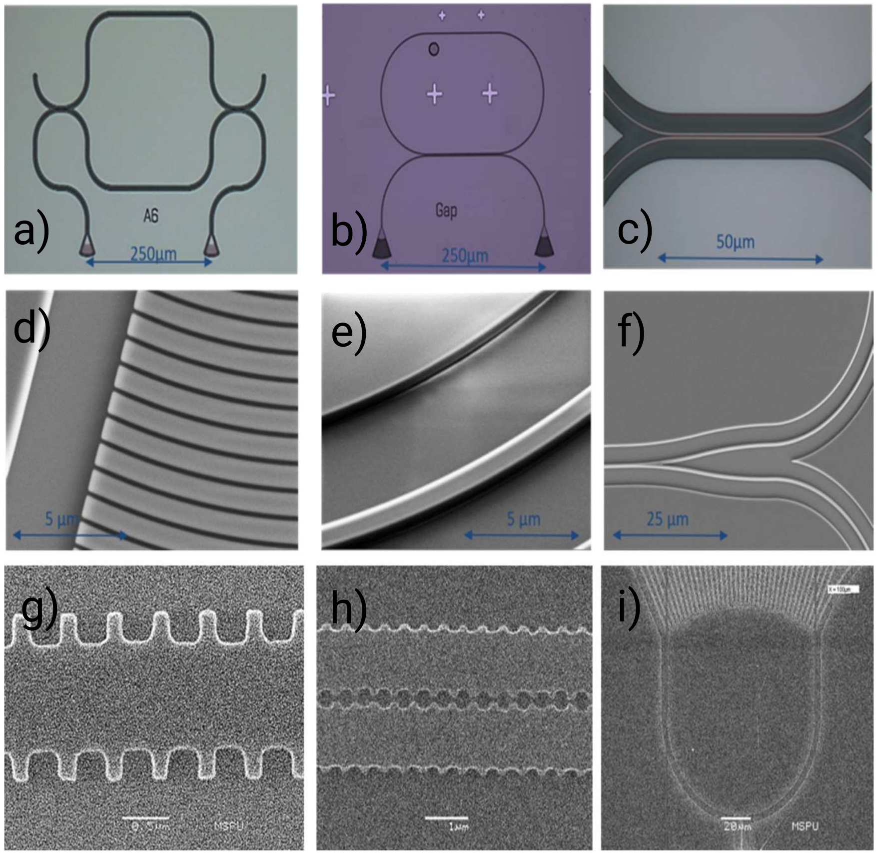






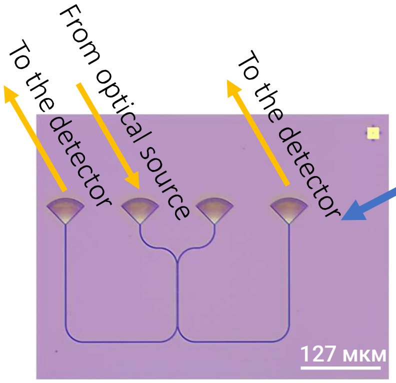
Integrated-on-chip photonics components

a) Mach-Zehnder interferometers
b) O-ring resonators
c) Directional couplers
d) Focusing grating couplers
e) Waveguides
f) Beam splitters
g) Bragg waveguides
h) Contra-directional couplers
i) Arrayed waveguide gratings

