Physics and Applications of Superconducting Nanowire Single Photon Detectors

683. WE-Heraeus-Seminar

November 12 - 16, 2018
at the Physikzentrum Bad Honnef/Germany

WILHELM UND ELSE
HERAEUS-STIFTUNG

Introduction

The Wilhelm und Else Heraeus-Stiftung is a private foundation that supports research and education in science with an emphasis on physics. It is recognized as Germany's most important private institution funding physics. Some of the activities of the foundation are carried out in close cooperation with the German Physical Society (Deutsche Physikalische Gesellschaft). For detailed information see https://www.we-heraeus-stiftung.de

Aims and scope of the 683. WE-Heraeus-Seminar:

Superconducting nanowire single photon detectors (SNSPD) are an enabling technology for many applications, including tests of fundamental physics, high-precision sensing, quantum communication protocols and tasks in quantum information processing. As such, the demand for SNSPDs in cutting edge science and technology has grown rapidly in recent years. With this seminar we aim at providing a forum for scientists investigating, developing and using SNSPDs in a variety of contexts. With this in mind, the workshop will include more than 20 invited contributions covering the following areas.

- Working principles and fundamental limits, in particular the role of timing jitter
- Comparison of different material systems, particularly amorphous versus crystalline thin films, and the potential of high-temperature superconductors
- Applications and emerging technologies, in particular integration on-chip

Scientific Organizers:

J.-Prof. Tim Bartley — Universität Paderborn, Germany
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Program

Program

Monday, November 12, 2018

09:00 – 16:00	Registration	
12:30	*LUNCH / Informal get together*	
14:00 – 14:10	Scientific organizers	**Opening and welcome**

<u>CHAIR: Alexej Semenov Sr</u>

14:10 – 15:10	Gregory Goltsman	**From hot-electron phenomena in disordered superconducting film to superconducting single-photon detectors**
15:10 – 15:40	Eric Bonvin	**Near-field imaging of single-photon counting superconducting nanowires**
15:40 – 16:10	Yuliya Korneeva	**From single-photon detection in micrometer-scale bridges to practical detectors**
16:10 – 16:30	COFFEE BREAK	

<u>CHAIR: Sae Woo Nam</u>

16:30 – 17:30	Karl Berggren	**Using the plasmonic character of superconducting nanowire microwave transmission lines**
17:30 – 18:10	Alexander Semenov Jr	**Can one use low-volume KID or SSPD to detect single 2Δ photon?**
18:30	DINNER	

Program

Tuesday, November 13, 2018

08:00	BREAKFAST	

CHAIR: Mariia Sidorova

09:00 – 10:00	Denis Vodolazov	**Minimal timing jitter in SNSPD**
10:00 – 10:30	Artem Kuzmin	**Timing jitter of RF-SNSPDs with different resonance frequencies**
10:30 – 11:00	*COFFEE BREAK*	

CHAIR: Alexander Kozorezov

11:00 – 11:40	Mariia Sidorova	**Timing jitter in photon detection by straight superconducting nanowires: Effect of magnetic field**
11:40 – 12:20	Xiaolong Hu	**Device timing jitter of superconducting nanowire single-photon detectors**
12:20	**Conference Photo** (in the foyer of the lecture hall)	
12:30	*LUNCH*	

CHAIR: Xiaolong Hu

14:00 – 14:30	Boris Korzh	**Experimental methods for studies of intrinsic jitter and latency in SNSPDs**
14:30 – 15:10	Alexander Kozorezov	**Intrinsic timing jitter and latency in superconducting single photon nanowire detectors**
15:10 – 15:40	Jason Allmaras	**Modeling of intrinsic detection latency and timing jitter in SNSPDs**
15:40 – 16:10	*COFFEE BREAK*	

CHAIR: Denis Vodolazov

16:10 – 16:40	Misael Caloz	**Intrinsically-limited timing jitter in MoSi SNSPDs**
16:40 – 17:40	**Discussion**	
18:00	*DINNER*	

Program

Wednesday, November 14, 2018

08:00	*BREAKFAST*	

<u>**CHAIR: Alexander Semenov Jr**</u>

09:00 -09:40	Adriana Lita	**Materials development for high efficiency superconducting nanowires single photon detectors**
09:40 – 10:20	Cheryl Feuillet-Palma	**Towards high critical temperature superconducting single photon detector**
10:20 – 10:50	Narendra Acharya	**MgB_2 nanowire photon detectors with a 70ps response time**
10:50 – 11:20	*COFFEE BREAK*	
11:20 – 12:30	**Poster session**	
12:30	*LUNCH*	

<u>**CHAIR: Gregory Goltsman**</u>

14:00 – 15:00	Alexej Semenov Sr	**Statistics of dark and photon counts in current-carrying superconducting nanowires**
15:00 – 16:00	**Discussion**	
16:00 – 16:30	COFFEE BREAK	

<u>**CHAIR: Cheryl Feuillet-Palma**</u>

16:30 – 17:10	Claire Autebert	**Performance characterization and applications of MoSi SNSPDs**
17:10 – 17:50	Iman Esmaeil Zadeh	**Superconducting single-photon detectors, a game changing technology, potentials and challenges**
17:50 – 18:30	Jonathan Finley	**Quantum detectors and sources of semiconductors**
18:45	*DINNER*	

Thursday, November 15, 2018

08:00	*BREAKFAST*	
CHAIR: Shigehito Miki		
09:00 – 10:00	Robert Hadfield	**Superconducting nanowire single-photon detectors: Current and emerging applications**
10:00 – 10:40	Lixing You	**Superconducting nanowire single photon detectors for quantum information**
10:40 – 11:00	*COFFEE BREAK*	
CHAIR: Lixing You		
11:00 – 11:40	Emma Wollman	**Superconducting nanowire single photon detectors for deep-space optical communication**
11:40 – 12:20	Labao Zhang	**Superconducting nanowire-array detectors for satellite laser ranging technology**
12:30	*LUNCH*	

Thursday, November 15, 2018

CHAIR: Labao Zhang

14:00 – 15:00	Shigehito Miki	**Research activities of superconducting nanowire single photon detectors in NICT**
15:00 – 15:30	Mack Johnson	**Addressing practicalities in a racetrack superconducting nanowire single-photon detector**
15:30 – 16:00	Menno Poot	**Linear optics quantum circuits with optomechanical phase shifters and integrated SSPDs**
16:00 – 16:30	COFFEE BREAK	

CHAIR: Robert Hadfield

16:30 – 17:10	Wolfram Pernice	**Waveguide integrated single photon detectors**
17:10 – 18:10	**Discussion**	
18:30	*HERAEUS DINNER* *(cold & warm buffet, free beverages)*	

