MICRO-428: METROLOGY

Edoardo Charbon, Claudio Bruschini, Georg Fantner

Institute of Electrical and Microengineering (IEM), School of Engineering (STI)

Swiss Federal Institute of Technology, Lausanne (EPFL), Switzerland

TAs: Samuele Bisi and Alexandre Domenech

MICRO-428: Metrology

Week Fourteen: Quantum Metrology

Edoardo Charbon

Advanced Quantum Architectures Laboratory (AQUA)

EPFL at Microcity, Neuchâtel, Switzerland

Simone Frasca

HQC

EPFL, Lausanne Campus, Switzerland

EPFL

Reference Books

- W. Nawrocki, *Introduction to Quantum Metrology: Quantum standards and instrumentation*, 1st ed., 2015
- D.S. Simon, G. Jaeger, A.V. Sergienko, *Quantum Metrology, Imaging and Communication*, 1st ed., 2017
- R.H. Hadfield, G. Johansson, *Superconducting Devices in Quantum Optics*, 1st ed., 2016

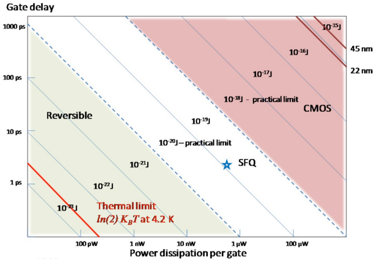
Outline

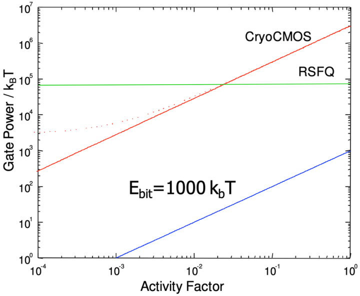
Outline

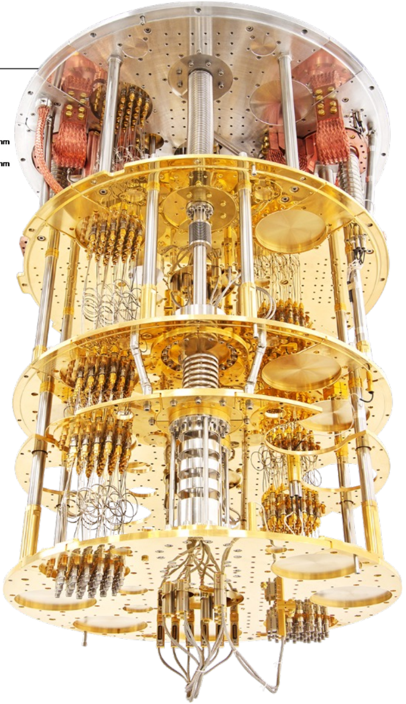
14.1 Superconducting Electronics

- In a world where cryogenics is playing a more and more relevant role, superconducting electronics has been given once again the possibility to assess itself as low power, high frequency substitute to classical CMOS electronics.

- In parallel to the known Rapid Single Flux Quantum (RSFQ) electronics, a new type of technology based on superconducting thin films, the nanocryotron family, has been developed in the last decade.





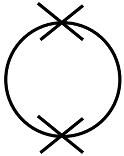


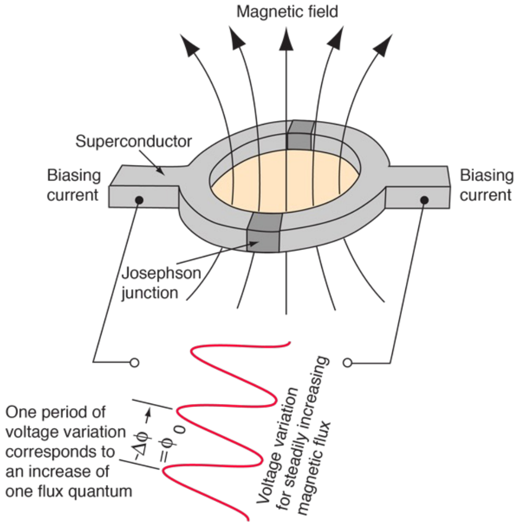
A. Herr, *Rapid Single Flux Quantum Logic*, lectures series in Chalmers University of Technology, Sweden

Outline

14.1.1 Superconducting Quantum Interference Devices (SQUIDs)

- A quantum interference effect in a superconducting loop with two Josephson junctions was first observed in 1964.
- The SQUID is a magnetic flux to voltage converter. There are two types of these superconductor sensors, the DC-SQUID, biased by direct current and containing two Josephson junctions, and the RF-SQUID, biased by a high-frequency signal and containing a single Josephson junction.
- The RF-SQUID developed in the 1970s allowed to obtain the energy resolution as high as 7×10^{-32} J/Hz. By the end of the 1980s the resolution of the DC-SQUID increased by a few orders of magnitude to ca. 3×10^{-34} J/Hz $= 0.5h$!





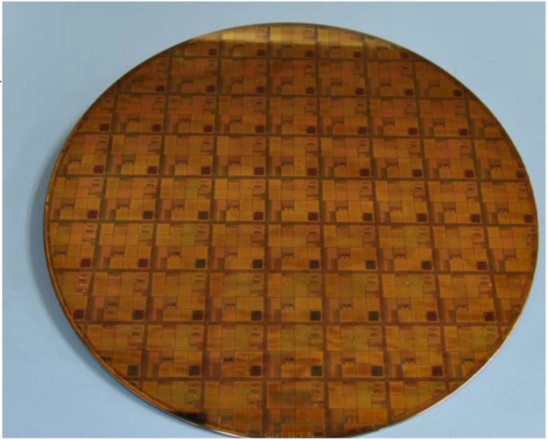
📖 W. Nawrocki, *Introduction to Quantum Metrology: Quantum standards and instrumentation*, 1st ed., 2015, Chap 5.1

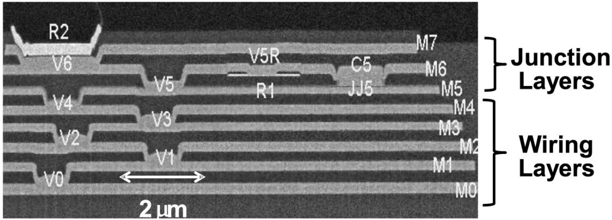
14.1.1 Rapid Single Flux Quantum Electronics (RSFQ)

- RSFQ circuit technology is not as mature as CMOS.

- PROs:
  - SFQ information process is uniquely energy efficient
  - SFQ circuits can be designed for 10X higher clocks than CMOS
  - SFQ circuits have access to a quantized reference (fluxon) → unique advantage for mixed-mode signal processing.

- CONs:
  - SFQ will not have the same density as CMOS circuits
  - Have not developed an optimal circuit design approach
  - Need an effective solution for data storage

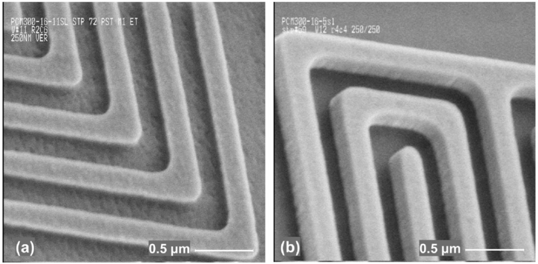


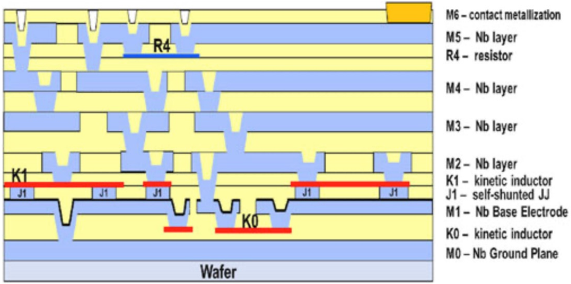


M. Gouker, *Single Flux Quantum (SFQ) Circuit Fabrication and Design: Status and Outlook*, slides from ORNL Beyond CMOS Workshop

14.1.1 Rapid Single Flux Quantum Electronics (RSFQ)

- Recent milestones:
  - MIT-LL has developed a high-density RSFQ process using either Nb/AlO_x-Al/Nb or Nb/Si_xNb_{1-x}/Nb Josephson Junctions and achieved an overall density of 4 10^6 devices per cm^2
  - In order to reduce further the footprint of the devices, ultrathin films of MoN_x have been employed as inductors, exploiting the kinetic inductance rather than the more common geometrical counterpart.