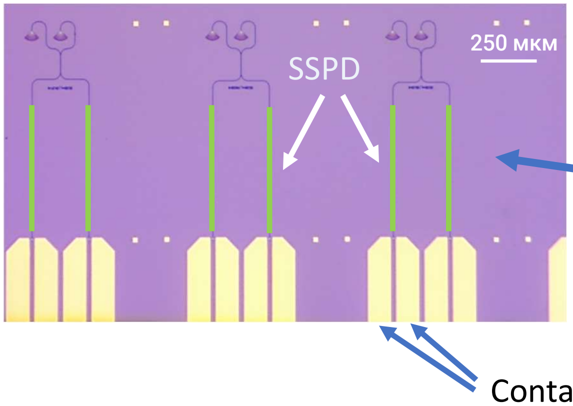


On the way to quantum computing based on quantum photonic integrating circuits

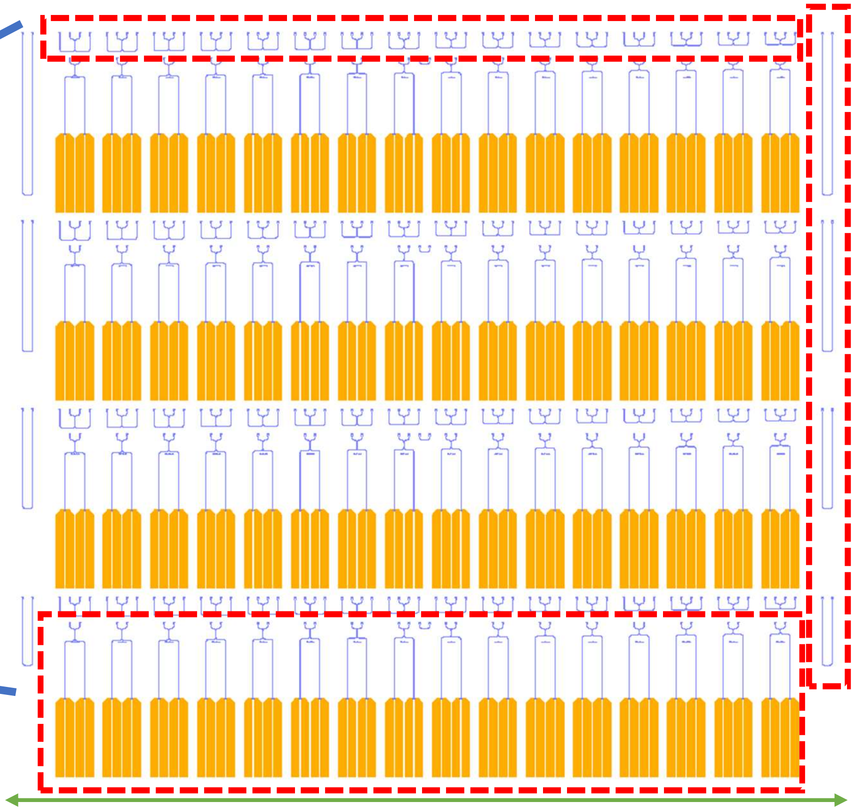
Directional coupler



Superconducting single-photon detectors with directional couplers

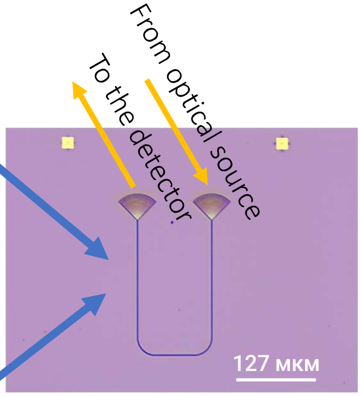


Contacts



12 x 12 mm2

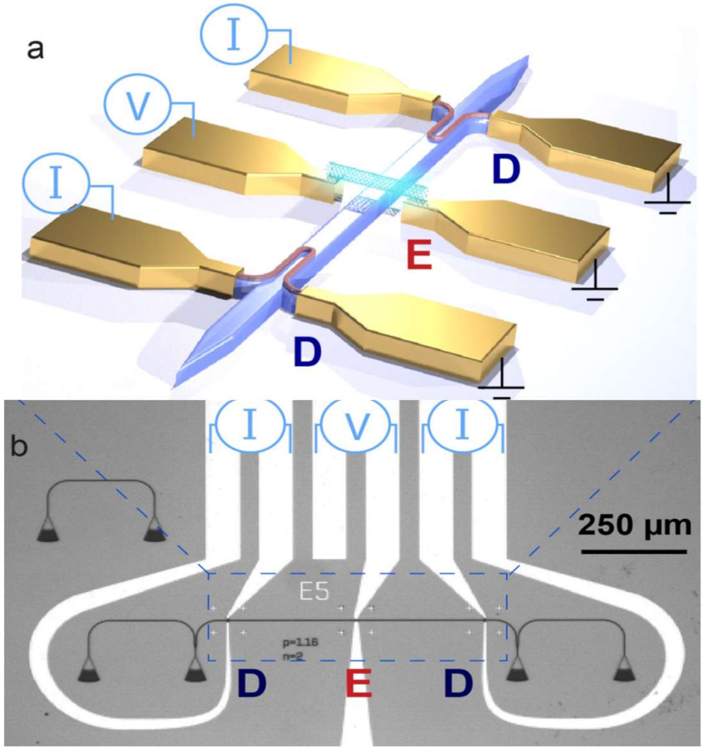
Optical waveguides with different lengths



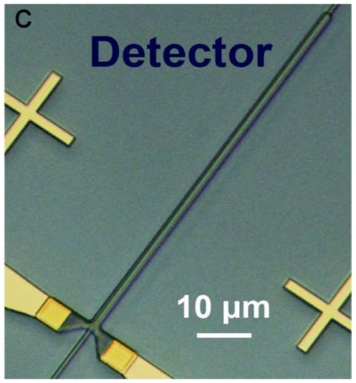
Fully integrated quantum photonic circuit with an electrically driven light source - waveguide-coupled semiconducting single-walled carbon nanotubes

