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INFRARED NBN SUPERCONDUCTING SINGLE-PHOTON DETECTOR FOR QUANTUM CRYPTOGRAPHY AND QUANTUM INFORMATION PROCESSING

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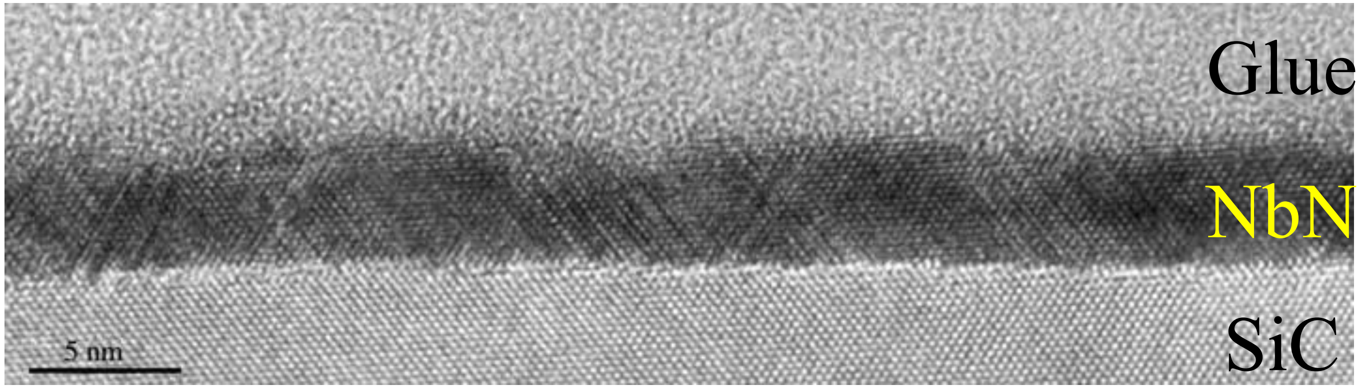
Outline

- Superconducting Single-Photon Detector (SSPD):
  - Introduction
  - Operation principle
  - Fabrication
- Performance
  - High detection efficiency limited by optical coupling
  - Temperature dependence of the performance parameters
  - High speed & Very low jitter
- Practical applications
  - Quantum cryptography
  - Other single-photon applications
- Devices under development
  - Photon-number resolving
  - Narrow parallel strip SSPD for middle infrared
  - Waveguide-coupled SSPD
- Conclusion

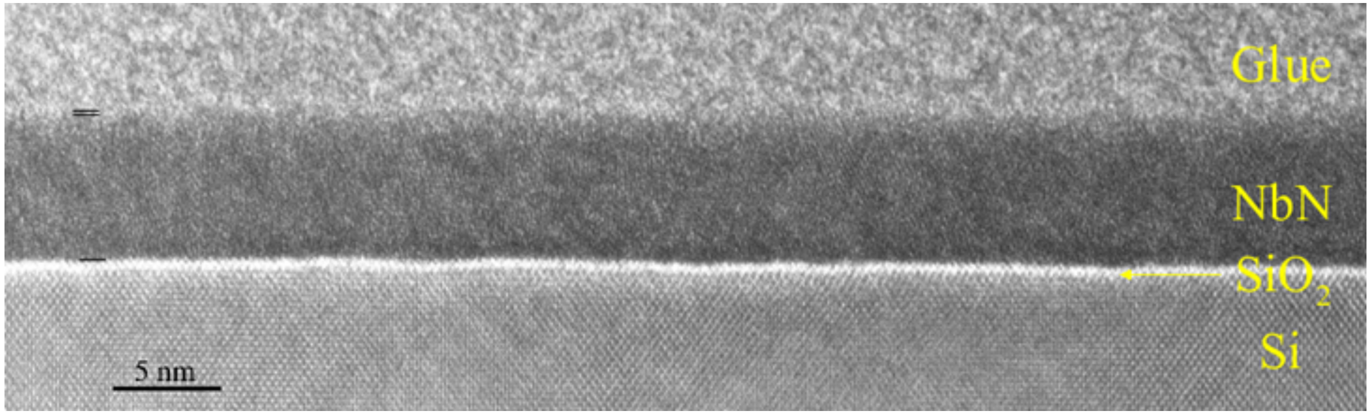
High quality ultrathin superconducting NbN film is a key element of the SSPD

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

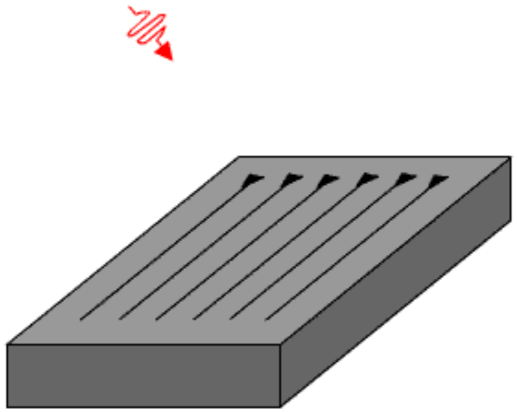
NbN on Si substrate

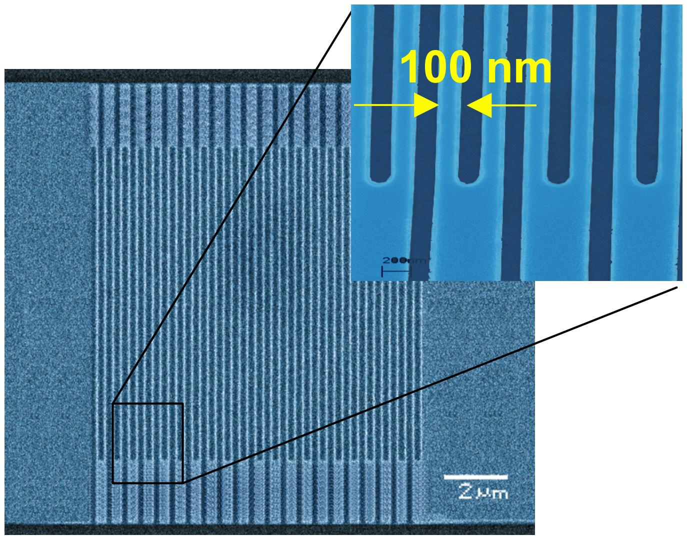


The NbN on Si is polycrystalline.