Program

Friday, November 16, 2018

08:00	*BREAKFAST*	
CHAIR: Adriana Lita		
09:00 – 09:40	Francesco Mattioli	**From PNRD based on superconducting nanowires to pulse position readout of SSPD arrays**
09:40 – 10:10	Di Zhu	**Delay-line-multiplexed single-photon detector array for photonic integrated circuits**
10:10 – 10:40	Xintong Hou	**Broadband microfiber-coupled superconducting nanowire single-photon detector for visible and near-infrared light**
10:40 – 11:00	*COFFEE BREAK*	
CHAIR: Karl Berggren		
11:00 – 12:00	Sae Woo Nam	**Superconducting nanowires: Progress and promise**
12:00 – 12:15	**Wrap-up discussion**	
12:15	Scientific organizers	**Poster awards and closing remarks**
12:30	*LUNCH*	

End of the seminar** and FAREWELL COFFEE / **Departure

*Please note that there will be **no** dinner at the Physikzentrum on Friday evening for participants leaving the next morning.*

Posters

Posters

1.	Paul Amari	**High-temperature superconducting nano-meanders made by ion irradiation**
2.	Jin Chang	**Superconducting nanowire single photon detectors with high efficiency at high count rates and low jitter**
3.	Ilya Charaev	**Single-photon detection using suspended nano- and micro-scaled wires**
4.	Qi Chen	**A single-photon detector with NbN nanowire arrays and parallel readout**
5.	Steffen Doerner	**Comparison of the detector properties between SNSPDs biased with microwave and direct currents**
6.	Fabian Flassig	**Resolving SNSPD dynamics in cw-measurements**
7.	Simone Frasca	**Determination of the depairing current in superconducting nanowire single photon detectors**
8.	Joonas Govenius	**Towards combining superconducting nanowires and silicon photonics**
9.	Gaëtan Gras	**Countermeasure against detector blinding attack in QKD using multi-pixel SNSPD**
10.	Antonio Guardiani	**Improvement of time correlated single-photon counting with ultra-high time resolution**
11.	William Guerin	**Intensity interferometry for the 21st century**
12.	Emanuel Knehr	**Nanowire single-photon detectors made from atomic layer deposited NbN thin films**
13.	Houssaine Machhadani	**Improvement of the critical temperature of NbTiN films on III-nitride substrates**

Posters

14.	Matthieu Perrenoud	**Superconducting nanowire single photon detectors (SNSPDs) with high count-rate in amorphous materials**
15.	Daniela Salvoni	**Superconductor to resistive state switching by multiple fluctuation events in NbTiN SSPD**
16.	Manju Singh	**Initiative towards establishment of single photon based metrology for quantum information sciences & technologies**
17.	Mikhail Skvortsov	**Superconductivity in the presence of microwaves: Full phase diagram**
18.	Gregor Taylor	**A testbed for mid infrared single photon detection with SNSPDs**
19.	Frederik Thiele	**High coupling efficiency into lithium niobate waveguides at cryogenic temperatures**
20.	Konstantinos Tsimvrakidis	**Singlet oxygen luminescence detection with SNSPDs**
21.	Martin Wolff	**Bolometric response of ultra-thin high-T_c superconducting nanowires on transparent substrate**
22.	Emma Wollmann	**SNSPDs for space observatories from the UV to the mid-IR: Opportunities and challenges**
23.	Julien Zichi	**Deposition of NbTiN superconducting thin films on a wide variety of substrates, and the influence of the Nb/Ti ratio on their critical temperature and critical current densities**
24.	Kai Zou	**Fractal superconducting nanowire single-photon detectors with reduced polarization sensitivity**

Abstracts of Lectures

(in chronological order)

From hot-electron phenomena in disordered superconducting film to superconducting single-photon detectors

Gregory Goltsman

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In a far, far away year of 1989 a brand-new DC magnetron sputtering unit by Leybold-Hereaus appeared in radiophysics laboratory of Moscow State Pedagogical University (MSPU) marking the beginning of a new era of research at MSPU. We discovered hot-electron phenomena in thin superconducting films deposited in this very machine. Hot-electron bolometers (HEB) made of NbN superconducting film were successfully used in many radioastronomy applications including Herschel space observatory launched in 2009. Almost 10 years of thorough study of energy relaxation in non-equilibrium processes induced by photon absorption brought us to a discovery of single-photon detection in narrow strips of 3.5-nm-thick NbN film. Thus, Superconducting Single-Photon Detectors (SSPD) came to life.

For several years SSPDs rapidly evolved: short straight strips turned into almost half-millimeter-long meanders coupled to single-mode fibres, new types of SSPD appeared: photon-number resolving detectors, ion- and neutral molecule detectors, SSPDs with the strips connected in parallel, SSPD arrays with RSFQ readout, and finally SSPDs integrated with plannar optical waveguides. Meanwhile, the physics of SSPD operation remained rather unclear, until recent time.

In my talk, I will present an early history of SSPD and an overview of the state-of-the-art trends in single-photon detection.

Near-field Imaging of Single-photon Counting Superconducting Nanowires

Eric Bonvin[1*], **Karol Luszcz**[1], **Lukas Novotny**[1]

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We intend to investigate superconducting nanowire single photon detectors (SNSPDs) in a scanning near-field optical microscopy (SNOM) setup that was developed and built within a helium bath cryostat. The collected data yields insight on the underlying detection process of these photodetectors.

While the operation of SNSPDs is well understood, the precise detection mechanism describing the superconductive-to-normal transition is still disputed. Two competing models are generally used to describe this—the hotspot model and the photon-assisted vortex entry model. These models are thought to differ in their local detection efficiency.

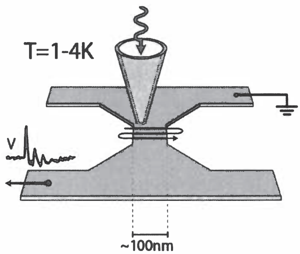

Figure 1: Diagram of the experiment. A SNOM fiber is scanned across the device. The sample is biased electrically, and a voltage pulse can be measured when a photon is absorbed.

Due to the small dimensions of these types of devices, it's hard to acquire any kind of detailed spatial information about their operation using conventional microscopy methods. To this end, we use a SNOM type setup to illuminate the devices through a coated fiber with a sub-wavelength aperture. By placing the detector within the confined near-field behind the fiber aperture, we get high-resolution information about the detection mechanism of the SNSPD.

We would like to thank NCCR QSIT and ETHZ for financial support of this project.

References: References should appear at the end of the paper in order of appearance in the abstract. The font should be 10-point and aligned to left.

1- G.N. Gol'Tsman et al., "Picosecond superconducting single-photon optical detector", Appl. Phys. Lett. vol.79, p: 705 (2001)

2- A. Engel et al., "Detection mechanism of superconducting nanowire single-photon detectors", Supercond. Sci. Technol. 28, 114003 (2015)

3- K. Luszcz et al., "Optical near-field mapping with a superconducting nanowire detector", Appl. Phys. Lett. 113, 011103 (2018)

From single-photon detection in micrometer-scale bridges to practical detectors

Yu.P. Korneeva[1], D.Yu. Vodolazov[2,1], A.V. Semenov[1,3], I.N. Florya[1], N.N. Manova[1], B.B. Akshalov[4], M.Mikhailov[5], A.A. Korneev[1,4], G.N. Goltsman[1,4], T.M.Klapwijk[6,1]

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Since the very discovery of single-photon detection in NbN strips in 2001 [1] the detection mechanism was described by 'hot-spot' model and its further improved versions. In that model, it was a common notion that the detection is possible only if the strip width is comparable with the hot spot size. Meanwhile in the recent theoretical works [2,3] an approach based on the solution of time-depended Ginzburg-Landau equations predicted that the single-photon detection is possible provided the bias current is sufficiently close to the pair-breaking current of the strip. We recently experimentally demonstrated single-photon detection in NbN bridge-type strips which allowed us to achieve bias current above 0.7 of depairing current [4].