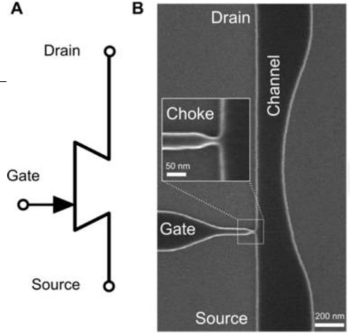


S.K. Tolpygo et al., *Developments Toward a 250-nm, Fully Planarized Fabrication Process With Ten Superconducting Layers And Self-Shunted Josephson Junctions*, ISEC, 2017

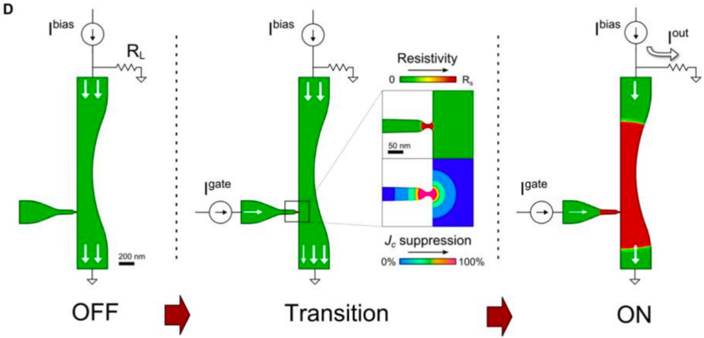
S.K. Tolpygo et al., *Superconductor Electronics Fabrication Process with MoNx Kinetic Inductors and Self-Shunted Josephson Junctions*, IEEE Trans. Appl. Supercond. 28, 2018

Outline

14.1.2 Superconducting Nanowire-based Electronics – nTrons



- The first use of superconducting nanowire-based electronics coupled to SNSPDs (*superconducting nanowire single-photon detectors*) is credited to the Universities of Salerno, Napoli and Rome in Italy in collaboration with CEA-Grenoble in 2011.
- Interesting new technology by Dr. A. McCaughan and Prof. K.K. Berggren, MIT.
- The nanocryotron, or nTron, is a three terminals superconducting device based on single-layer superconductor.
- nTrons operate as follows:
  - Injection of a small current in the gate makes the constricted area to switch to normal state (resistive).
  - As the available area for the superconducting current of the channel shrinks with the superconductivity suppression, the whole channel switches.
  - The larger channel bias current is redirected to the readout.

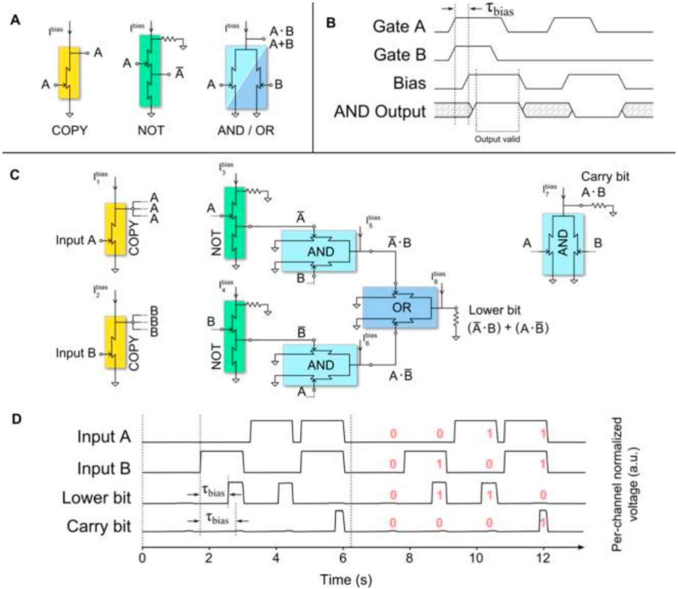


S. Pagano et al., *Nano-Strip Three-Terminal Superconducting Device for Cryogenic Detector Readout*, IEEE Trans. Appl. Supercond. 21, 2011

A.N. McCaughan and K.K. Berggren, *A Superconducting-Nanowire Three-Terminal Electrothermal Device*, Nano Letters 14, 2014

14.1.2 Superconducting Nanowire-based Electronics – nTrons

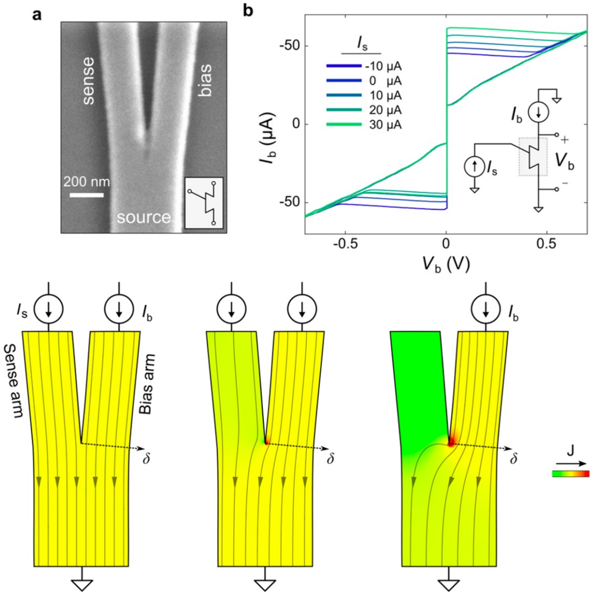
- So far, basic electronics based on nTrons has been developed, but nothing more than proof of concepts.
- The nTrons has also been used as current amplifier in combination with SNSPD, increasing the signal-to-noise ratio of the detectors of a factor 2.
- PROs:
  - ➢ relatively easy to fabricate,
  - ➢ very low heat dissipation,
  - ➢ Reasonably big current signal.
- CONs:
  - ➢ still quite large,
  - ➢ not terahertz frequency like RSFQs,
  - ➢ requires large current biases.



A.N. McCaughan and K.K. Berggren, *A Superconducting-Nanowire Three-Terminal Electrothermal Device*, Nano Letters 14, 2014

14.1.2 Superconducting Nanowire-based Electronics – yTrons

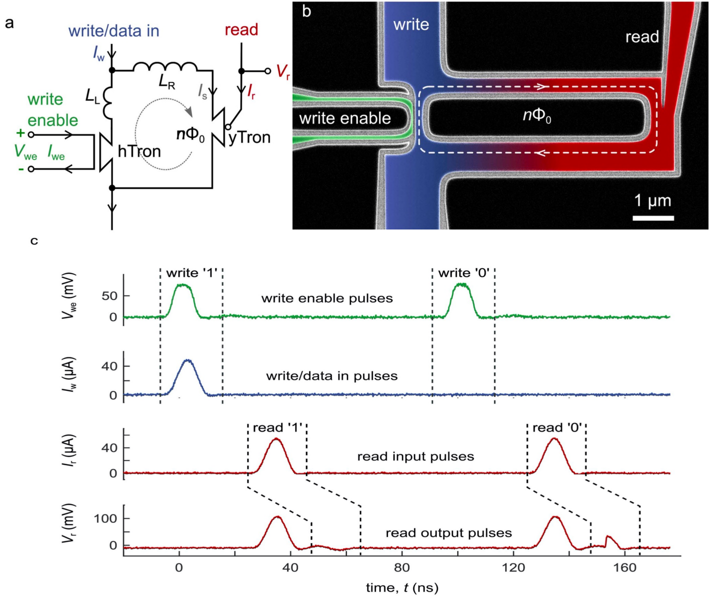
- A variation of the nTron is the so-called y-Trons.
- Differently from nTrons, where the injection of current in the gate results into high impedance between source and drain (just like an n-MOS with a voltage peak), in y-Trons it's the opposite: reduction of current in the sense arm below a threshold causes the superconductivity to be broken due to **current crowding** effect, causing a jump in impedance (like with a p-MOS with a voltage peak).
- Just like n-MOS and p-MOS, nTrons and yTrons are both equivalently necessary for higher level logic circuit design. The only big difference is in the gain design, which is trickier to optimize.