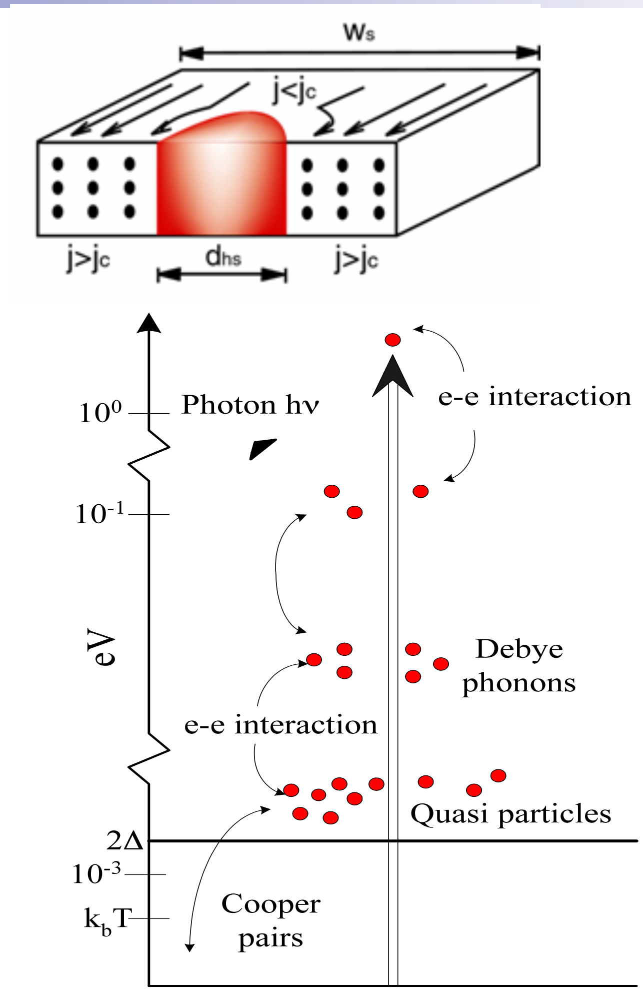
J.-R. Gao, G. Gol'tsman, B.Voronov, *et al, APL (2007)*

SSPD: Detection mechanism



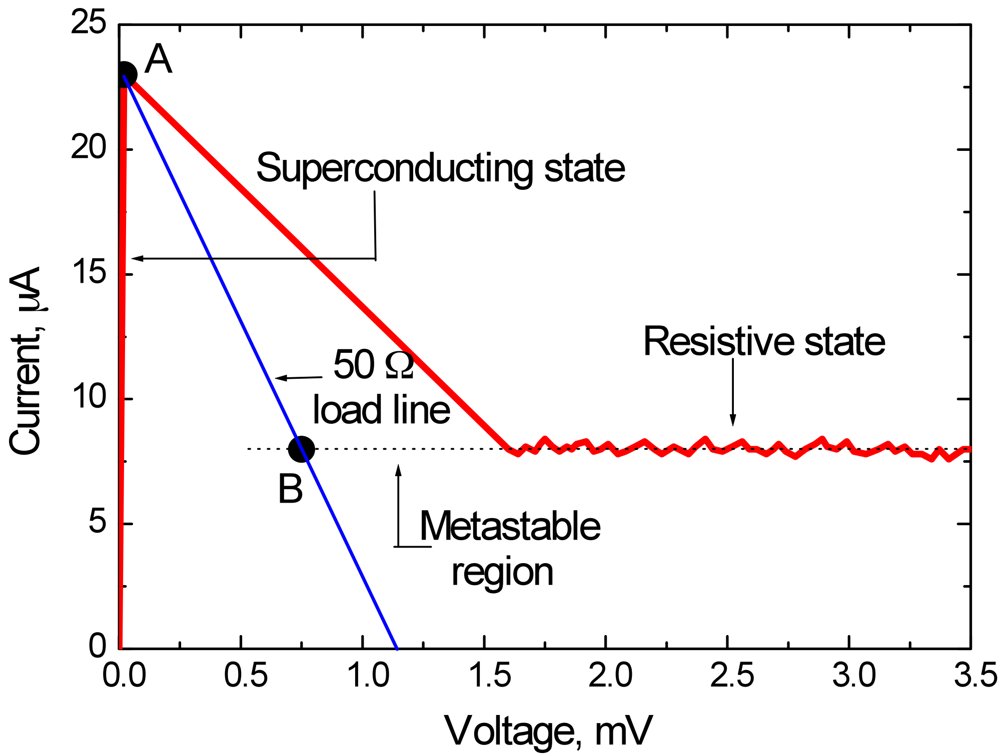


G. Gol'tsman *et al*, Applied Physics Letters 79 (2001), pp. 705-70
A. Semenov *et al*, Physica C, 352 (2001), pp. 349-356

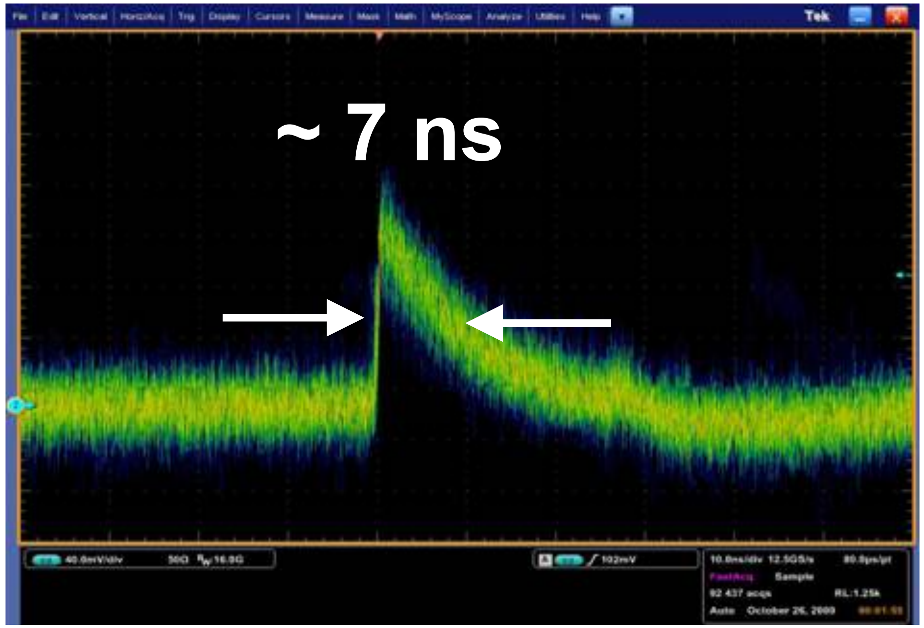


Schematic description of relaxation process in an optically excited superconducting thin film.

SSPD: operation principles

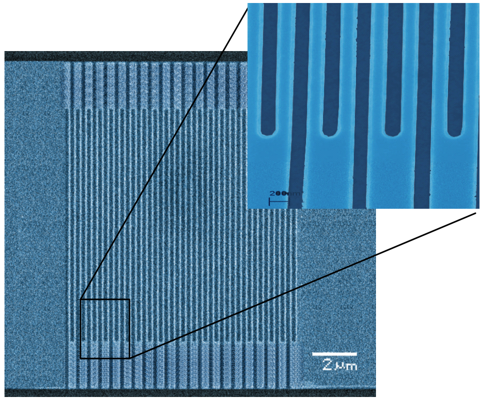


Typical IV-curve of the SSPD



Absorbed photon produces ~7 ns long voltage pulse

SSPD Fabrication



Present day challenges:
- increase detection efficiency beyond absorption of NbN film by using optical cavity
- increase filling factor (presently about 60%)
- reduce strip width from 100 nm to 50 nm or even less