Here we present the results of our further study of this matter. In particular, we demonstrate single-photon detection in visible and infrared range in straight bridges with the width in range from 0.5 to 5 μm made from both NbN and amorphous MoSi. We also demonstrate large-area detectors suitable for practical applications.

This work was supported by Russian Science Foundation project 17-72-30036.

1- G.N. Gol'Tsman et al., "Picosecond superconducting single-photon optical detector", Appl. Phys. Lett. vol.79, p: 705 (2001)
2- A. N. Zotova and D. Y. Vodolazov, "Photon detection by current-carrying superconducting film: A time-dependent Ginzburg-Landau approach", Phys. Rev. B 85, 024509 (2012).
3- D.Yu. Vodolazov, "Single-Photon Detection by a Dirty Current-Carrying Superconducting Strip Based on the Kinetic-Equation Approach", Phys. Rev. Applied 7, 034014 (2017).
4- Yu. P. Korneeva,et al "Optical Single-Photon Detection in Micrometer-Scale NbN Bridges" Phys. Rev. Applied 9, 064037 (2018)

Using the plasmonic character of superconducting nanowire microwave transmission lines

Karl K. Berggren

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Recent studies on microwave dynamics in SNSPDs [1] have revealed the intrinsic transmission-line nature of thin-film superconducting nanowires. The kinetic inductance, which is several orders of magnitude higher than the magnetic inductance, results in ~kΩ characteristic impedance and an effective group velocity only a few percent of speed of light. Such peculiarities have been recently exploited to realize a single photon imager (SNSPI) [2] and a scalable multi-photon coincidence detector, both relying on a delay-line-multiplexed readout [3].

The small size of the nanowire transmission lines allows them to be precisely placed as close together as tens of nanometers, strongly enhancing the electromagnetic coupling. In this talk, I will propose and discuss applications of microwave transmission lines to a new class of superconducting microwave devices such as interferometers, filters and non-linear switches. These compact, high impedance nanowire-based devices will allow us to directly read out and process electrical signals from other superconducting-based devices such as superconducting nanowire single-photon detectors, memories, resonators, and qubits.

I will present here a recent theoretical understanding of microwave dynamics in nanowire devices and show the progress toward the realization of advanced superconducting microwave devices.

References

[1] Santavicca, Daniel F., Journal of Applied Physics 119.23 (2016): 234302.
[2] Zhao, Qing-Yuan, et al. Nature Photonics 11.4 (2017): 247.
[3] Zhu, Di, et al. Nature nanotechnology (2018): 1.

Can one use low-volume KID or SSPD to detect single 2Δ photon?

Alexander Semenov[1,2], **Igor Devyatov**[3,2], **Mikhail Kupriyanov**[3,2], **Oleg Astafiev**[4,2,5]

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The existing superconducting detectors, like KID, SSPD or TES, can efficiently count single photons, but energy of these photons is orders of magnitude greater than the limit set by superconducting gap. We address the question - is it possible to reach this limit and how – considering some issues related to the operation principle of these detectors in the limit of low volume, including fluctuations of order parameter and mechanisms of recombination of quasiparticles. In particular, we show that to realize ultimate performance, one has to reach the regime where recombination of quasiparticles is governed by emission of *photons*.

Basing on this, we propose a kinetic-inductance single-photon detector for microwave photons with frequency of order 10 GHz. Operational principle of the detector is based on the change of kinetic inductance of a small-volume superconducting bridge due to the absorption of a photon and creation of a pair of quasiparticles. The kinetic inductance is monitored via ancillary intense RF signal on sub-gap frequency. The detector is intrinsically wide-band and) is of great importance in quantum-optics experiments with superconducting artificial quantum systems.

Minimal timing jitter in SNSPD

D. Yu. Vodolazov

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Using two-temperature model coupled with modified time-dependent Ginzburg-Landau equation we calculate the delay time τ_d in appearance of growing normal domain in the current-biased superconducting strip after absorption of the single photon. We demonstrate that τ_d depends on the place in the strip where photon is absorbed and monotonically decreases with increasing of the current. The last result is not surprising and resemble previous theoretical findings on the time delay in destruction of superconducting state by current pulse [1-5]. We argue, that the variation in τ_d (timing jitter), connected either with position-dependent response or Fano fluctuations could be as small as the lowest characteristic relaxation time of the superconducting order parameter ~h/k_BT_c (T_c is the critical temperature of the superconductor) when the current approaches the depairing current.

The work was supported by the Russian Science Foundation (RSF), grant No. 17-72-30036.

1- J. Zhang, W. S³ysz, A. Pearlman, A. Verevkin, R.Sobolewski, O. Okunev, G. Chulkova, G. N. Gol'tsman, "Time delay of resistive-state formation in superconducting stripes excited by single optical photons", Phys. Rev. B vol. 67, 132508 (2003).
2- M. Tinkham, "Heating and dynamic enhancement in metallic weak links", in *Nonequilibrium Superconductivity, Phonons, and Kapitza* Boundaries, Proceedings of NATO Advanced Study Institutes, edited by K. E. Gray (Plenum, New York, 1981), p. 231.
3- J.A. Pals and J. Wolter, "Measurement of the order parameter relaxation in superconducting Al strips", Physics Letters A vol. 70, p. 150 (1979).
4- A. Geier and G. Schon, "Response of a Superconductor to a Supercritical Current Pulse", J. of Low Temp. Phys. vol. 46, p. 151 (1982)
5- D. Yu. Vodolazov and F. M. Peeters, "Temporary cooling of quasiparticles and delay in voltage response of superconducting bridges after abruptly switching on the supercritical current", Phys. Rev. B vol. 90, 094504 (2014).

Timing jitter of RF-SNSPDs with different resonance frequencies

Artem Kuzmin[1], Steffen Doerner[1], Hana Chehade[1], Konstantin Ilin[1], Stefan Wuensch[1], Michael Siegel[1]

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Different optical applications require a large number of single-photon detectors with high timing accuracy integrated in an array. The timing accuracy, i.e. jitter, of a system with a standard meander-type DC-SNSPD is strong dependent on the matching to the first-stage amplifier and its noise performance. Due to high kinetic inductance of the nanowire it works as a slow-wave high-impedance waveguide for electrical pulses, generated in the nanowire by single photons. A long taper is required to avoid reflection of the SNSPD pulses from a 50-Ohm line on the way to the input of the amplifier. Additionally, it is challenging for commercial amplifiers to ensure high return loss and low noise in the full bandwidth of the SNSPD pulse, which starts from 100 MHz and can extend up to 3 GHz.