Sc-SWCNT and two SNSPDs, all biased electrically

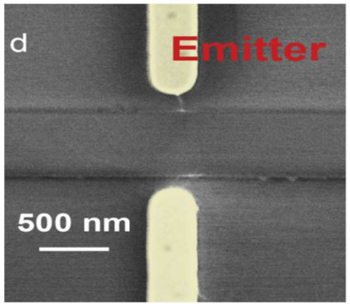
Optical micrograph



SNSPD



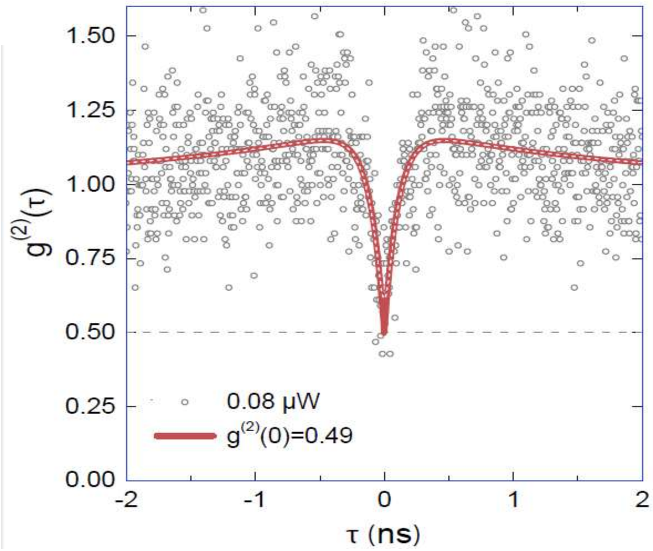
Sc-SWCNT



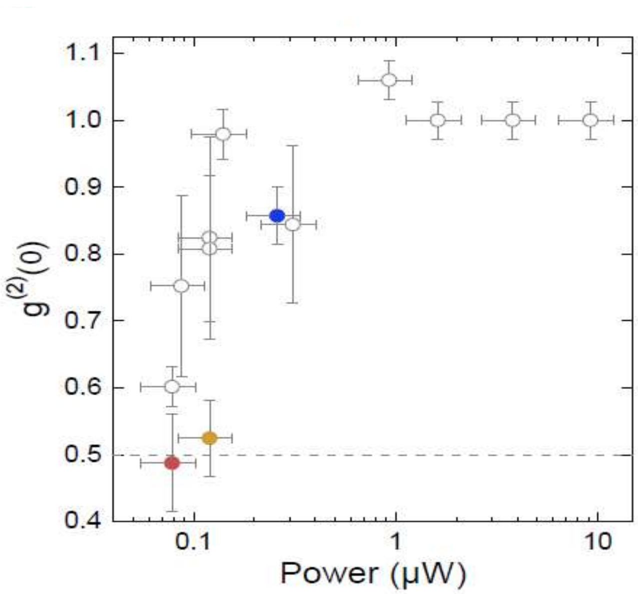
S. Khasminskaya, F. Pyatkov, K. Słowik, S. Ferrari, O. Kahl, V. Kovalyuk, P. Rath, A. Vetter, F. Hennrich, M. M. Kappes, G. Gol’tsman, A. Korneev, C. Rockstuhl, R. Krupke, and W. H. P. Pernice, “Fully integrated quantum photonic circuit with an electrically driven light source” *Nat. Photonics*, 10, 727–732 (2016)

Non-classical light from carbon nanotube

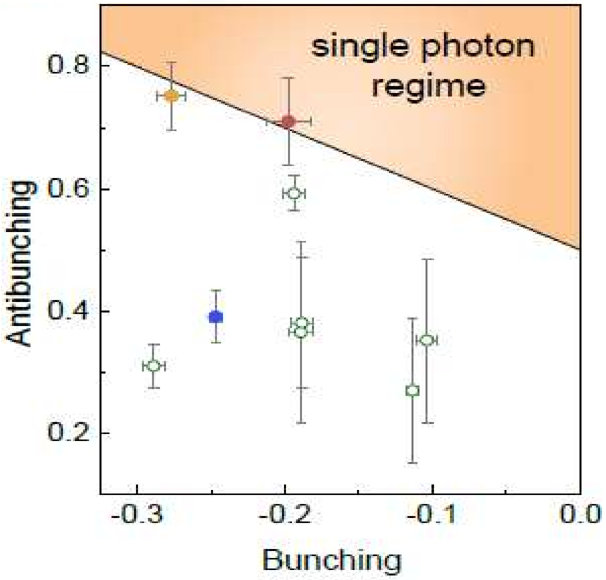
Coincidence histograms of non-classical light from sc-SWCNT



Correlation function at zero delay vs power



Antibunching (c_2) vs bunching amplitude (c_1)