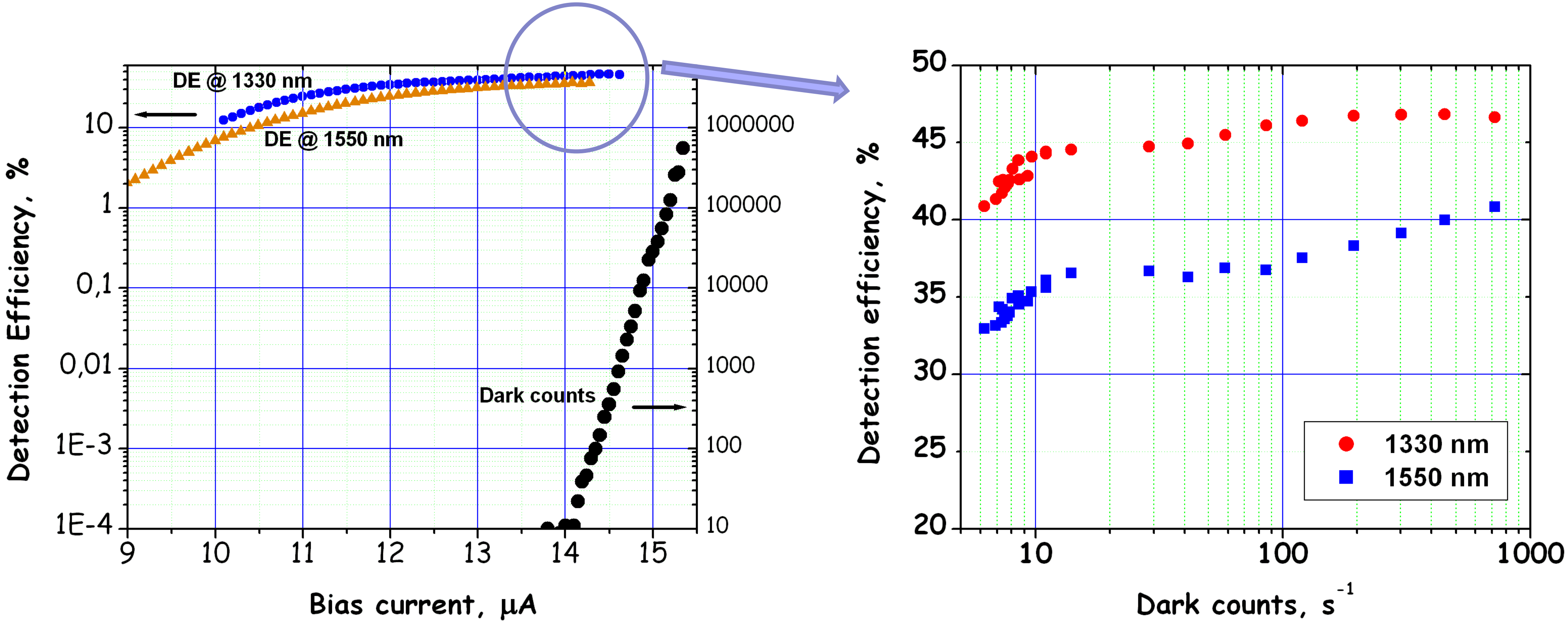
Fabrication:
- Substrate: Si with SiO_2 layer comprises optical cavity (Si with SiO_2 interface acts as a mirror)
- NbN film deposition: DC magnetron sputtering
- Patterning: E-beam lithography, reactive ion etching

Gol'tsman G. *et al*, *Appl. Phys. Lett.* 79 (2001) 705
Korneev A. *et al*, *Appl. Phys. Lett.* 84 (2004) 5338

Detection efficiency and dark counts rate

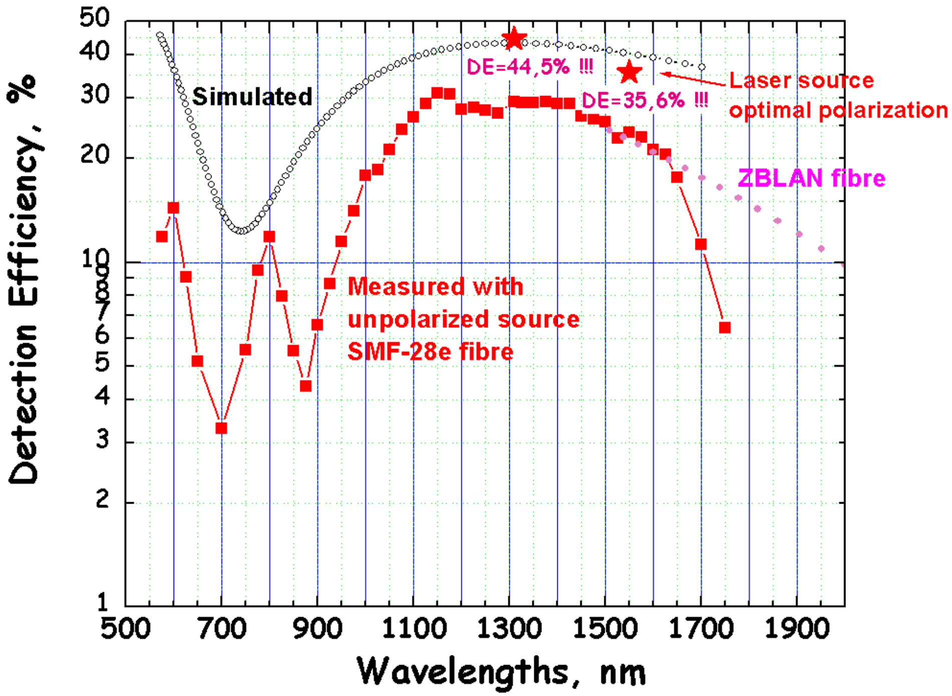
Light source: laser diodes.

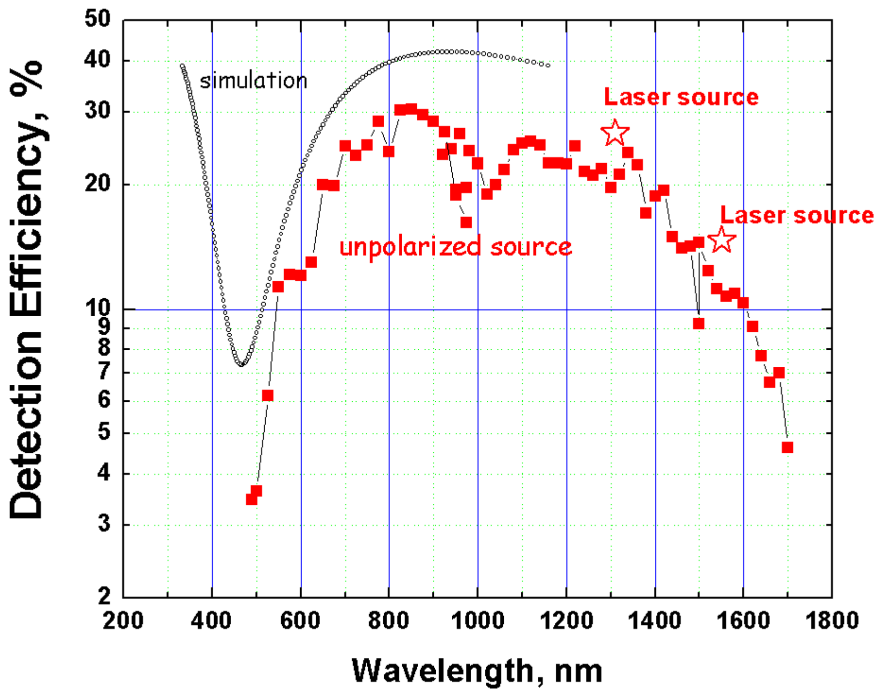
Polarized light. Polarization adjusted for maximum detection efficiency.