📖 A.N. McCaughan et al., *Using Geometry To Sense Current*, Nano Letters 16, 2016

14.1.2 Superconducting Nanowire-based Electronics – hTrons

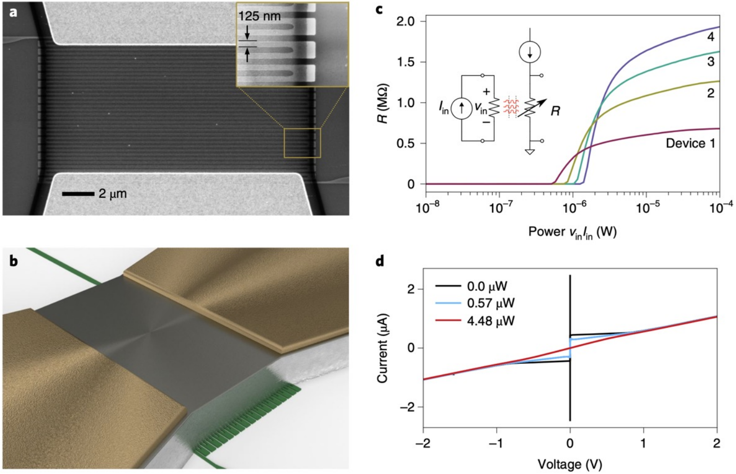
- Last, but only chronologically, we find the hTron.
- The hTron is probably the most intuitive of the nTrons family of devices. It exploits heat to suppress superconductivity.
- However, as all heat transmission dependent devices, it is not as fast as their current driven counterparts.
- hTrons and yTrons have been used by Zhao et al. write and read a superconducting memory based on a kinetic inductance driven SQUID (nanoSQUID).



Q.-Y. Zhao et al., *A compact superconducting nanowire memory element operated by nanowire cryotrons*, Supercond. Sci. Technol. 31, 2018

14.1.2 Superconducting Nanowire-based Electronics – hTrons

- Another interpretation of the hTron can be the one of impedance matching switch developed at NIST.
- This version of the device is slightly faster as it uses suppression of superconductivity driven by phonons rather than purely from heat.
- This four terminals device allows abrupt change in impedance on the main line (the nanowire) from zero to megaohms.
- This device has several utilities such as potentially allow impedance matching between superconducting and CMOS logic.



A.N. McCaughan et al., *A superconducting thermal switch with ultrahigh impedance for interfacing superconductors to semiconductors*, Nature Electronics 2, 2019

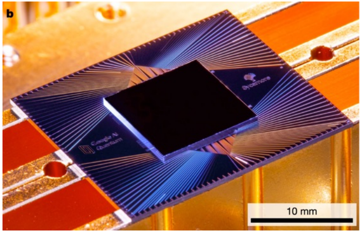
Outline

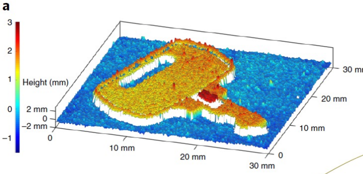
14.2 Superconducting Single-Photon Detectors

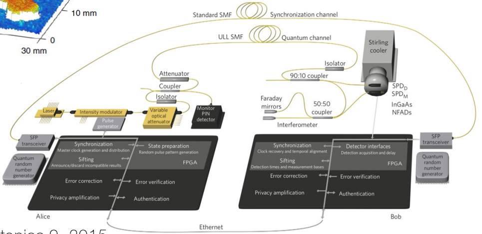
- Cryogenic single-photon detectors provide unparalleled performance with respect to their room temperature counterparts, mostly due to lower noise ambient, higher sensitivity and better timing response.

- They require, however, to be used in extremely low temperature conditions, which is a non-negligible effort in terms of energy, physical space and money.

- For this reason, cryogenic and, in particular, superconducting technologies are the aim of niche application that require the best performance achievable despite all else, or for applications where cryogenics is already in place, such as space telescopes, high-energy particles research, quantum computing..







J.M. Martinis, *Quantum supremacy using a programmable superconducting processor*, Nature 574, 2019

B.A. Korzh et al., *Provably secure and practical quantum key distribution over 307 km of optical fibre*, Nature Photonics 9, 2015

14.2 Superconducting Single-Photon Detectors – Comparison Table

Comparison of single-photon detectors							
Detector Type	Operation temperature (K)	Detection efficiency, η	Jitter time, Δt (FWHM)	Dark count rate, DCR (ungated)	Maximum count rate, MCR	Sensitivity Bandwidth	Photon number resolving?
PMT (NUV-NIR)	300	40% @500 nm	300 ps	100 Hz	10 MHz	NUV-NIR	Yes
PMT (IR)	200	2% @1,550 nm	300 ps	200 kHz	10 MHz	IR	Yes
MCP-PMT (NUV-NIR)	300	25% @500 nm	< 55 ps	100 Hz	10 MHz	NUV-NIR	Yes
Si SPAD (thick junction)	RT	65% @650 nm	400 ps	25 Hz	10 MHz	Visible	No
Si SPAD (shallow junction)	RT	49% @550 nm	35 ps	25 Hz	10 MHz	Visible	No
CMOS SPAD (shallow junction)	RT	50% @550 nm	80 ps	50 Hz	10 MHz	Visible	No
InGaAs SPAD (self-differentiating)	240	55% @1,550 nm	55 ps	10 Hz	500 MHz	NIR	Yes
Visible Light Photon Counter	6	88% @694 nm	270 ps	20 kHz	—	Visible	Yes
TES	0.1	97% @1,550 nm	100 ns	3 Hz	100 kHz	—	Yes
SNSPD	1-4	98% @1,550 nm	< 3 ps	$< 10^{-5}$ Hz	1.25 GHz	X rays-MIR	Yes
MKID	0.1	90% @285 nm	50 ns	1 Hz	—	—	Yes

Update of: R.H. Hadfield, *single-photon detectors for optical quantum information applications*, Nature Photonics 3, 2009

Outline

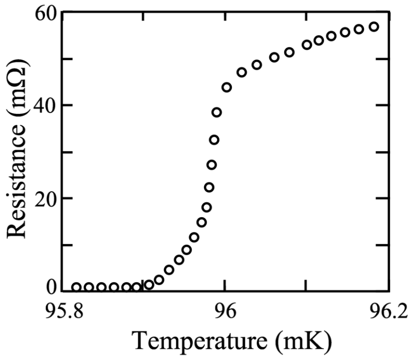
14.2.1 Transition-Edge Sensors (TESs)

- Transition-Edge Sensors exploit the steep superconducting-resistive state transition of low-Tc superconductors with temperature.

- The devices are made of an ultra-thin superconducting film. Typical dimensions are in the order of 25x25 μm^2 active area and a thickness that ranges between 5-50 nm, depending on the target application (wavelength).

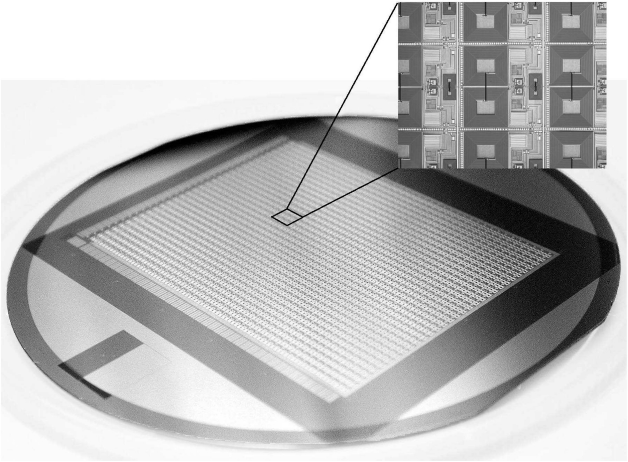
- The TES are cooled down at a temperature close to the critical temperature of the detector. Upon photon absorption, a certain number of cooper pairs are broken, and some quasiparticles are created. **The number of quasiparticles is proportional to the difference between the photon energy $E_{ph} = h\nu$ and the superconducting energy gap of the film $2\Delta = 3.5\ k_B T_c$.**

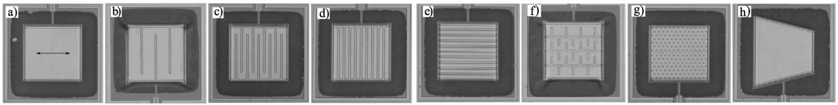
- The temperature increase, detected as resistance change of the film, is then proportional to the number of quasiparticles. In this sense, the TES is considered as an energy resolving detector.