A microwave biased and readout SNSPD (RF-SNSPD) is a promising device for applications, requiring multi-pixel arrays and matrices of detectors [1-2]. The RF-SNSPD is based on a high-Q superconducting resonator, which allows for Frequency-Division Multiplexing in GHz range and thus high multiplexing ratio (number of detectors per one readout line). As a single-photon response, an RF-SNSPD generates pulses with transient envelope and a carrier at resonance frequency. It was shown that the envelop has a relatively short rise time which allows precise timing of the photon arrival.

Here, we present results of jitter measurements of RF-SNSPDs with different resonant frequencies. The transients are obtained with homodyne and heterodyne detection schemes to simulate parallel readout of many detectors. The analysis of the influence of the carrier frequency on jitter along with concepts for a parallel readout scheme and post processing will be presented and discussed.

References:

1- Doerner, Steffen, et al. "Operation of superconducting nanowire single-photon detectors embedded in lumped-element resonant circuits." IEEE Transactions on Applied Superconductivity 26.3 (2016): 1-5.

2- Doerner, Steffen, et al., "Frequency-multiplexed bias and readout of a 16-pixel superconducting nanowire single-photon detector array." Applied Physics Letters 111.3 (2017): 032603.

Timing jitter in photon detection by straight superconducting nanowires: Effect of magnetic field

Mariia Sidorova[1], Alexej Semenov[1], Heinz-Wilhelm Hübers[1], Artem Kuzmin[2], Steffen Doerner, K. Ilin[2], Michael Siegel[2], Ilya Charaev[3], Denis Vodolazov[4]

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Timing jitter is one of the crucial application metrics of modern superconducting photon detectors. Moreover, studding the timing jitter inherent in the detector itself allows one to look into underlying physical mechanisms and also to clarify the photon-detection mechanism in general. Partially it has been done in Ref. 1 where the timing jitter was studied with meanders of different sizes. In terms of the probability theory, the jitter was associated with the probability density function of the random time delay between absorption of a photon in the current-carrying superconducting nanowire and appearance of the normal domain. Strikingly different statistic of photon counts has been found which reveals two different physical detection regimes deterministic and probabilistic. Conceptually, each photon count was considered as a composite event including at least two elementary sequential events described by Gaussian and exponential distributions of probability densities. These events were associated with the growth of the hot-spot (Gaussian distribution) and consequent jump of a magnetic vortex across the nanowire (exponential distribution). The former dominates in the deterministic regime, while the later in the probabilistic one. Since bend and straits in a meander often obey different detection regime, we further studied the timing jitter in straight strips without bends [2]. We found that timing jitter increases in external magnetic field and decreases when the incident photon flux grows. We show that the hot-spot concept is essential for understanding our experimental results.

References:

1- Mariia Sidorova, Alexej Semenov, Heinz-Wilhelm Hübers, Ilya Charaev, Artem Kuzmin, Steffen Doerner, and Michael Siegel, "Physical mechanisms of timing jitter in photon detection by current-carrying superconducting nanowires," Phys. Rev. B 96, 184504, 2017.
2- Mariia Sidorova, Alexej Semenov, Heinz-Wilhelm Hübers, Artem Kuzmin, Steffen Doerner, K. Ilin, Michael Siegel, Ilya Charaev, Denis Vodolazov, "Timing jitter in photon detection by straight superconducting nanowires: Effect of magnetic field and photon flux", PRB (accepted), arxiv: 1806.07183

Device timing jitter of superconducting nanowire single-photon detectors

Xiaolong Hu[1], Hao Wu[1], Chao Gu[1], Yuhao Cheng[1], Xiaoming Chi[1], Kai Zou[1], Nan Hu[1], and Xiaojian Lan[1]

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Timing jitter characterizes the time-resolving capability of a single-photon detector. The measured total timing jitter of a SNSPD system is a quadratic sum of the timing jitter induced by multiple factors, including electronic noises and transmission-line effect of the nanowire. Recently, we illustrated two additional mechanisms—vortex crossing [1] and spatial inhomogeneity of the nanowire [2] —that both induce device timing jitter of SNSPDs.

Vortex-crossing-induced timing jitter [1] occurs prior to the electro-thermal evolution of the initial resistive region generated by incident photons. By investigating the timing properties of single-photon-triggered vortex crossing in an SNSPD, we found that the time delays caused in the vortex-crossing process vary with the transverse positions on the nanowire where the photons are absorbed. The position-dependent time delays indicate that the vortex-crossing process induces timing jitter, which appears to be an intrinsic mechanism that fundamentally limits the time-resolving capability of SNSPDs.

On the other hand, spatial-inhomogeneity-induced timing jitter [2] occurs during the electro-thermal evolution of the photon-generated resistive region. Distributed electronic and geometric inhomogeneity along the nanowire can induce timing jitter and this inhomogeneity-induced timing jitter could be further exacerbated by localized constrictions. The magnitude of the spatial-inhomogeneity-induced timing jitter depends on the degree of inhomogeneity of the nanowire and on how fast the electro-thermal evolution of the resistive hotspot is and can be reduced by engineering the device structures.

This work was supported by the National Natural Science Foundation of China (61505141 and 11527808) and Tianjin Municipal Science and Technology Commission (15JCYBJC52500).

References

[1] H. Wu et al., Applied Physics Letters **111**, 062603 (2017).
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Experimental methods for studies of intrinsic jitter and latency in SNSPDs

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The temporal resolution, or jitter, in superconducting nanowire single-photon detectors (SNSPDs) has recently gained vast interest within the community. From a theoretical modelling point of view, it provides insights into the initial moments of the detection process. By developing a practical, multi-channel, cryogenic readout of SNSPDs and using structures to minimize the geometric jitter, we have recently measured timing jitter of 2.6±0.2 ps for visible wavelengths (see Fig. 1a) and 4.6±0.2 ps at 1550 nm in niobium nitride (NbN) devices[1]. We also report timing jitter of 4.8±0.2 ps at 532 nm and 10.3±0.5 ps at 1550 nm using a tungsten silicide (WSi) SNSPD through the use of an impedance matching taper for improved readout signal characteristics. The wavelength, temperature and transverse nanowire geometry dependence of the timing jitter of these devices strongly suggests that intrinsic effects dominate. These record low jitter values have enabled us to experimentally observe the dependence of the detection latency on photon energy, for the first time. Since jitter is simply the fluctuation of latency, it proves to be the key to understanding intrinsic jitter mechanisms. Using a second harmonic generating crystal to frequency double a pulsed source, the relative latency between photons of two energies can be measured under the same electrical and optical configuration. We present experimental relative latency results for photon pairs of 1550nm/775nm and 1064nm/532nm photons (Fig. 1b) in niobium nitride (NbN) nanowires. By combining the photo-response count rate curves, timing jitter, and relative latency curves for varying transverse geometries at different temperatures, we have a unique dataset which can be used to test the current understanding of the detection mechanism in SNSPDs.