Detection efficiency vs wavelength

Fibre-coupled devices



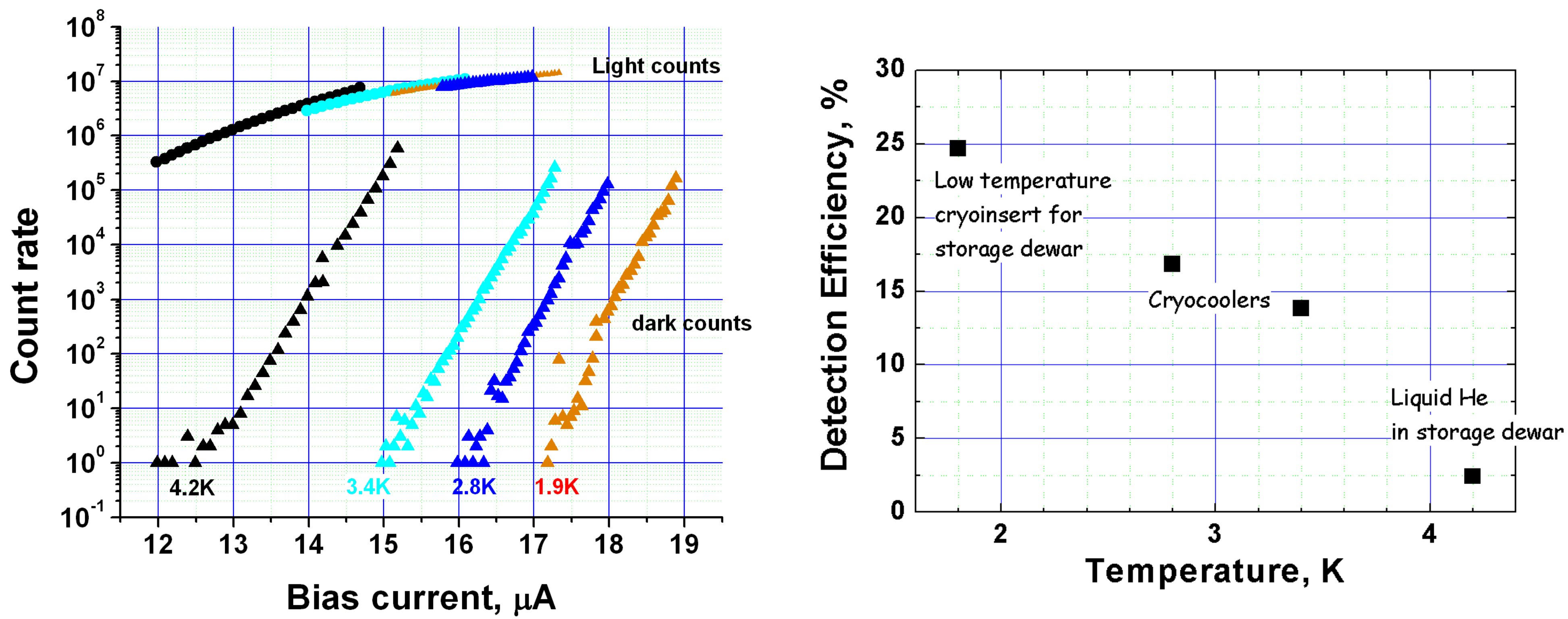


SiO_2 thickness: 200 nm

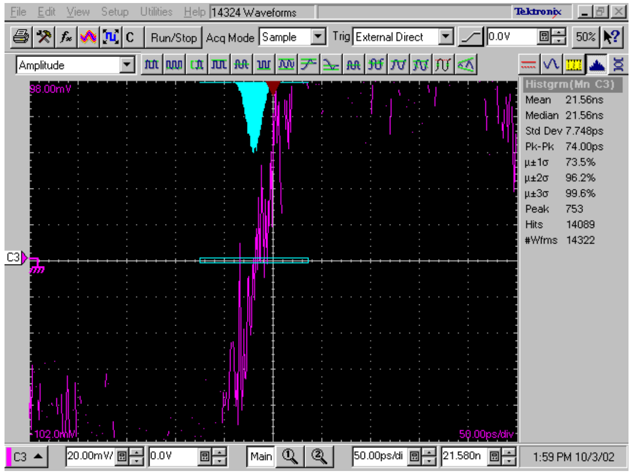
SiO_2 thickness: 160 nm

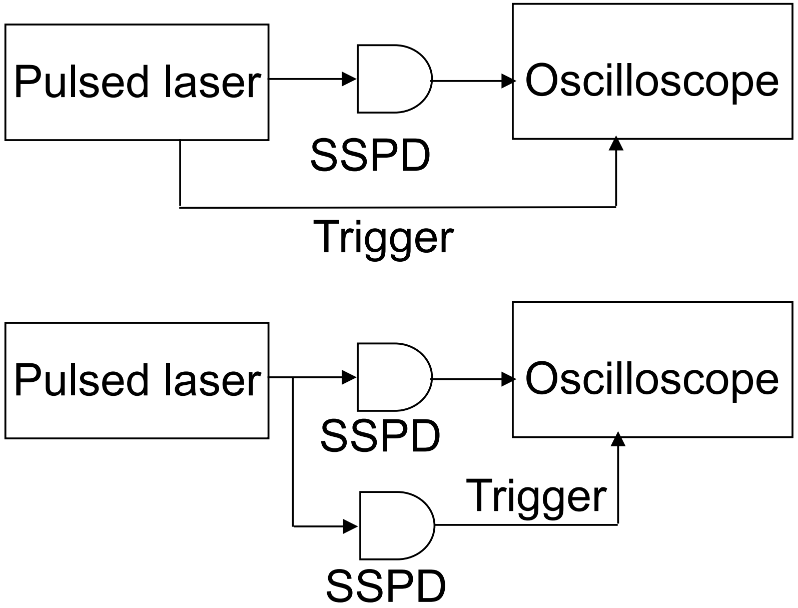
Dark counts rate in both cases 10 counts per second