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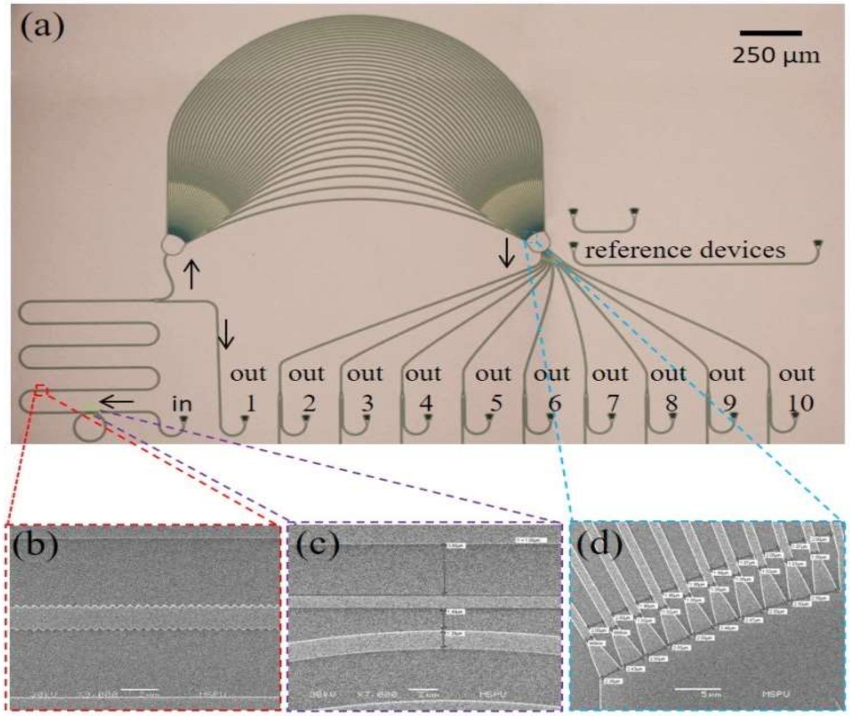
S. Khasminskaya, F. Pyatkov, K. Słowik, S. Ferrari, O. Kahl, V. Kovalyuk, P. Rath, A. Vetter, F. Hennrich, M. M. Kappes, G. Gol’tsman, A. Korneev, C. Rockstuhl, R. Krupke, and W. H. P. Pernice, “Fully integrated quantum photonic circuit with an electrically driven light source” *Nat. Photonics*, 10, 727–732 (2016)

QPIC for entangled photons generation by four-wave mixing, filtering, and detection using an array of planar waveguides (AWG) and SSPDs



a) Optical micrograph of a QPIC for generating entangled quantum states and their detection, obtained with a optical microscope

The numbers show the outputs of the focusing grating couplers with outputs from the QPIC for external testing.

b) SEM image of a Bragg waveguide

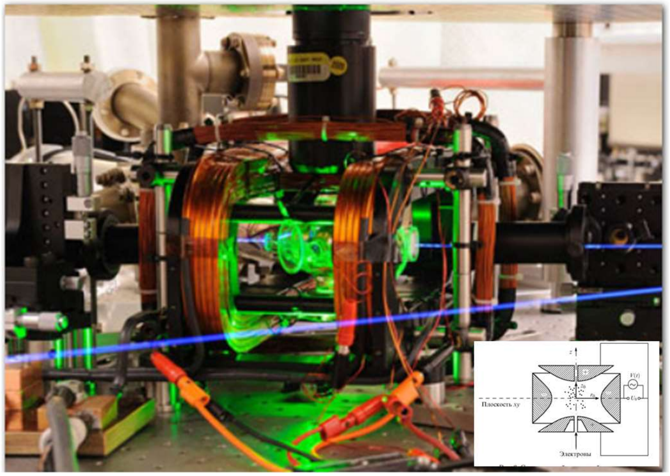
c) SEM image of the gap between the waveguide and the O-ring resonator

d) SEM image of a "star coupler" in an AWG optical demultiplexer

Golikov A, Kovalyuk V, An P, Zubkova E, Ferrari S, Pernice W, Korneev A and Goltsman G 2018 Silicon nitride nanophotonic circuit for on-chip spontaneous four-wave mixing *J. Phys. Conf. Ser.* **1124** 1–4

Ion trap with SNSPDs and PICs (Concept)

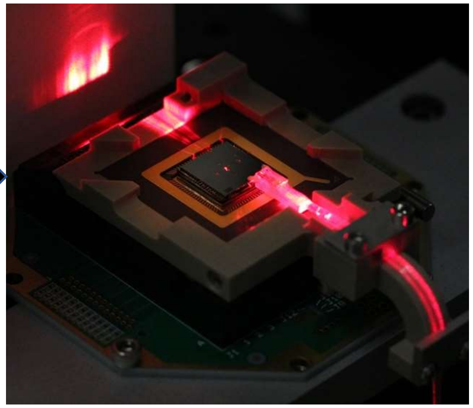
3D image of the Paul ion trap (NIST)



- **Principle of operation:** capture of ions in a potential well (RF and DC field)
- **Excitation:** free space optics
- **Readout:** CCD camera photon detection (slow, inefficient)
- **Advantages:** well-studied
- **Disadvantages:** limited area of ion accumulation (no scalability)

Ion capture

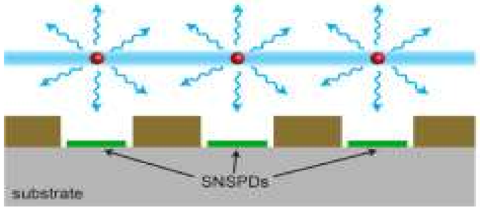
Planar trap with fiber interface and SNSPDs on a chip (Model)



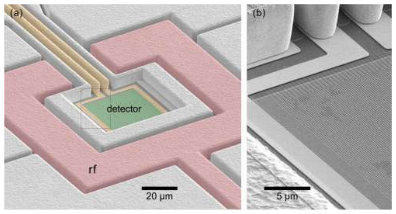
- **Operating principle:** as in a 3D trap
- **Excitation:** integrated optics
- **Readout:** photon detection of SNSPDs on a trap chip (fast, high efficiency)
- **Advantages:** scalability
- **Disadvantages:** difficult to manufacture