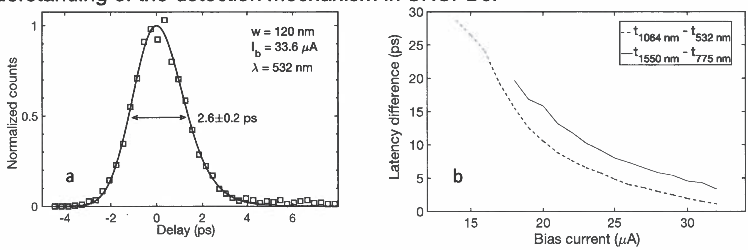

Figure 1: (a) Jitter in a short, 120 nm-wide NbN nanowire at visible wavelengths. (b) Relative latency as a function of bias current between two photon pairs, for the same device. These results indicate that the latency in these detectors, just as the jitter, reduces for photons of increased energy.

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Intrinsic timing jitter and latency in superconducting single photon nanowire detectors

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We analyze the origin of the intrinsic timing jitter in superconducting nanowire single photon detectors (SNSPDs) in terms of fluctuations in the latency of the detector response, which is determined by the microscopic physics of the photon detection process. We demonstrate that fluctuations in the physical parameters which determine the latency give rise to the intrinsic timing jitter. We develop a general description of latency by introducing the explicit time dependence of the internal detection effciency. By considering the dynamic Fano fluctuations together with static spatial inhomogeneities, we study the details of the connection between latency and timing jitter. We develop both a simple phenomenological model and a more general microscopic model of detector latency and timing jitter based on the solution of the generalized time-dependent Ginzburg-Landau equations for both the 1D hotbelt and 2D hotspot geometries. While the analytical model is sufficient for qualitative interpretation of recent data, the general approach establishes the framework for a quantitative analysis of detector latency and the fundamental limits of intrinsic timing jitter. These theoretical advances can be used to interpret the results of recent experiments measuring the dependence of detection latency and timing jitter on photon energy to the few-picosecond level.

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Modeling of Intrinsic Detection Latency and Timing Jitter in SNSPDs

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Recent measurements of record-low timing jitter in SNSPDs have enabled the measurement of relative latency, providing a new means of studying the SNSPD detection mechanism. The introduction of latency to the photodetection model indicates the mechanism by which dynamic Fano fluctuations and static non-uniformities lead to timing jitter. Fluctuations in the energy deposited in the nanowire system lead to shifts in the detector latency, which contribute to timing uncertainty for a given incident photon energy. We present a mathematical representation of this contribution to timing jitter which leads to a non-Gaussian form, as observed experimentally. The non-Gaussian tail observed in experiments at longer detection times is attributed to the positive curvature of the latency vs energy profile.

We model the detection latency by numerically solving the modified time-dependent Ginzburg Landau (TDGL) equations[1] in one and two dimensions. We find that the standard TDGL formulation is able to qualitatively match experimental trends, but provides inadequate quantitative fitting due to suppression of the order parameter on timescales faster than observed experimentally. By moving to a generalized TDGL[2] approach which scales the order parameter evolution according to the average electron scattering time, the experimental data can be fit with improved accuracy. Our model results are compared to experimental latency difference results for photon wavelength pairs of 1064/532 nm and 1550/775 nm and timing jitter results for the same four wavelengths. We find that the one dimensional model provides reasonable fitting to the experimental data for narrow nanowires of 60 nm and 80 nm widths, but fails to predict the appropriate behavior of 100 nm and 120 nm width nanowires. The two dimensional model predicts a transition from a 'w' shaped latency profile with transverse coordinate at high photon energies to a 'bell' shaped profile at the lowest energies near the detection latency singularity. This transformation in detection profile can be attributed to the differing dynamics of vortex-antivortex unbinding in the nanowire interior compared to vortex entry from the edge of the nanowire.

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Intrinsically-limited timing jitter in MoSi SNSPDs

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Temporal temporal jitter, is a crucial characteristic of superconducting nanowire single photon detectors[1] (SNSPD). Improving it has an impact on many applications with time-resolved measurement such as light detection and ranging and high-speed quantum communication. A wide range of values have been reported for different geometries and materials, typically from few to hundreds of picoseconds. A value below 3 ps has been very recently reported with short NbN nanowires[2], and 26 ps with meandered MoSi devices[3].

In this work, we report our advances on the jitter in MoSi devices, and more particularly on the intrinsic component and its fundamental limit. Specific detectors with a short nanowire and a series inductance have been fabricated for this study, a structure which has proved useful for studies of the fundamental jitter[2]. More than 70 nanowires with varying width, thickness and series inductance have been measured. The lowest value obtained by optimizing the series inductance and geometry of the MoSi device is 5.9 ps, at 532 nm, c.f. Figure 1. A clear wavelength dependency of the intrinsic jitter is observed, forming a comprehensive dataset for comparison to detection theories. Being crucial parameters for low jitter operation, the trade-off between the latching current and the rising time has also been studied.

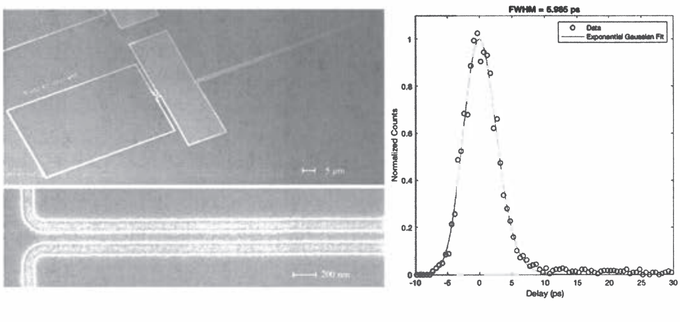

Figure 1: (left) SEM image of one of the device, (right) Jitter histogram for the optimum device with 532 nm light operating at 0.95 K.

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Materials Development for High Efficiency Superconducting Nanowires Single Photon Detectors

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Superconducting nanowire single-photon detectors (SNSPDs) based on ultra-thin films have become the preferred technology for applications that require high detection efficiency, ultrafast timing performance and low noise for wide spectral sensitivity spanning UV to near IR spectrum. The wide range of applications such as fundamental tests of quantum mechanics, fluorescence microscopy, optical communication and quantum computing, also requires various performance benchmarks which cannot be achieved in one single optimized detector.

As a result, a variety of materials have been investigated with the goal of finding the optimum detector for specific applications. With the success of amorphous W_xSi_{1-x} SNSPDs [1,2], our group has investigated a number of amorphous materials [3-5] pursuing higher operation temperatures while maintaining the other high performance metrics that characterize SNSPDs.