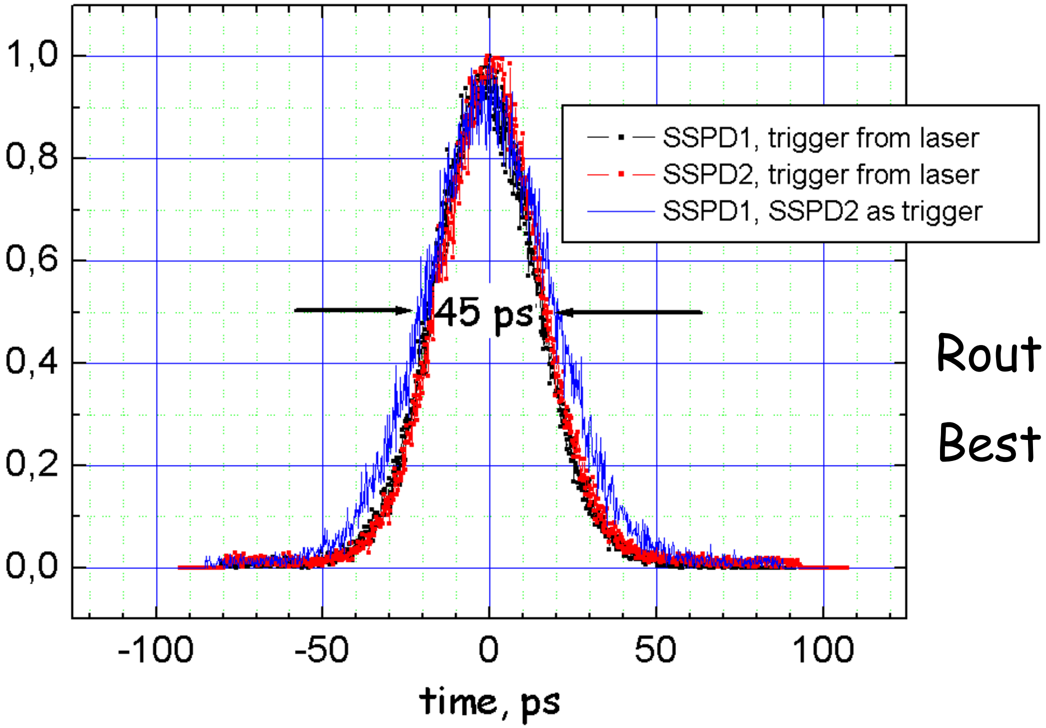
Detection efficiency vs temperature



Timing jitter







Routinely achieved: 35 - 45 ps

Best value: 18 ps (Verevkin et al JMO 2004)

Practical detector systems

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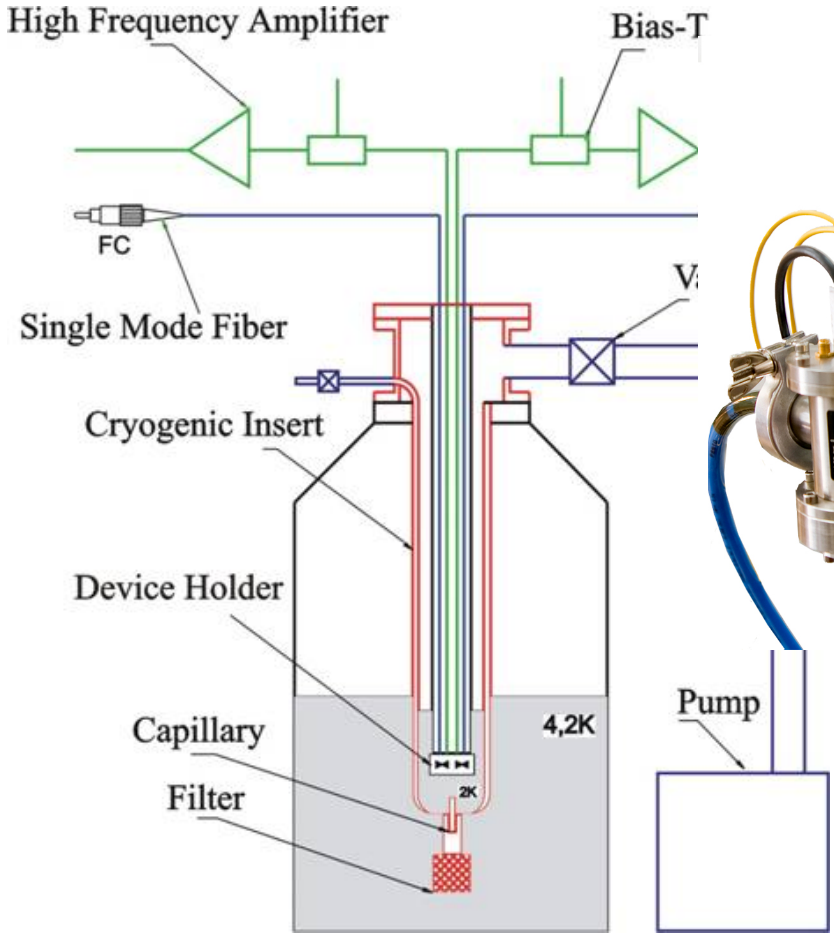