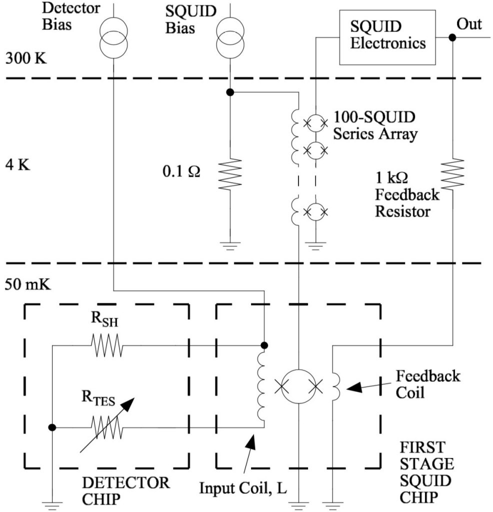


K.D. Irwin and G.C. Hilton, *Transition-Edge Sensors*, Topics in Applied Physics 99, 2005

14.2.1 Transition-Edge Sensors (TESs)







K.D. Irwin and G.C. Hilton, *Transition-Edge Sensors*, Topics in Applied Physics 99, 2005

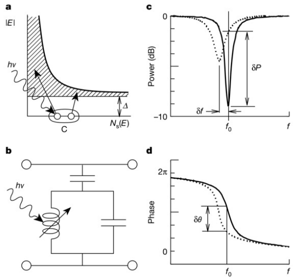
Outline

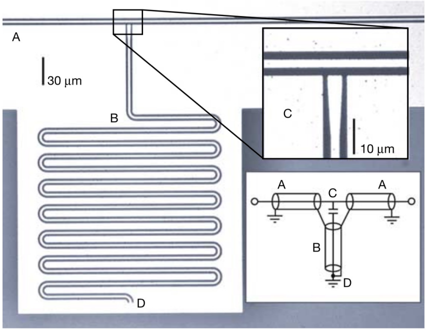
14.2.2 Microwave Kinetic Inductance Detectors (MKIDs)

- In order to understand the working principle of MKIDs, it is necessary to go back to the definition of superconductivity. A superconductor has zero resistance for d.c. electrical current: this supercurrent is carried by pairs of electrons, called Cooper pairs. Cooper pairs have a binding energy $2\Delta = 3.5\ k_B T_c$, where T_c is the superconducting transition temperature.

- However, superconductors have a nonzero impedance for AC currents. An electric field applied near the surface of a superconductor causes the Cooper pairs to accelerate, allowing energy storage in the form of kinetic energy.

- Because the supercurrent is non-dissipative, **this energy may be extracted by reversing the electric field**. Similarly, energy may be stored in the magnetic field inside the superconductor, which penetrates only a short distance, $\lambda \approx 50\ \mathrm{nm}$, from the surface. The overall effect is that a superconductor has a surface inductance $L_s = \mu_0 \lambda$

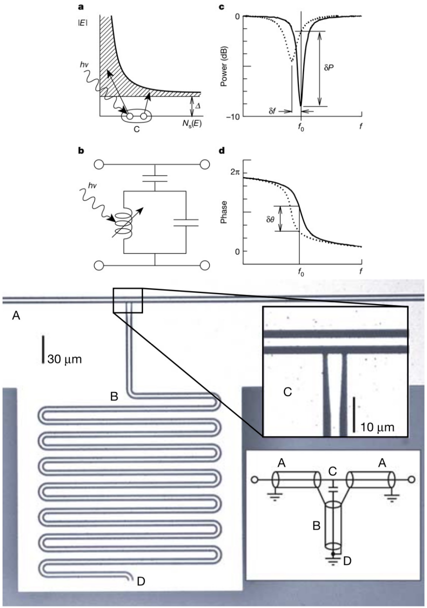




P.K. Day et al., *A broadband superconducting detector suitable for use in large arrays*, Nature 425, 2003

14.2.2 Microwave Kinetic Inductance Detectors (MKIDs)

- The surface impedance $Z_s = R_s + i\omega L_s$ also includes a surface resistance R_s, which describes a.c. losses at angular frequency ω caused by the small fraction of electrons that are not in Cooper pairs, which are called quasiparticles. For temperatures T much lower than T_c, $R_s \ll \omega L_s$.
- Photons with sufficient energy ($h\nu > 2\Delta$) may break apart one or more Cooper pairs. The absorption of a high-energy photon creates $N_{qp} \approx \eta h\nu/\Delta$ quasiparticles. Here η is the efficiency with which the photon energy is converted to quasiparticles.
- Since the excess quasiparticles take $\tau_{qp} \approx 10^{-3}$–$10^{-6}$ s to recombine in Cooper pairs, they are allowed to diffuse in the material by a length $l \approx D\tau_{qp}$, where D is the diffusion constant of the material.



P.K. Day et al., *A broadband superconducting detector suitable for use in large arrays*, Nature 425, 2003

14.2.2 Microwave Kinetic Inductance Detectors (MKIDs)

- This would imply a change of impedance given by:

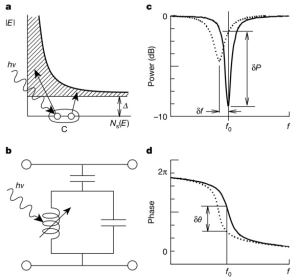
$$\delta Z_s = \delta n_{qp}\, \partial Z_s / \partial n_{qp}$$

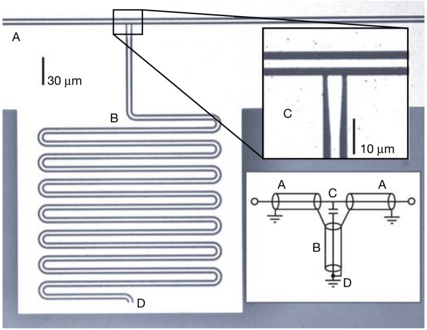
$$\delta L_s / L_s = \delta n_{qp} / 2 N_0 \Delta$$

- The resulting fractional change in the resonance frequency f_0 is $|\delta f|/f_0 = 0.5\, \alpha\, \delta L_s / L_s$, where α is the fraction of the circuit inductance that is contributed by the surface inductance L_s.

- Finally, this frequency shift should be compared against the width of the resonance of a superconducting resonator detector, which is the inverse of the quality factor: $\Delta f / f_0 = Q^{-1}$. In order to have single photon detection:

$$|\delta f|/f_0 > \Delta f / f_0$$

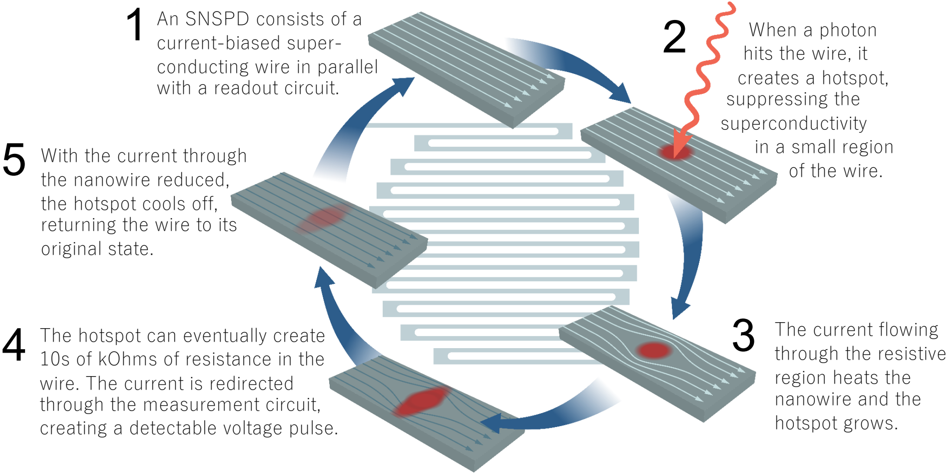


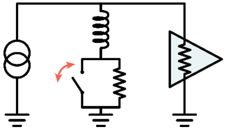


P.K. Day et al., *A broadband superconducting detector suitable for use in large arrays*, Nature 425, 2003