We will review some of the SNSPD materials used and discuss optimization of Mo_xSi_{1-x} sputter-deposited films of different compositions and structures for higher operating temperatures (above 3K) and with saturated internal efficiency. Variations of deposition parameters and stoichiometry effects on film structure were investigated through X-ray diffraction measurements as well as DC transport measurements (critical temperature (Tc) measurements, coherence lengths and diffusion constants extraction). Device critical currents were compared to theoretical predictions of depairing current in order to explore what determines saturated internal efficiency in the Mo_xSi_{1-x} devices.

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Towards High Critical Temperature Superconducting Single Photon detector

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In the past years, we have been developing High-Tc Josephson nano-junctions made by ion irradiation [1]. Based on commercial $YBa_2Cu_3O_{7-x}$ thin films, this versatile and highly scalable technique opens a new route towards superconducting electronics in the temperature range between 20K and 80K. DC [2,3,4] and RF applications have been explored, with very encouraging results.

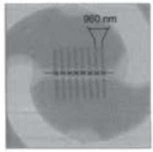

FIGURE 1 : Optical picture the array geometry with eight Jospehson junctions in series separated by 960 nm

In particular, we built a heterodyne High-Tc Superconductor (HTSc) receiver in the THz range, made of a Josephson mixer embedded in a broad-band antenna, operating at 50K-60K. High-frequency mixing properties of such device up to 420 GHz has been obtained, with interesting conversion gain [3]. The operation of the detector is undersood in the framework of a three-ports model. Recently, we have reported on Josephson mixing on Giant Shapiro steps of ion-irradiated Josephson arrays [5]. Moreover, we have shown that phase locking between junctions is possible depending on the spacing of the Josephson junctions in the array, illustrated figure 1.

FIGURE 2 : AFM image of HTSc meanders made by ion irradiation embedded in a CPW line

On the other hand, we also realize very long YBa2Cu3O7-x nanowires in a meander shape patterned in a CeO2-capped thin film by high-energy oxygen ion irradiation, presented figure 2. The fabrication of narrow long and thin (20 and 30 nm thick) YBa2Cu3O7-x nanowire with hysteretic IV curves is the building block of a SNSPD [6]

In this presentation, I will present our last results on HTS nanowires, that pave the way for a SNSPD operating at higher temperature.

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MgB_2 nanowire photon detectors with 70ps response time

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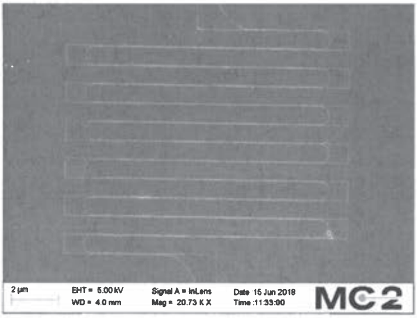
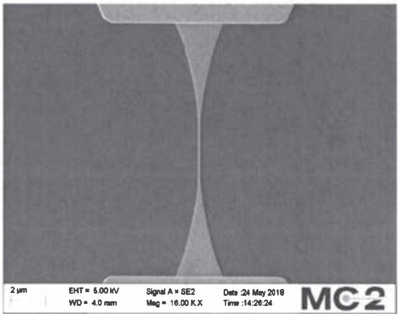
We investigate MgB_2 thin film nanowires for single photon detection for visible and and IR ranges. Using in-house Hybrid Physical Chemical Vapour Deposition (HPCVD) system, MgB_2 films as thin as 5-10nm were made with critical temperatures 30-35K [1]. Such films showed electron energy relaxation rate of about 10GHz [2], hence a factor of 3 faster than in NbN. Recently, we developed technique to fabricate MgB_2 nanowires as narrow as 40nm and as long as 120μm. Varying the nanowire width and length, we measured its kinetic inductance using microwave scattering parameters approach. Consistently, we obtain a 1.5 pH kinetic inductance per square (90pH/sqr in NbN), which is independent of nanowire width varying from 20nm to 400nm. It suggests a drastic increase in the reset time for nano-wire photon detectors. A full-width-halve-maximum pulse width is measured to be 70ps, independently on the device geometry. It means, that is it limited not by the device, but rather by the readout electronics. Finally, we show that at bias currents at the vicinity of I_c the pulse count rate is linear with the incident photon flux, suggesting single photon counting regime. Based on device characteristics, we will also discuss validity of BCS theory for MgB_2.





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Statistics of dark and photon counts in current-carrying superconducting nanowires

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Timing characteristics of the single-photon response in superconducting nanowire detectors have twofold importance for applications. Timing jitter restricts the accuracy in defining flight-times of photons referenced to the time of emission while intrinsic statistics of photon counts may disguise the statistics of photon arrivals from the light source.
Here we discuss timing statistics of photon and dark counts in bended and straight nanowires and show that the statistics is different for different locations of count events and it is different for photon and dark counts.
We present a statistical model of vortex-assisted dark counts and vortex-assisted photon counts in the deterministic and probabilistic regimes. A photon-detection event falls in one of two regimes, depending on whether the energy transferred from the photon to electrons is sufficiently large in order to create a critical state. The critical state occurs when the velocity of superconducting condensate drops locally below the critical, depairing value. We compared our model with available experimental results and found out that it explains qualitatively statistics of photon counts. Contrary, statistics of dark counts contradicts to the model predictions. We discuss alternative mechanisms of dark counts.

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Performance characterization and applications of MoSi SNSPDs

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Superconducting nanowire single-photon detectors (SNSPDs) are a key technology for optical quantum information processing [1]. Their low dark count rate, fast response time, small jitter, and high system detection efficiency (SDE) favours their use in various demanding quantum optics applications such as high-speed or long-distance quantum key distribution, quantum networking, device-independent quantum information processing and deep-space optical communication. Amorphous superconductors such as tungsten silicide (WSi), molybdenum silicide (MoSi) and molybdenum germanium (MoGe) have recently been introduced. SNSPDs based on these materials allow to achieve high SDE [2], a saturated detection efficiency (a plateau), as well as a high fabrication yield, favouring their use in complex structures such as detectors arrays or alternative SNSPD structures.

In this talk we will report on different means of characterizing the speed and recovery time of SNSPDs, which is a topic of great importance when the intent is to use SNSPDs in high-performance quantum communication tasks such as high-speed quantum key distribution. The characterization is applied on different kinds of nanowire structures, and their behaviour in the high-count rate regime is investigated. We will discuss some applications such as ultra-long-distance quantum key distribution [3] and characterization of integrated multi-photon-pairs sources.

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Superconducting single-photon detectors, a game changing technology, potentials and challenges

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Over the past decade, superconducting nanowire single-photon detectors (SNSPDs) have set the standard for single-photon detection in the visible and infrared. While these detectors have been routinely utilized in most modern quantum optics labs around the world, the true potentials of them are yet to be explored in many fields of science. Potential applications of SNSPDs range from particle physics and astronomy to biology and chemistry. Most of those applications require large area detectors together with enhanced performance in all key aspects: detection efficiency, dark counts, deatime and jitter. On the other hand, however, most of these parameters have tradeoffs among each other and with the active area of the detectors. By careful engineering of the device nano-structure and also tuning the superconducting properties of the film, we demonstrate detectors outperforming conventional SNSPDs in all performance aspect simultaneously: we show detectors with 89-93% detection efficiency and 8-15ps time resolution [1, 2, 3], and the efficiency remains high even at high countrates [1, 3]. Furthermore, we fabricate ultra-wideband and large active area detectors coupled to multimode fibers with high efficiencies and sub 20ps jitter [3]. Our multi-pixel detectors offer very large active area together with the high performance of small size detectors [3]. A novel integration method, developed in our lab, holds major promises for scalable on-chip quantum optics by eliminating yield issues in practical complex circuits [4]. We discuss the prospect of these developments in the fields of communication, nuclear physics and biology.