SNSPDs

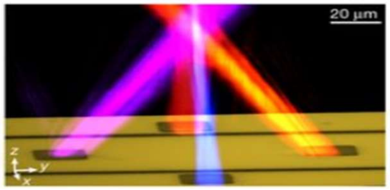
PIC



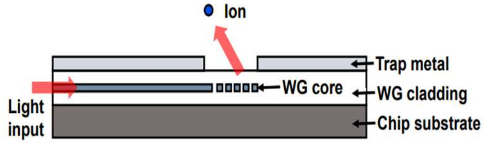
SNSPD in a planar ion trap



Pumping an ion through a grating

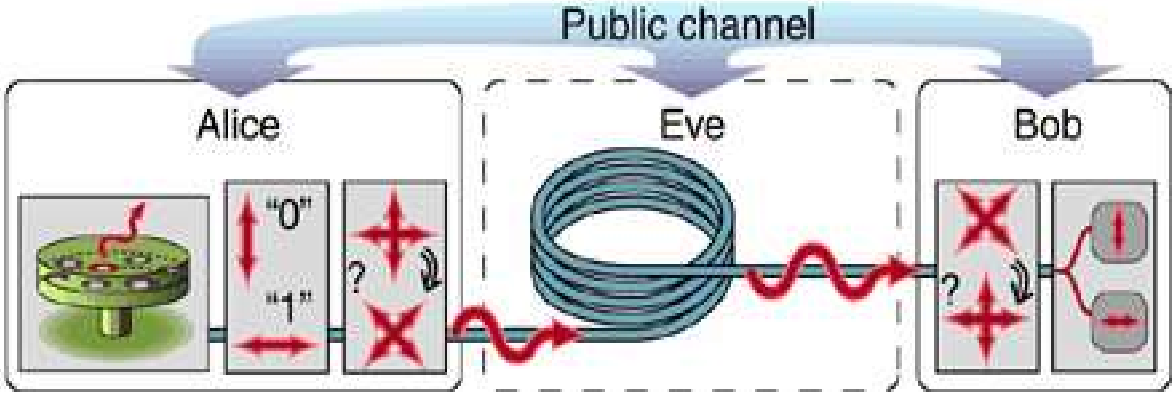


Longitudinal section of the chip



Quantum Cryptography (QC) based on single-photon communication assures unconditional security

Alice (Sender)



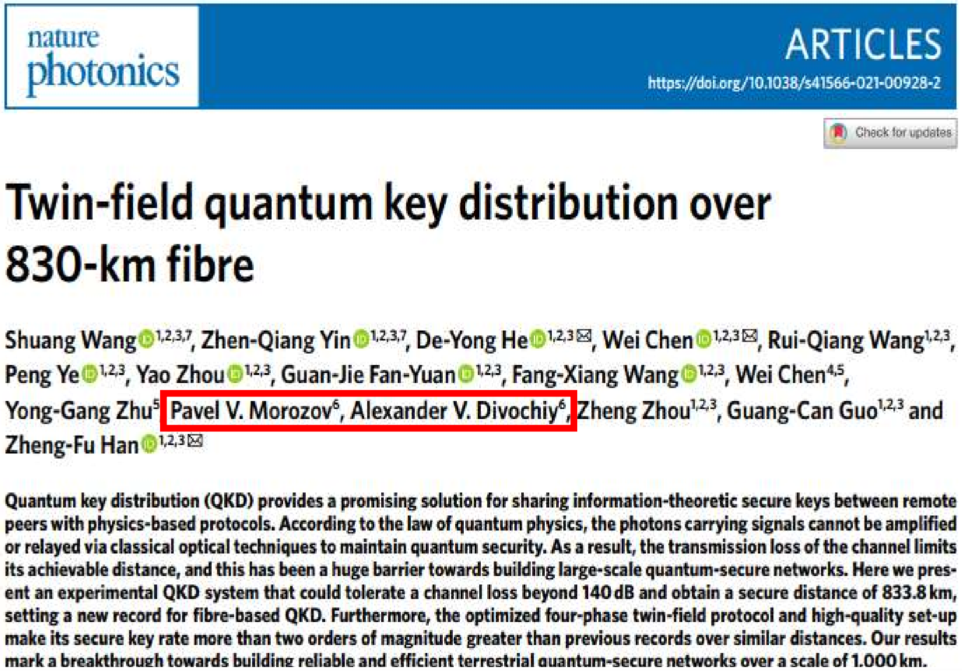
Bob (Receiver)

[from Simon Benjamin, Science 290, 2273 (2000)]

- **Unconditionally secret, quantum key distribution is possible in actual physical environments due to Heisenberg Indeterminacy Principle:** ***It is impossible to measure the state of a quantum bit without altering it.***
- **Alice (Sender) - single-photon source.**
- **Bob (Receiver) - single-photon detector.**

SCONTEL

Record 2022 for the longest distance to distribute a quantum key over a fiber optic communication line



nature photonics

ARTICLES

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Twin-field quantum key distribution over 830-km fibre