Outline

14.2.3 Superconducting Nanowire Single-Photon Detectors (SNSPDs)

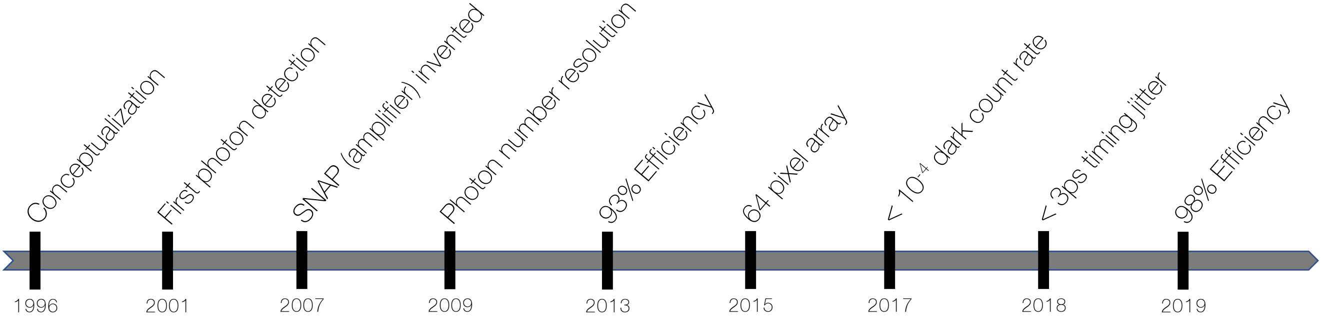


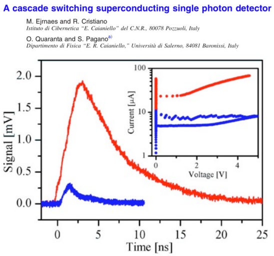


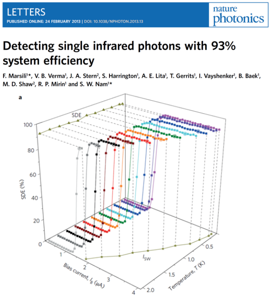
Classical readout circuit for SNSPDs

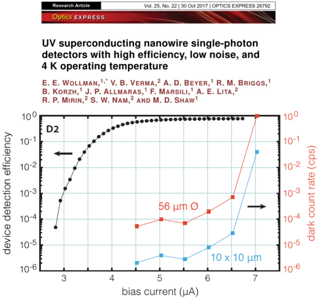
V. Verma et al., *Superconducting Nanowire Single-Photon Detectors for Exoplanet Spectroscopy in the Mid-Infrared*, NASA Astronomy Abstract, 2017

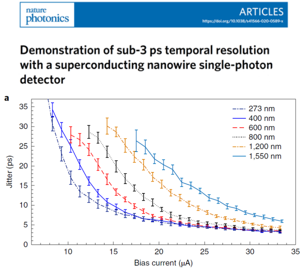
14.2.3 Superconducting Nanowire Single-Photon Detectors (SNSPDs)









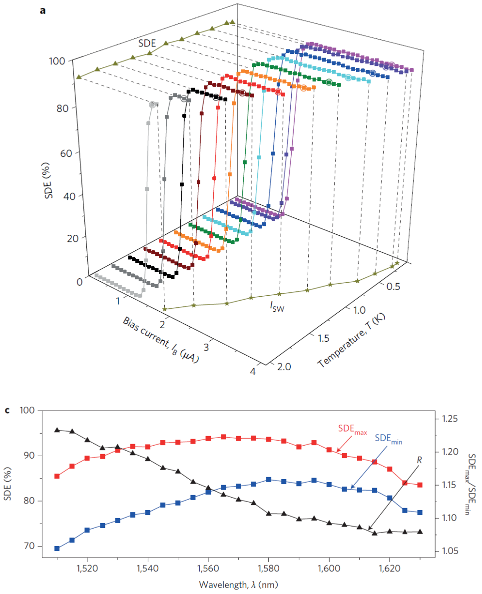


14.2.3 Superconducting Nanowire Single-Photon Detectors (SNSPDs)

- The SNSPD's system detection efficiency (SDE) can be considered as product of several efficiencies:
  - absorption efficiency ($\eta_{absorption}$), the probability that a photon is absorbed in the superconducting film,
  - quantum efficiency (η_{QE}), the probability that, upon absorption, the device is capable creating a state switch,
  - coupling efficiency ($\eta_{coupling}$), the efficiency for the photons at the input aperture to be delivered to the active area of the device within the detector system,
  - trigger efficiency ($\eta_{trigger}$), the efficiency with which the counting electronics actually registers the electrical signal as a count.

$$SDE = \eta_{coupling} \cdot \eta_{absorption} \cdot \eta_{QE} \cdot \eta_{trigger}$$

- SNSPDs have reached 93% SDE in 2013 and 98% in 2019 (both from NIST)



📖 R.H. Hadfield, G. Johansson, *Superconducting Devices in Quantum Optics*, 1st ed., 2016, chap 1.2.1

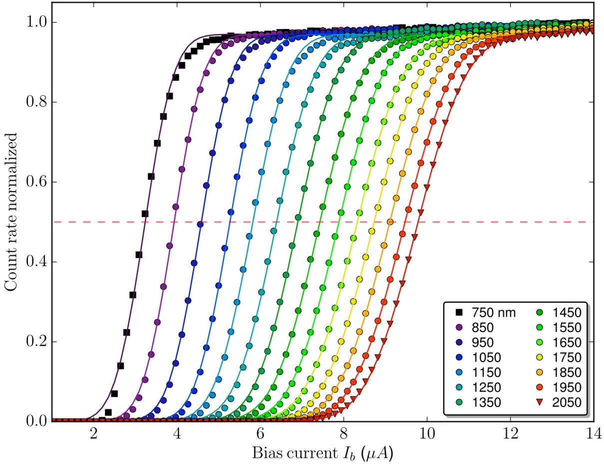
📖 F. Marsili et al., *Detecting single infrared photons with 93% system efficiency*, Nature Photonics 7, 2013

14.2.3 Superconducting Nanowire Single-Photon Detectors (SNSPDs)

- The quantum efficiency (η_{QE}) of SNSPDs has to do with the energy distribution in the electron and phonon systems of the superconductor. Upon absorption, the photon energy is transferred to the superconducting system.

- This energy is partitioned between charged and neutral elementary excitations, for example between electrons and phonons. Fano fluctuations are caused by the branching processes and result in variations in the fraction of energy deposited in each system.

- This effect has influence on both the Photon Count Rate curves (PCR) as well as in timing performance of the detectors, as it will be shown later.



M. Caloz et al., *Optically probing the detection mechanism in a molybdenum silicide superconducting nanowire single-photon detector*, Appl. Phys. Lett. 110, 2017

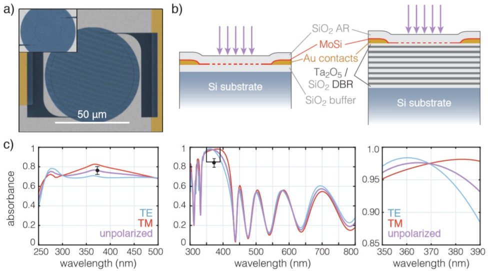
A.G. Kozorezov et al., *Fano fluctuations in superconducting-nanowire single-photon detectors*, Phys. Rev. B 96, 2017

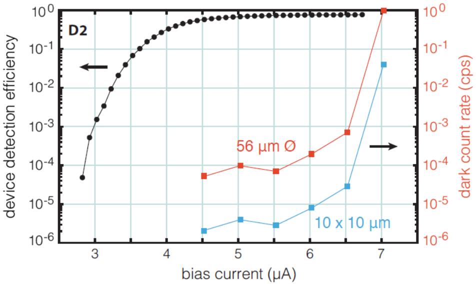
14.2.3 Superconducting Nanowire Single-Photon Detectors (SNSPDs)

- The SNSPDs' dark count rate is another very important detector metric. The DCR is sum of the following noise sources:
  - intrinsic dark count rate ($DCR_{intrinsic}$), which source is still under investigation. There are reasons to think that the generation of intrinsic noise might be related to defects in the SNSPDs,
  - background dark count rate (DCR_{bg}), is the count rate coming from unwanted, background stray light,
  - electronics dark count rate ($DCR_{electronics}$), which is the noise coming from the electronics, counts that are not generated from photon absorption.

$$DCR = DCR_{intrinsic} + DCR_{bg} + DCR_{electronics}$$

- SNSPD's DCR is orders of magnitude smaller than the competing technologies, as it was demonstrated by JPL/NIST in 2017 with a measured 10^{-4} Hz dark count rate.