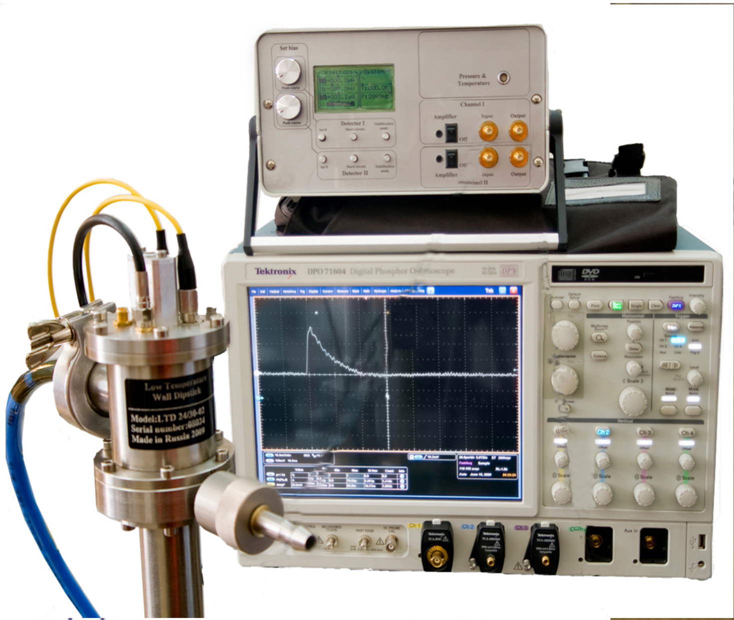

Multy-channel single-photon receiver

Storage dewar and cryocooler-based solution

Applications for QKD

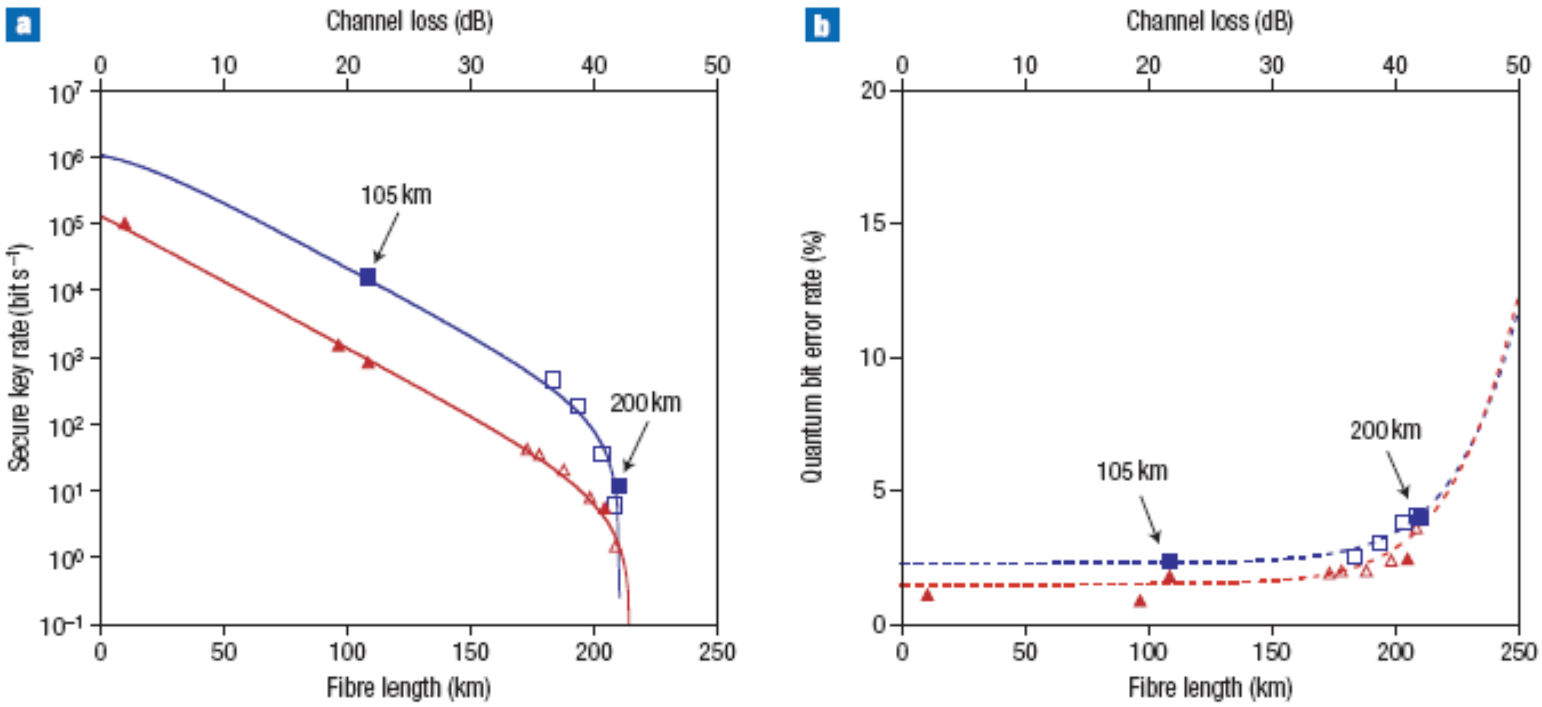

Figure 5 DPS-QKD experimental results. **a**, Secure key rate, and, **b**, quantum bit error rate, both as a function of fibre length with 0.2-dB km^{-1} loss and channel loss. The squares and triangles show measured secure key rates generated respectively by 10-GHz and 1-GHz clock systems with SSPDs. The filled and open symbols denote fibre transmissions and optical attenuation, respectively. The channel loss does not include the loss of the planar-lightwave-circuit interferometer.

H. Takesue, et. al., Nature Photonics, 1:343–348, 2007.

Applications for QKD

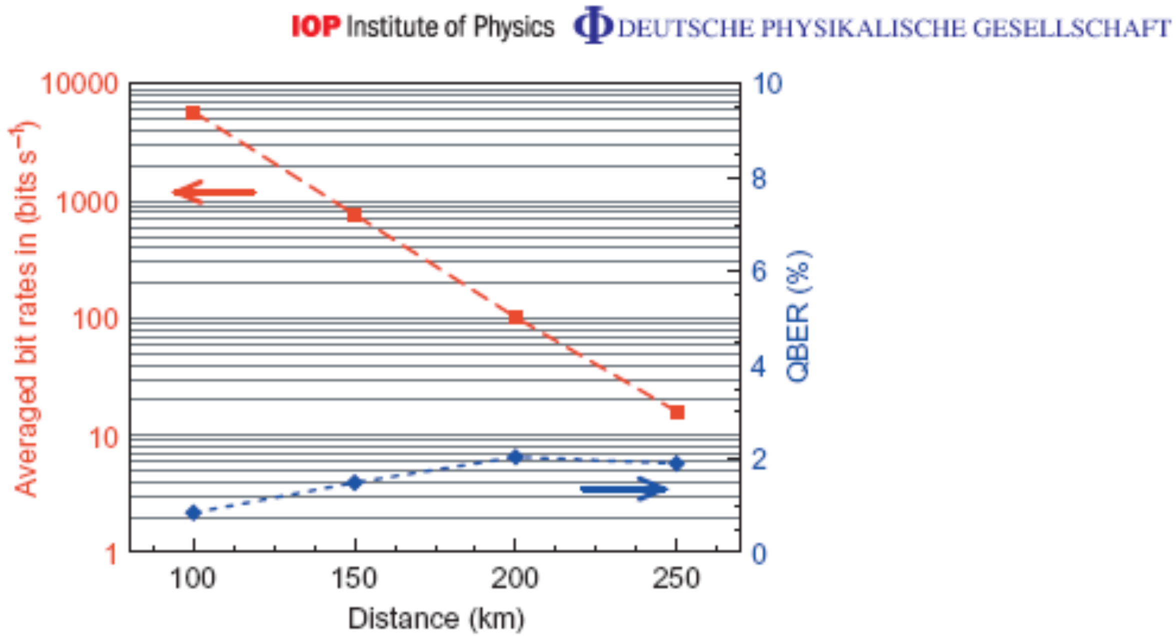

Figure 6. Averaged secret bit rates (red squares) and QBER (blue diamonds) for a range of SMF-28® ULL fibre lengths.

D. Stucki, et. al., New J. of Physics, 11 (2009) 075003

Other applications

2009: Detection of electrically neutral organic molecules

M. Marksteiner, et al, Nanotechnology 20 455501, 2009

2008: Biology: Photon-counting optical coherence domain reflectometry

N.Mohan,et al., Optics Express 16, 18118-18130, 2008

2006: Characterization and research into emission of single-photon sources

C. Zinoni, et. al., Applied Physics Letters, 91:031106, 2007
M. Stevens, et. al., Applied Physics Letters, 89:031109, 2006

2001: CMOS integrated circuits debug by time-resolved detection of single-photon emission from both *n*MOS and *p*MOS transistors

S. Somani, et. al., J. Vac. Sci. Technol. B 19(6), 2001 pp. 1071-1023.
J. Zhang, et. al., Elect. Lett. 39, 1086–1088. (2003)

Photon-number resolving SSPD (PNR-SSPD)