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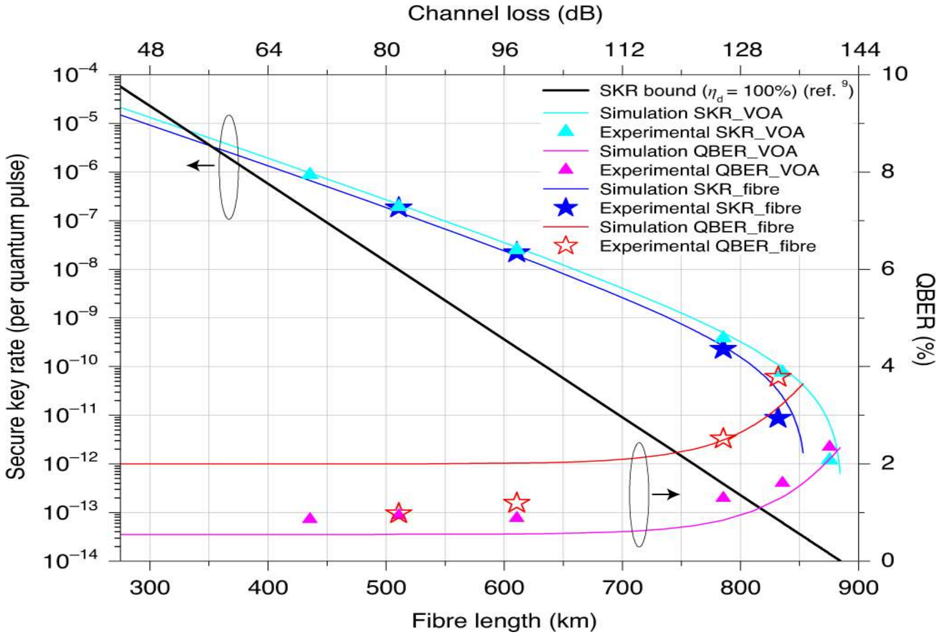
Quantum key distribution (QKD) provides a promising solution for sharing information-theoretic secure keys between remote peers with physics-based protocols. According to the law of quantum physics, the photons carrying signals cannot be amplified or relayed via classical optical techniques to maintain quantum security. As a result, the transmission loss of the channel limits its achievable distance, and this has been a huge barrier towards building large-scale quantum-secure networks. Here we present an experimental QKD system that could tolerate a channel loss beyond 140 dB and obtain a secure distance of 833.8 km, setting a new record for fibre-based QKD. Furthermore, the optimized four-phase twin-field protocol and high-quality set-up make its secure key rate more than two orders of magnitude greater than previous records over similar distances. Our results mark a breakthrough towards building reliable and efficient terrestrial quantum-secure networks over a scale of 1,000 km.



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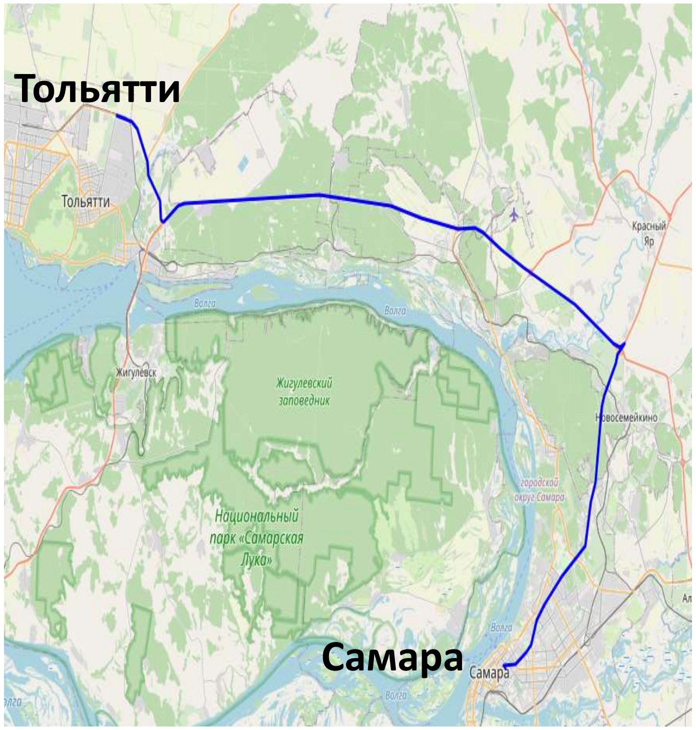
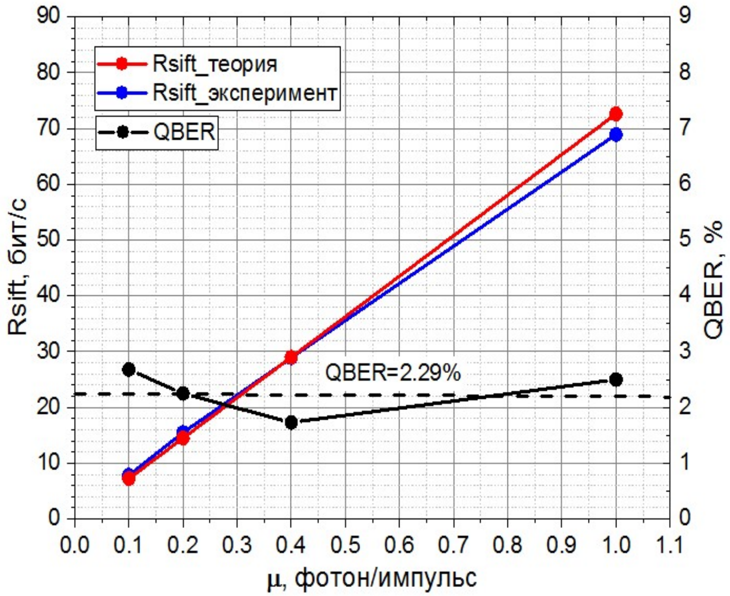
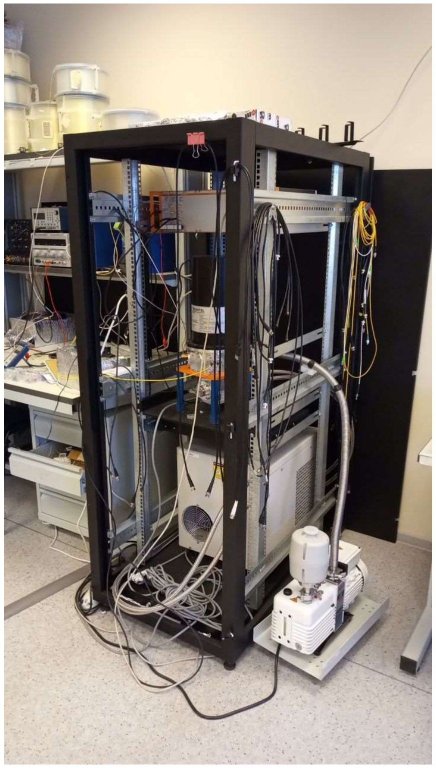
Московский институт электроники и математики НИУ ВШЭ