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Quantum Detectors and Sources of Semiconductors

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We present recent studies of superconducting nanowire single photon detectors (SNSPD) on both GaAs and SiO_2 substrates [1-6] and their integration with non-classical quantum sources. For SNSPDs on GaAs, we report the generation, routing and detection of resonance fluorescence emitted by resonantly pumped self-assembled InGaAs quantum dots (QDs) in an all-optical circuit [2]. We observe common QD excited state resonances both in on-chip and off-chip detection geometries and, by applying a temporal filtering technique, demonstrate resonant fluorescence from a single quantum dot with a line-width of 10.2±1.3 µeV, guided in the optical modes of a GaAs ridge waveguide and efficiently detected via evanescent coupling to a NbN-SNSPD integrated on the same chip (Fig. 1). By measuring the autocorrelation function with off-chip detection, we prove the non-classical character of the on-chip detected light.

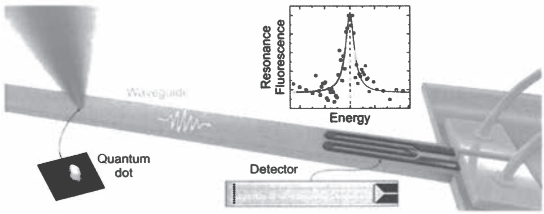

Figure 1: Schematic illustration of sample under investigation consisting of a single self-assembled quantum dot, a multi-mode ridge waveguide and a superconducting single photon detector. Inset: Resonant fluorescence signal detected with the on-chip SNSPD showing a QD line-width of 10.2 ± 1.3 µeV

On SiO_2, a much higher T_c=14.4K is achieved for 4nm thick films as compared to T_c=10.2 K on GaAs. First detectors from these films exhibit moderate quantum efficiencies up to ca. ~25% at 980 nm. Our attention will then shift to integrated semiconductor devices capable of *converting* laser pulses with Poissonian counting statistics into *single* and *multi-photon* pulses. Our results demonstrate that a two-level quantum emitter, that has long been studied for single-photon generation, can surprisingly operate in a two-photon bundling regime [7|. The dynamics of both processes, generation of single photons and two-photon pulses, will be discussed [8]. Specifically, the influence of the pulse length, pulse shape and coupling to acoustic phonons is examined and the prospects of multi-level quantum systems will be discussed [9].

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Superconducting nanowire single-photon detectors: current and emerging applications

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Superconducting nanowire single-photon detectors (SNSPDs) have emerged an important alternative to conventional photon counting technologies such as photomultipliers and single-photon avalanche photodiodes. Single pixel SNSPDs offer best in class performance at infrared wavelengths and are an important enabler for advanced photon counting applications including quantum communications, single-photon remote sensing and dosimetry for laser cancer treatment. The advent of integrated SNSPD arrays with extended infrared sensitivity is an exciting prospect. I will review developments in SNSPD device design, materials and practical cryogenics. I will introduce case studies of applications and give an outlook on future opportunities.

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Superconducting nanowire single photon detectors for quantum information

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Quantum information and control (includes quantum communication, quantum computation and quantum precision measurement et al) has turned to be one of the most fascinating scientific fields owing to the advances of quantum device technologies, in which single photon detector (SPD) plays an irreplaceable role. As a novel SPD, superconducting nanowire single photon detector (SNSPD) surpasses the semiconducting SPDs with many merits, such as high detection efficiency, low dark count rate, low timing jitter, higher counting rate etc. SNSPDs have advanced various QIP experiments in the past decade. Now you may buy the commercial SNSPD systems including the cryogenics from several start-up companies. In this talk, we will present the latest results of SNSPDs (for example, SNSPD with SDE over 90%; Low DCR SNSPD; How to tune SDE of SNSPD with He4 ion irradiation; operation with space compatible cryocooler; micro-fiber coupled SNSPD etc) and the applications in quantum information (QKD, quantum computation, quantum random number generation and Big Bell Test etc).

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Superconducting Nanowire Single Photon Detectors for Deep-Space Optical Communication

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We present recent results in the development of a 64-pixel SNSPD array for the ground terminal of NASA's Deep Space Optical Communication (DSOC) technology demonstration project. We have recently demonstrated a free-space coupled WSi SNSPD array with over 300 µm diameter active area, over 1 Gigacount per second maximum count rate, over 75% system detection efficiency through cryogenic filters, 80 ps FWHM timing jitter, and a background-limited dark count rate below 20 cps per pixel. We will discuss the development of readout electronics capable of streaming time-tagging photon arrival events across 64 pixels at rates up to 900 megatags per second. We will also discuss the design of the larger DSOC ground terminal, as well as the optical communication demonstration as a whole.

Superconducting nanowire-array detectors for satellite laser ranging technology

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Satellite laser ranging technology (SLR) [1] is the unique technology to accurately determining the orbits of both satellites and space debris. Currently, most SLR adopted silicon-based single photon avalanche diode (SPAD), which can register echo photon at 532 nm generated after frequency doubling of 1064 nm Nd:Yag laser. The main barrier of SLR at 1064 nm wavelength is single photon detector with high performance, including large detector area, high efficiency, low dark count rate and high time resolution[2]. For the SLR application, we developed SNSPD arrays with a beam compression setting, which produced an equivalent detection area of ø300 μm and four-quadrant resolution. An optical telescope (ø1.2 m) coupled the echo photons to our SNSPD with an efficiency about 60% (without optimizing the polarization). Then, a closed-loop tracking system can be achieved. Over the past three years, we accurately measured 200+ space targets at an altitude of 400-36 000 km. The Typical resolutions are <1 cm for cooperative targets, and <1 m for non-cooperative targets respectively. The smallest measured debris is only 0.04 m^2. This work may lead the development of next generation SLR.

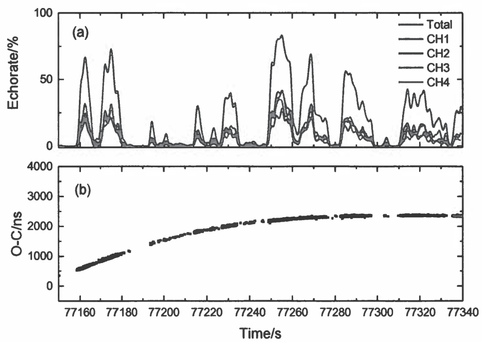

Figure 1: Echo rate(a) and The orbit curve of COMPASS i6 satellite (b).