📖 R.H. Hadfield, G. Johansson, *Superconducting Devices in Quantum Optics*, 1st ed., 2016, chap 1.2.2

📖 E.E. Wollman et al., *UV superconducting nanowire single-photon detector with high efficiency, low noise and 4K operating temperature*, Optics Express 25, 2017

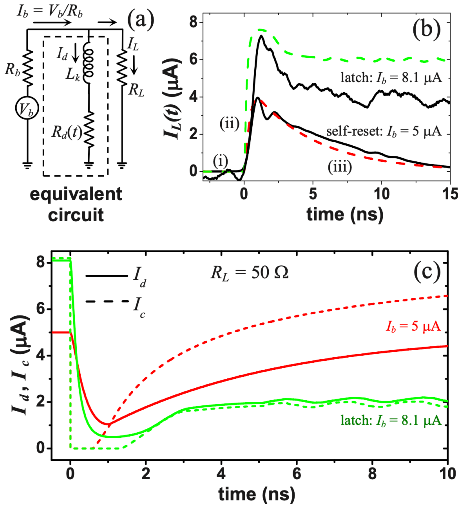
14.2.3 Superconducting Nanowire Single-Photon Detectors (SNSPDs)

- The maximum count rate of an SNSPD is limited by its reset time. There are some limitations given by the electrothermal model developed by Yang et al., the two main governing equations are:

$$J^2\rho + \kappa\frac{\partial^2 T}{\partial x^2} - \frac{\alpha}{d}(T - T_{sub}) = \frac{\partial}{\partial t} cT$$

$$C_{bt}\left(\frac{dL_k I}{dt^2} + \frac{d(IR_n)}{dt} + Z_0\frac{dI}{dt}\right) = I_{bias} - I$$

- Under certain biasing conditions, the SNSPD encounters the so-called latching condition, i.e. the condition in which the device has no time to damp down the heat generated by a detection event that the current is redirected into it, making it switch again in a metastable fashion.



R.H. Hadfield, G. Johansson, *Superconducting Devices in Quantum Optics*, 1st ed., 2016, chap 1.2.4 and 1.3.3

J.W.K. Yang et al., *Modeling the Electrical and Thermal Response of Superconducting Nanowire Single-Photon Detectors*, IEEE Trans. Appl. Supercond. 17, 2007

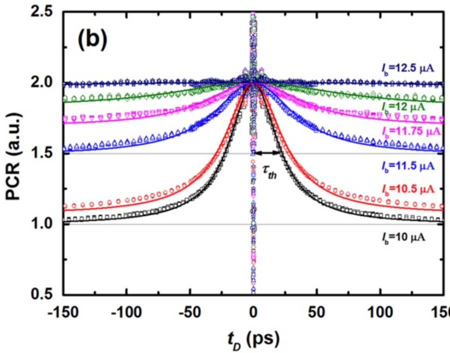
A.J. Annunziata et al., *Reset dynamics and latching in niobium superconducting nanowire single-photon detectors*, J. Appl. Physics 108, 2010

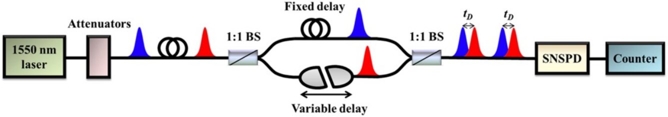
14.2.3 Superconducting Nanowire Single-Photon Detectors (SNSPDs)

- As Annunziata et al. demonstrated experimentally, latching can be dealt with by increasing the kinetic inductance or reducing the load resistance, but with an increase in detector rise and fall times, which is in turn linked to the timing resolution and the maximum count rate of the detectors.

- Zhang et al. have been investigating the effect of substrate thermo-acoustic coupling with the nanowires to study the thermal time delay required for the device to reset.

- As shown in the figure, by creating a delay between two photon pulses and checking the count rate of the detector, it is possible to estimate which pulses are caused by single-photon events and which are caused by multi-photon events, giving information regarding the thermal coupling of SNSPDs and substrates.





📖 R.H. Hadfield, G. Johansson, *Superconducting Devices in Quantum Optics*, 1st ed., 2016, chap 1.2.4 and 1.3.3

📖 L. Zhang et al., *Hotspot relaxation time of NbN superconducting nanowire single-photon detectors on various substrates*, Scientific Reports 8, 2018

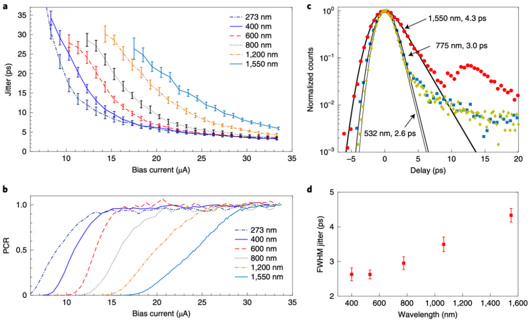
📖 A.J. Annunziata et al., *Reset dynamics and latching in niobium superconducting nanowire single-photon detectors*, J. Appl. Physics 108, 2010

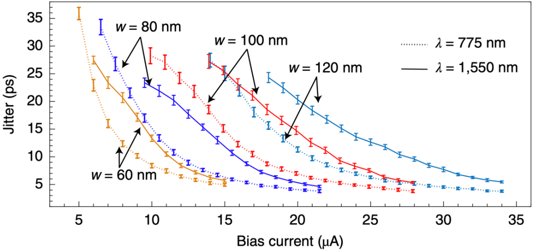
14.2.3 Superconducting Nanowire Single-Photon Detectors (SNSPDs)

- One of the most interesting capability of SNSPD is surely the timing resolution. The system timing resolution is obtained as the sum of the variances of the several jitter components:
  - Intrinsic jitter (j_{intr}), is the jitter of the detector itself. This property has been studied for long time, but only recently a qualitative description has been demonstrated
  - electrical noise jitter (j_{noise}), is the contribution of the front-end readout
  - optical jitter ($j_{optical}$), is the contribution of the optical components, e.g. the laser used to excite the SNSPD.

$$j_{tot} = \sqrt{j_{intr}^2 + j_{noise}^2 + j_{optical}^2}$$

- The lowest timing jitter recorded for SNSPDs is of 2.6ps, which is almost an order of magnitude lower than classical room temperature single-photon detectors.





R.H. Hadfield, G. Johansson, *Superconducting Devices in Quantum Optics*, 1st ed., 2016, chap 1.2.3

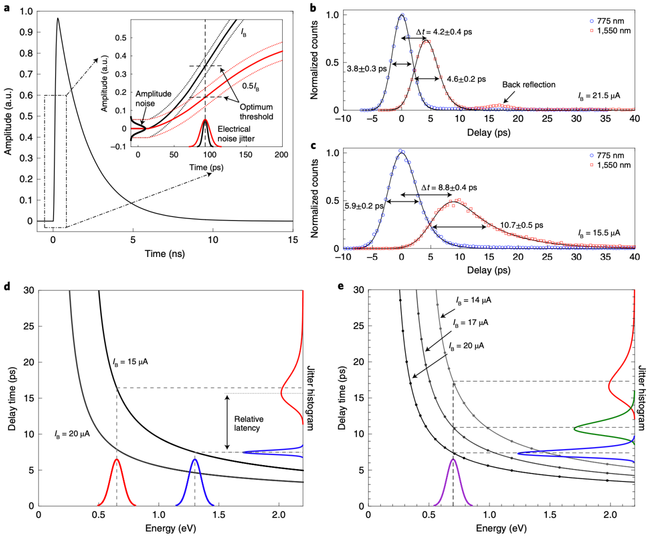
B. Korzh et al., *Demonstration of sub-3 ps temporal resolution with a superconducting nanowire single-photon detector* , Nature Photonics 14, 2020

14.2.3 Superconducting Nanowire Single-Photon Detectors (SNSPDs)

- For what concerns the origin of the intrinsic jitter, no absolute certain answer has been accepted in the community. However, it has been demonstrated that intrinsic jitter is energy dependent, hence pointing to the direction of Fano fluctuation.