Квантовое распределение ключа в полевых условиях на расстояние свыше 200 км по маршруту Самара-Тольятти-Самара

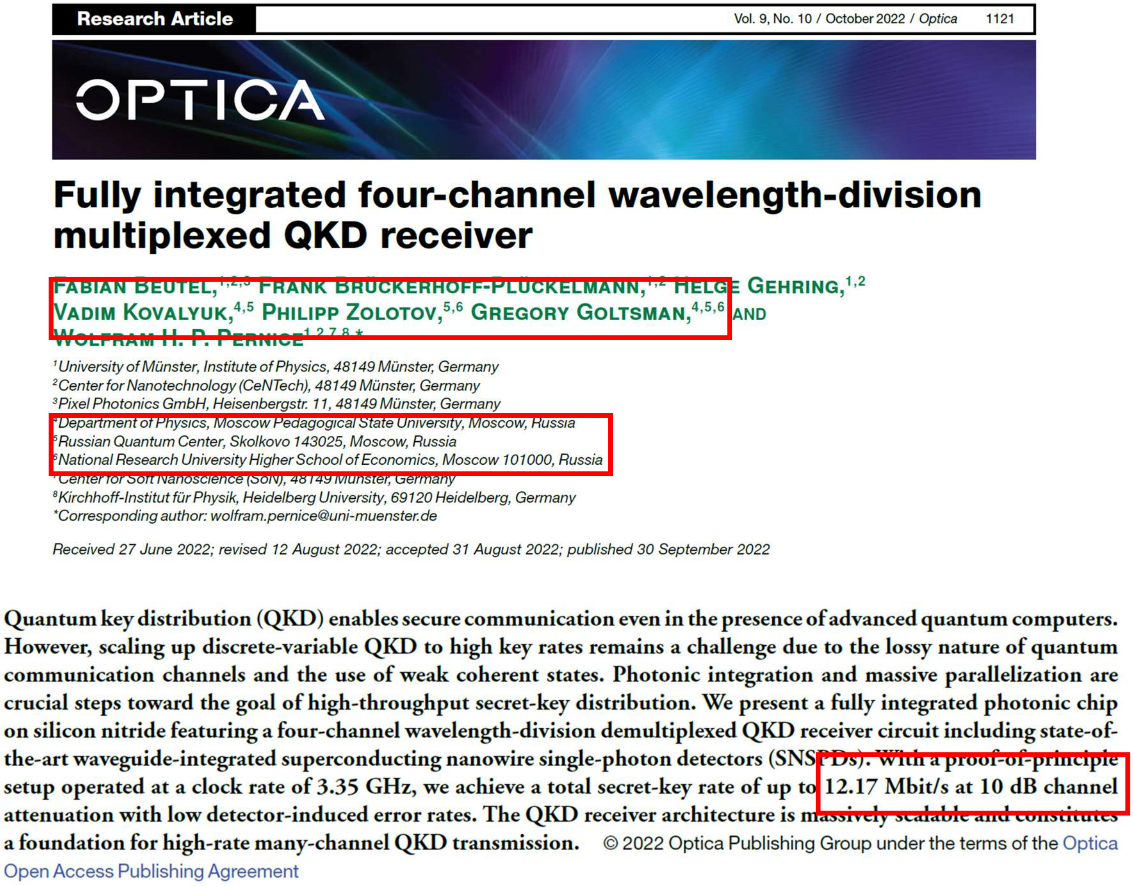
НИОКР «Разработка технологий и устройств квантовых коммуникаций для магистральных линий большой протяженности», 2021-2024гг., ОАО «РЖД».