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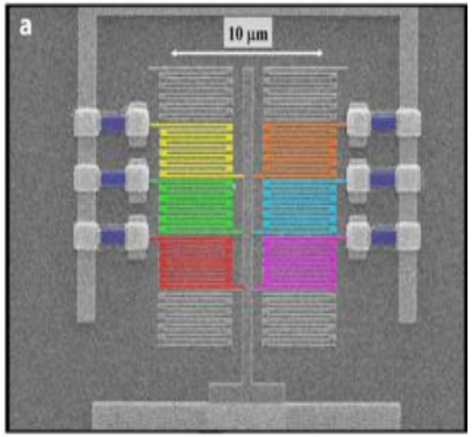
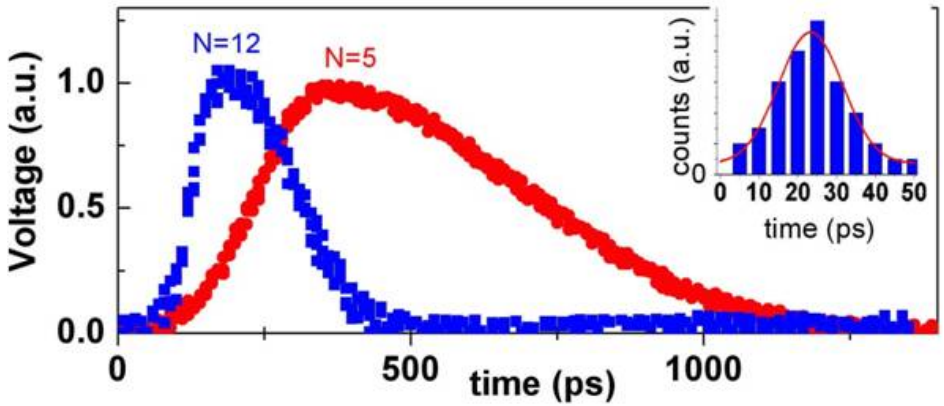
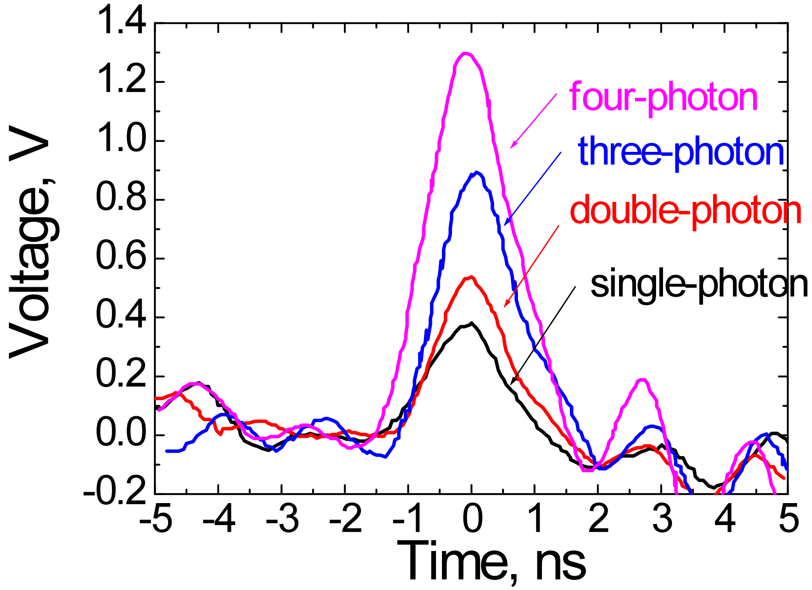
EPFL

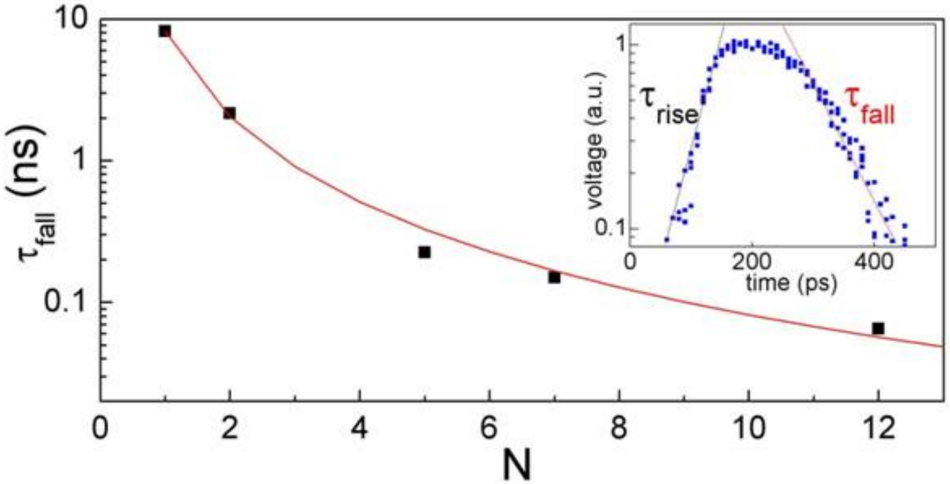
Detection efficiency 6% for single photons