- As Allmaras et al. have shown, there is a so-called latency between photon absorption and state transition in SNSPD. This time delay can be related to the time it takes for the electron system energy to reach the value required to force the transition from superconductivity to normal state.

- Allmaras was able to link the energy spread (due to Fano fluctuations) to the timing spread in the detector with respect to different biasing conditions.

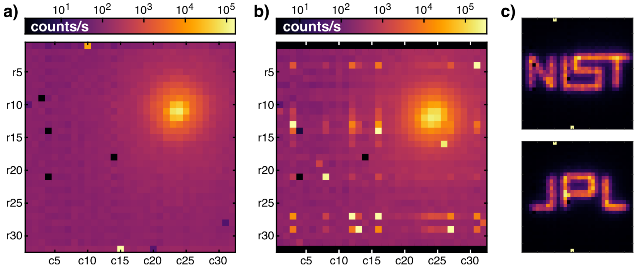


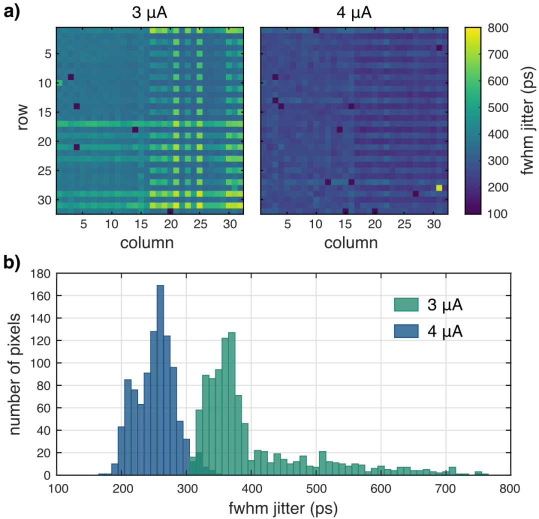
J.P. Allmaras et al., *Intrinsic Timing Jitter and Latency in Superconducting Nanowire Single-photon Detectors*, Phys. Rev. Appl. 11, 2019

B. Korzh et al., *Demonstration of sub-3 ps temporal resolution with a superconducting nanowire single-photon detector* , Nature Photonics 14, 2020

14.2.3 Superconducting Nanowire Single-Photon Detectors (SNSPDs)

- Probably the most challenging aspect of SNSPDs is scaling.
- Row-column readout approach has obtained the largest scaling factor recorded to date (32x32 pixels), reduces the electronics requirements (in terms of amplifiers etc..) from N^2 to “only” 2N, but not without performance losses in terms of timing resolution.

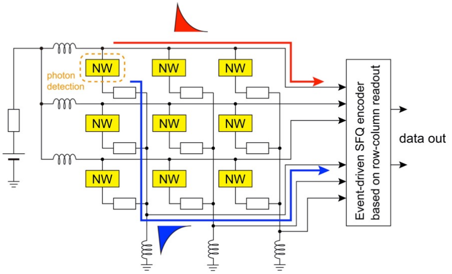


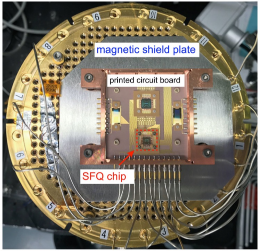


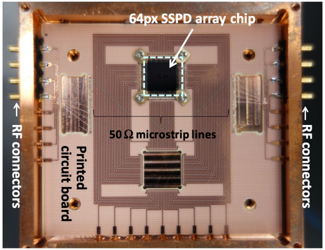
Q.-Y. Zhao, *Superconducting-nanowire single-photon-detector linear array*, Appl. Phys. Lett. 103, 2013
M.S. Allman et al., *A near-infrared 64-pixel superconducting nanowire single photon detector array with integrated multiplexed readout*, Appl. Phys. Lett. 106, 2015
E.E. Wollman et al., *Kilopixel array of superconducting nanowire single-photon detectors*, Optics Express 27, 2019

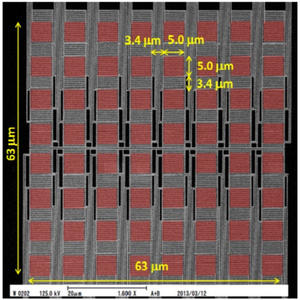
14.2.3 Superconducting Nanowire Single-Photon Detectors (SNSPDs)

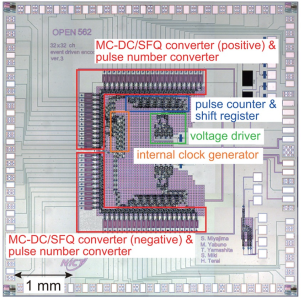
- Another way is to couple the SNSPD array with RSFQ electronics, as was presented by Miki et al.
- However, despite the quality of the work performed, some questions still remain, such as the implications of a loss in fill factor, and the degradation of timing performance linked to the row-column readout approach.









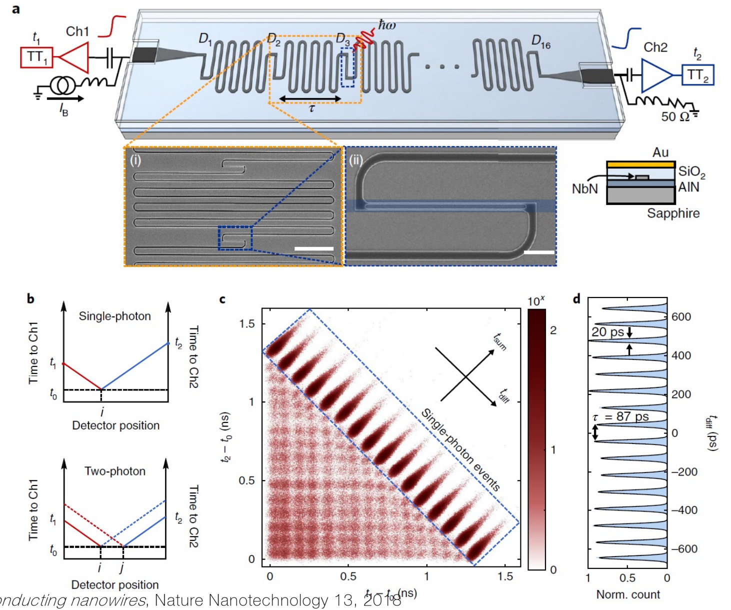


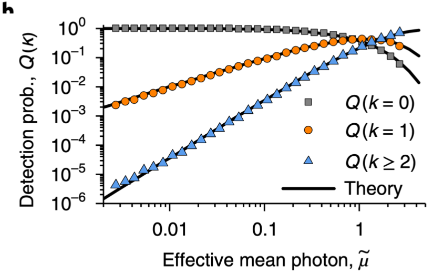
S. Miyajima et al., *Single-Flux-Quantum Based Event-Driven Encoder for Large-Pixel Superconducting Nanowire Single-Photon Detector Array*, IEEE Trans. Appl. Supercond. 29, 2018

S. Miki et al., *A 64-pixel NbTiN superconducting nanowire single-photon detector array for spatially resolved photon detection*, Optics Express 22, 2014

14.2.3 Superconducting Nanowire Single-Photon Detectors (SNSPDs)

- Finally, the novel approach presented by Zhu et al. at MIT is to create virtual multiplexing via delay lines.
- Very case specific, to avoid ambiguity it is necessary to work in a photon-starved regime. However, performance such as the timing resolution may be preserved up to a certain extent.