РАЗРАБОТКА ФОТОННЫХ ИНТЕГРАЛЬНЫХ СХЕМ ДЛЯ СИСТЕМ КРК.



Research Article Vol. 9, No. 10 / October 2022 / *Optica* 1121

OPTICA

Fully integrated four-channel wavelength-division multiplexed QKD receiver

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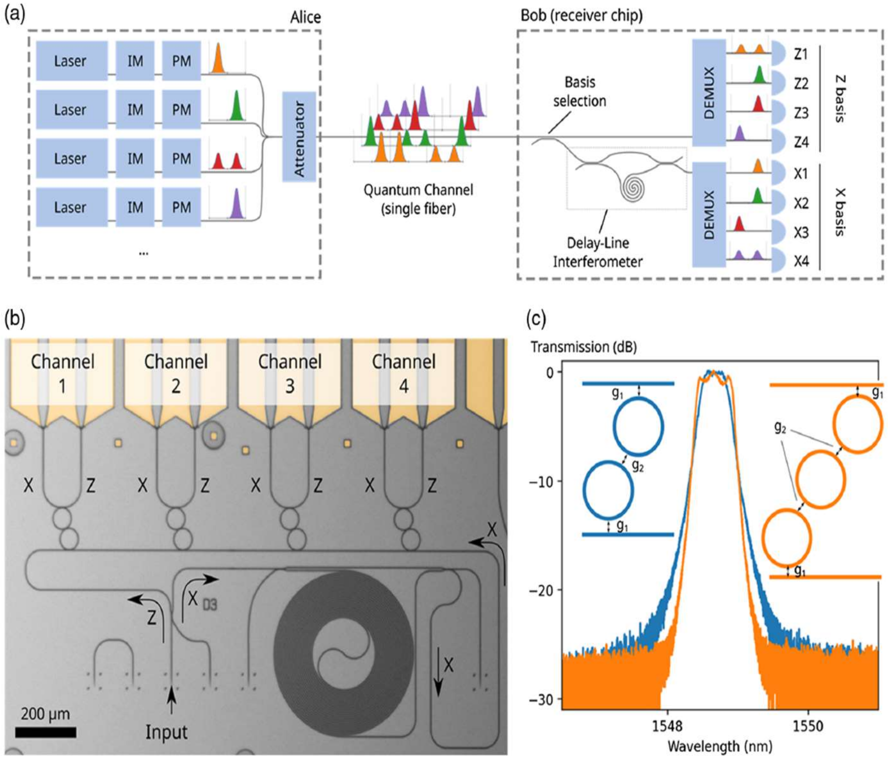
Quantum key distribution (QKD) enables secure communication even in the presence of advanced quantum computers. However, scaling up discrete-variable QKD to high key rates remains a challenge due to the lossy nature of quantum communication channels and the use of weak coherent states. Photonic integration and massive parallelization are crucial steps toward the goal of high-throughput secret-key distribution. We present a fully integrated photonic chip on silicon nitride featuring a four-channel wavelength-division demultiplexed QKD receiver circuit including state-of-the-art waveguide-integrated superconducting nanowire single-photon detectors (SNSPDs). With a proof-of-principle setup operated at a clock rate of 3.35 GHz, we achieve a total secret-key rate of up to 12.17 Mbit/s at 10 dB channel attenuation with low detector-induced error rates. The QKD receiver architecture is massively scalable and constitutes a foundation for high-rate many-channel QKD transmission. © 2022 Optica Publishing Group under the terms of the Optica Open Access Publishing Agreement



Conclusions

- SNSPDs combine high detection efficiency, low dark count rate, and high temporal resolution in a single device in visible and near IR range. SNSPDs have been successfully employed for classical and quantum optics applications ranging from optical time domain reflectometry (OTDR), light detection and ranging (LiDAR), space-to-ground communications, quantum dot photonics, quantum key distribution to experiments with indistinguishable and entangled photon pairs and applications in the life sciences.

- Recent results show that for a single-photon response, a superconducting strip does not need to be fabricated into a nanowire. It turns out that a small hot spot can turn even a micron size strip to a resistive state if the bias current density in it is close to the depairing current density
- This opens up new opportunities for using standard photolithography process instead of advanced electron-beam lithography and significantly simplifies device fabrication, which in turn simplifies the development of large-area single-photon detectors, detector arrays and so on.

- SNSPD is the only technology to count photons on an optical chip and this is our way to quantum photonic integrating circuits and also to quantum computing based on photons.

Thank you for your attention!