A. Divochiy, et al, Nature Photonics, vol. 2, pp 302-306, 2008

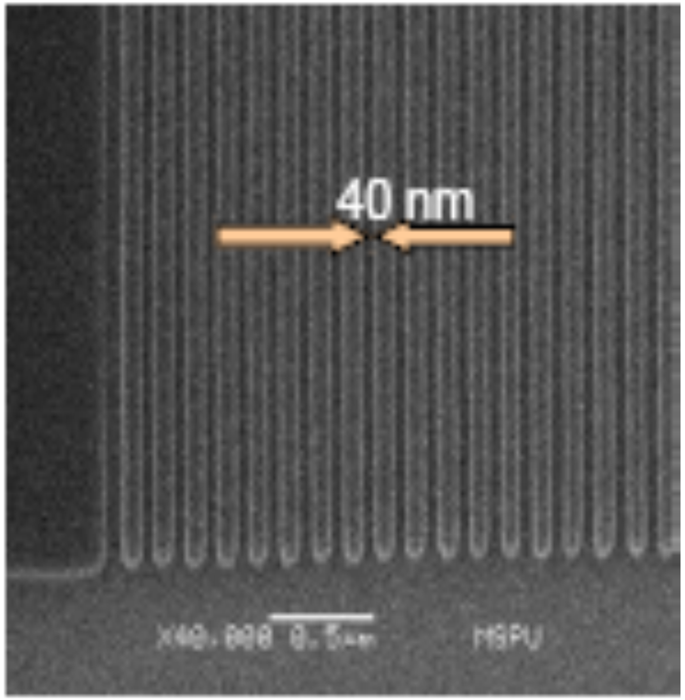


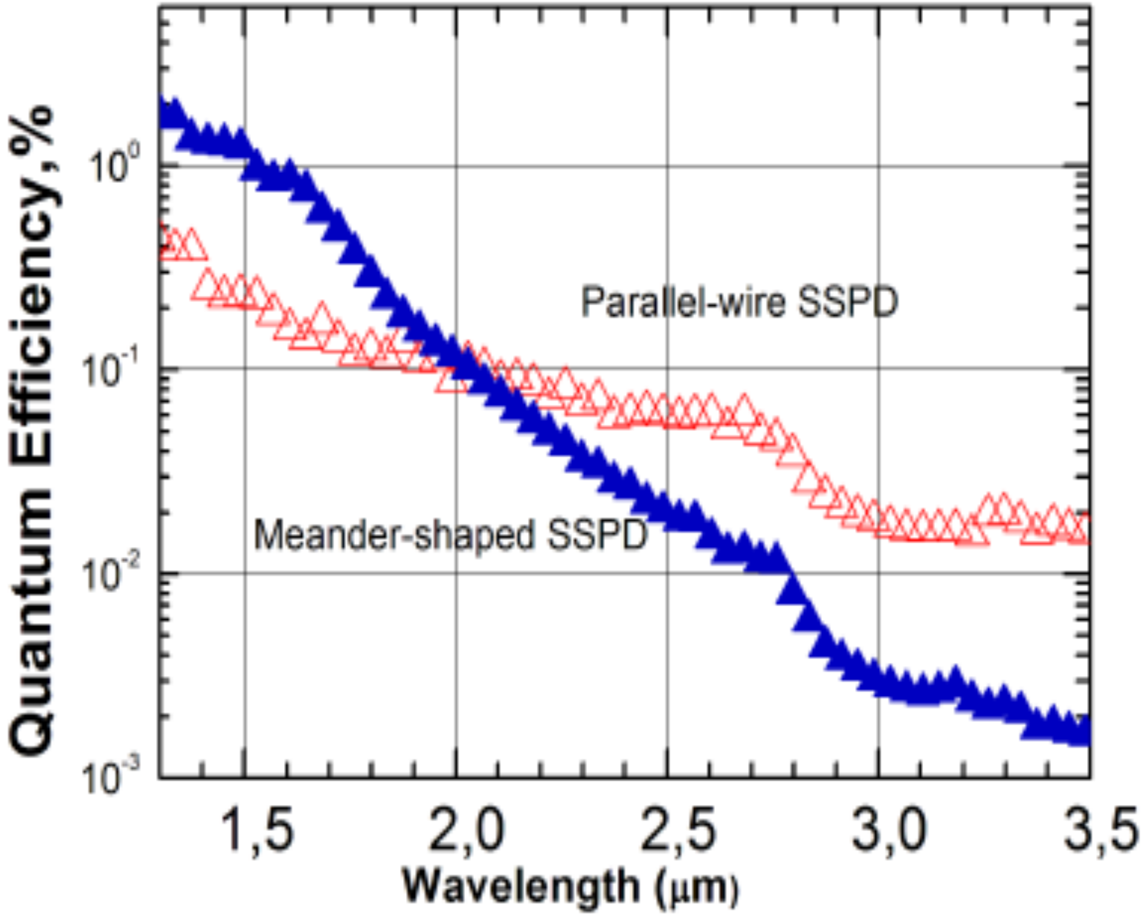
Tarkhov M. *et al*, *Appl. Phys. Lett.* 92 (2008) 241112

Parallel-wire SSPD

Better detection efficiency at wavelengths above 2 μm.

Response time 0.3 ns.

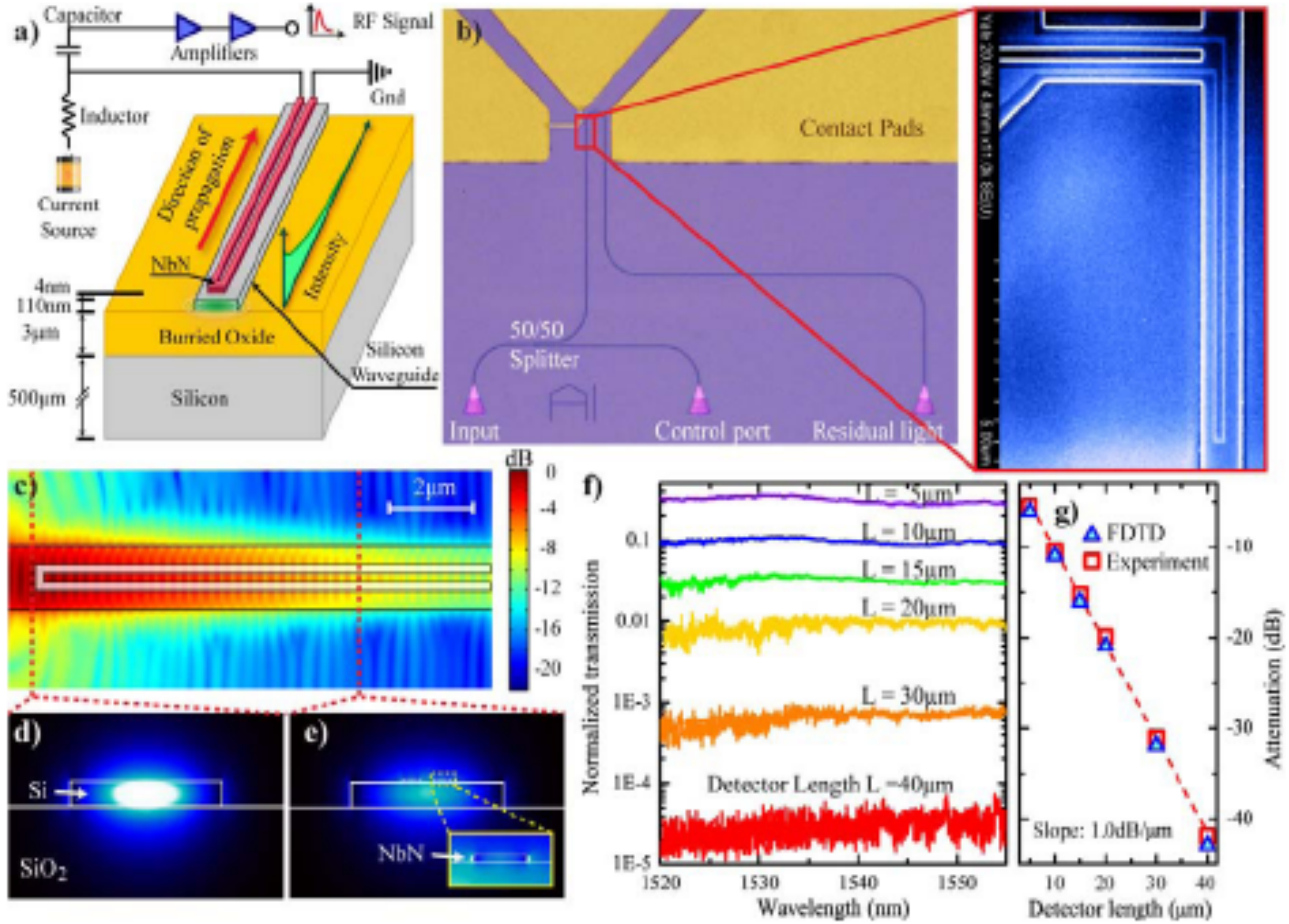




Y. Korneeva,et al Trans on Appl Supercond, 2011

Waveguide-coupled SSPD

94% internal detection efficiency



W. Pernice, et al arXiv:1108.5299v1 [physics.optics]

In conclusion...

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	Best Lab Devices	Commercial Systems
Spectral range	0.4 – 5 μm	0.4 – 1.8 μm above 2 μm with ZBLAN
Counting rate	100MHz- 2 GHz	100 MHz
Detection efficiency @ 1550 nm	34%	20%
Dark counts rate	10 Hz	10 Hz
Jitter	16 ps	45 ps
Operation temperature	2 K	2 K

Thank you very much!