D. Zhu et al., *A scalable multi-photon coincidence detector based on superconducting nanowires*, Nature Nanotechnology 13, 2018

Outline

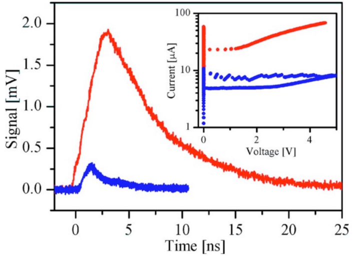
14.2.4 Superconducting Nanowire Avalanche Photodiodes (SNAPs)

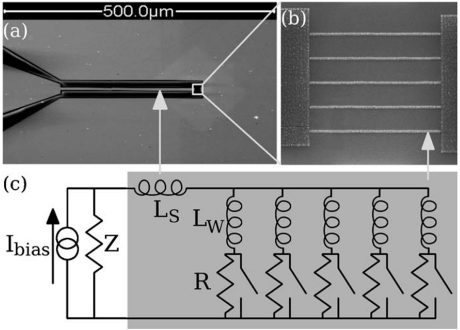
- A simple variant of the classical SNSPD was proposed in 2007 by Ejrnaes *et al*. The geometry proposed used a number of nanowires connected in parallel and biased by the same source.

- The working principle is very simple: the idea is to design n identical detectors and bias them all at a current $I_{\text{bias}} > \frac{n-1}{n} I_{\text{sw}}$, where I_{sw} is the switching current of the detectors.

- Then, upon absorption of a photon, the suppression of superconductivity of one detector will redirect the current, equally repartitioned, to the others detectors, which will then be biased above their switching current. Following this cascade, the n detectors will switch within a very short time.

- This approach allows the increase of the amount of signal coming from the detector of a factor n, while sacrificing detector timing.

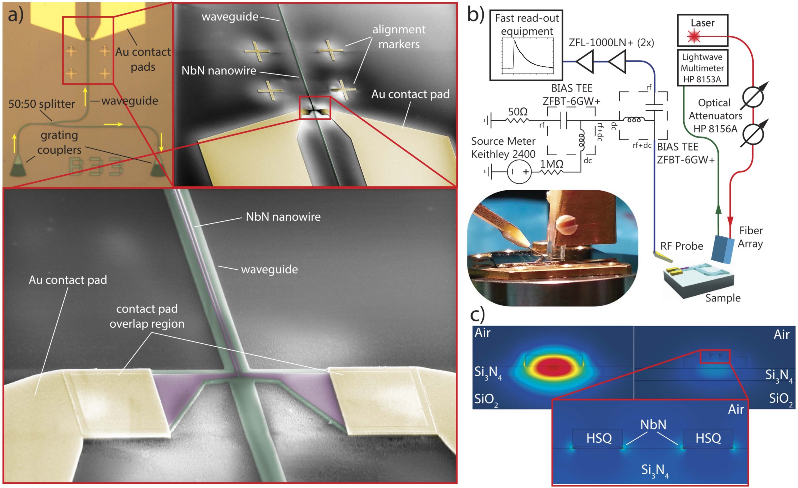




M. Ejrnaes et al., *A cascade switching superconducting single photon detector*, Applied Physics Letters 91, 2007

14.2.4 SNSPDs on Photonic Integrated Circuits

- SNSPDs have been also integrated in photonic circuits as signal sensors.
- By placing them at the end of the waveguide, where the light gets trapped, the SNSPDs have shown quantum efficiency saturation and overall optical efficiency larger than 80%.
- Despite the requirement of low temperature, having single-photon detectors working at telecom wavelength (1550 nm) with such efficiency is still a reasonable drawback for some photonic circuits applications.



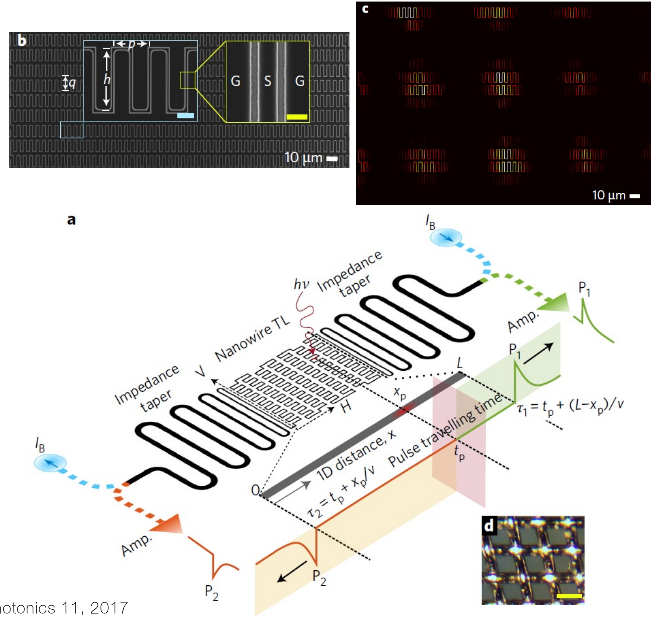
O. Kahl et al., *Waveguide integrated superconducting single-photon detectors with high internal quantum efficiency at telecom wavelengths*, Scientific Reports 5, 2015

14.2.4 Superconducting Nanowire Single-Photon Imager (SNSPI)

- Finally, the Superconducting Nanowire Single Photon Imager (SNSPI), exploits the high kinetic inductance of the superconducting transmission lines to virtually multiplex a large active area detector by differential readout.

- This approach allows very simple multiplexing capabilities (which is extremely difficult for SNSPD in general) by using only two cryogenic feedthrough lines.

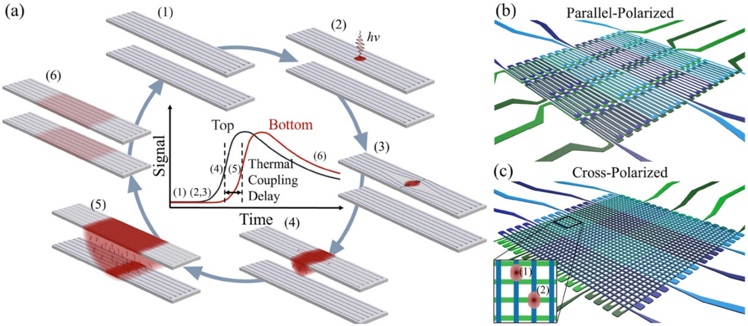
- The drawbacks are given by a limited maximum count rate and a non optimal timing resolution. The photon-generated signal needs to cross the whole SNSPI transmission line in a time τ_{travel}: if during this time another photon is absorbed, ambiguity in the detection position arises.

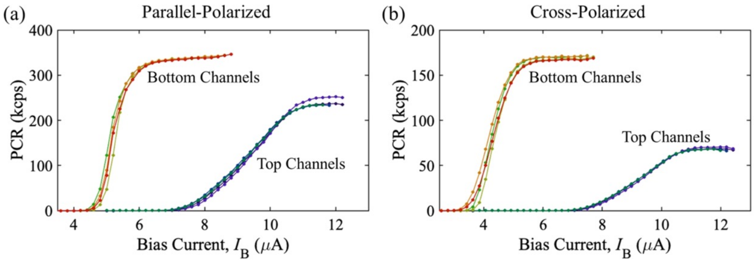


Q.-Y. Zhao et al., *Single-Photon imager based on a superconducting delay line*, Nature Photonics 11, 2017

14.2.4 Thermal Row-Column SNSPD Array

- Allmaras et al. presented a novel readout technique which also reduces the electronics required from N^2 to 2N.
- However, this approach relies on the thermal crosstalk of the top and bottom layers, hence does not present the ambiguity probability of the readout presented by Allman et al.
- Anyway, thermal processes are much slower than electronic processes, as we said before for when we compared the hTrons and the nTrons. Timing resolution then is still partially compromised in this approach.





J.P. Allmaras et al., *Demonstration of a Thermally Coupled Row-Column SNSPD Imaging Array*, Nano Letters 20, 2020

Conclusions

- Quantum SI represents the future of metrology, as it decouples itself from samples and depends only on fundamental physics constants.
- Quantum metrology is tricky, as it often requires cryogenically cooled components in a quantum limited experiment.
- Superconductors have an important role to play but it must be recognized that, like in the case of SNSPDs, that timing performance of a single device should not be degraded scaling it up to arrays.
- As usual, design of experiments play an essential role in any metrological setup, including quantum metrology setups.

Q&A

Friday June 13th at 13:30 in ELG120

End of Class

2025