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Research activities of superconducting nanowire single photon detectors in NICT

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We have been studying the superconducting nanowire single photon detectors [1], especially for use in quantum information technologies. Our SNSPD system showed excellent performance as results of various efforts and were successfully demonstrated [2] with various kinds of QI experiment [3-5] such as Tokyo QKD field demonstration [6]. We also focus on the development for high functionality such as single photon imaging system by utilizing single quantum flux (SFQ) circuit [7-9]. In the presentation, we will introduce the R&D of SNSPD system and their application in NICT from 2006 to date.

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Addressing practicalities in a racetrack superconducting nanowire single-photon detector

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Superconducting nanowire single-photon detectors (SNSPD) and their on-chip integration are promising for many applications including quantum optics [1,2]. Here, we report on our cavity-enhanced SNSPDs. We expand on our previous cavity design on the SOI platform [3], implementing a small (<20 x 20 micron) multi-mode waveguide region with an intrinsic loss of 0.015 dB and a crosstalk level of -38 dB into the racetrack cavity as shown in Figure 1. A central focal point from self-imaging in the multi mode waveguide provides a region to place nanowires and tune absorption (and therefore the cavity Q and linewidth). This design allows the nanowires to be routed to contact pads via a waveguide arm (see Figure 1(left)). The arm extends perpendicular to the light propagation without inducing deleterious losses, preserving high detection efficiencies. Furthermore, the structure can be etched in the same, single step as the waveguides.

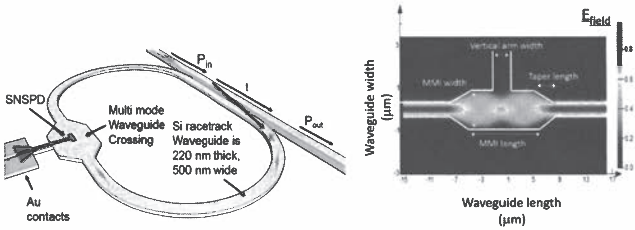

Figure 1: (Left) Schematic of the detector showing silicon (Si) waveguides, the SNSPD and gold (Au) contact pads. (Right) FDTD simulation of light propagating through the multi mode waveguide region. Self-imaging can be observed in the centre.

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Linear optics quantum circuits with optomechanical phase shifters and integrated SSPDs

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Integrated photonics provides unprecedented flexibility, scaling possibilities, and stability of optical circuits. We will discuss our efforts towards fully-integrated linear-optics quantum circuits. We show the design, fabrication, and characterization of the essential elements, including directional couplers, photonic CNOT gates, phase detection, and superconducting single photon detectors [1,2]. The latter consists of NbTiN that is deposited onto the silicon nitride layer in which the optical waveguides are defined.

All of these elements are integrated monolithically on the same chip, so that no chip-to-chip interconnects are required. However, since the SSPDs require operation at cryogenic temperatures, the conventional approach of using thermo-optic phase shifters is not feasible. Instead, by combining movable structures with electrostatic actuation, we developed an opto-electromechanical platform that – besides being a perfect platform for fundamental optomechanics experiments - can be employed as a broadband integrated phase shifter [3]. These enable programmable initialization and tomography of photonic qubits on the same chip as the detectors.

Another example where optomechanics meets SSPDs is the on-chip frequency shifter [4]. Here single photons from a non-degenerate SPDC source are sent through a piezo-electric waveguide that vibrates at GHz frequencies. This shifts the frequency of the photons and their indistinguishability from their partners is measured with the help of SSPDs.

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Waveguide integrated single photon detectors

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Nanophotonic circuits employ waveguiding devices to route light across integrated optical chips in analogy to electrical wires in integrated electrical circuits. Interaction with the environment is possible through near-field coupling to the evanescent tail of propagating optical modes. This approach is particularly interesting for designing highly sensitive detectors which are able to register individual photons and constitute fundamental building blocks for emerging quantum photonics. Superconducting nanowire single photon counters (SNSPDs) provide high efficiency and good timing performance, as well as broad optical detection bandwidth. To move towards applications in high bandwidth quantum communication, we realize compact SNSPDs with sub-micrometer effective length by embedding them in photonic crystal cavities to recover high absorption efficiency [1,2]. These detectors possess sub-nanosecond recovery times and ultralow noise equivalent power. Being made by scalable fabrication techniques, waveguide SNSPDs hold promise for photonic integrated quantum technologies.

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From PNRD based on superconducting nanowires to Pulse Position Readout of SSPD arrays

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Applications such as linear optical quantum computing, near-infrared spectroscopy, or optical and quantum communications need a detector able to count the number of photons down to the single photon regime in the near infrared optical region. As the detection mechanism of a SSPD is highly nonlinear, one of the approach with which PNRD functionality can been obtained is the spatial multiplexing of different pixels. In this presentation, an overview of the spatial multiplexing with a single read out approach will be given: the parallel configuration [1] will be described together with its limitations that paved the way to the serial configuration that allows to resolve up to 24 photons in a single pulse [2]. Moreover, this approach has been further developed to implement a detector able to measure the position and the number of the absorbed photon in an array with a single electrical readout [3].

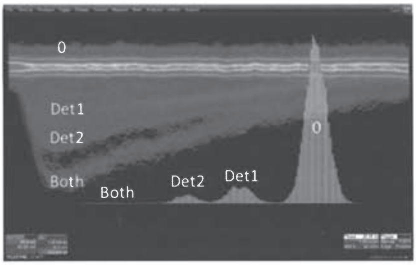

Figure 1: Persistence trace of the output pulse of a 2 pixel PPR integrated on SiN ridge waveguides.

As a proof of principle, Pulse Position Readout (PPR) of a two elements array has been fabricated on top of a silicon nitride Photonic Integrated Circuit (PIC) designed to measure the second order correlation function ($g^2(\tau)$). Fig. 1 shows the persistence traces of the output pulse of the detectors. Three levels are clearly visible. They correspond to single photon absorption in the detector 1, detector 2, and single photons simultaneously absorbed in both detectors. The use of the PPR leads to a thermal load reduction, allowing the integration of a large array of detectors in standard GM cryostats.

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Delay-line-multiplexed single-photon detector array for photonic integrated circuits

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Waveguide-integrated superconducting nanowire single-photon detectors (SNSPDs) offer efficient optical absorption with a small footprint, resulting in fast reset, low dark count rates, and low timing jitter. Many applications, such as boson sampling, photonic deep learning, and dense wavelength-division multiplexing, require large arrays of detectors. Though parallel-operated on-chip SNSPD arrays have been demonstrated [1], further scale-up presents formidable a challenge in electrical readout.

To overcome this challenge, we exploit the slow-wave property of superconducting nanowire transmission lines [2], and demonstrate a delay-line-multiplexed two-terminal detector array [3]. The array can resolve both single-photon and multi-photon events over a large number of spatial modes (see Figure 1(a)). Here, we further report our recent progress on integrating such a detector array on a photonic integrated circuit (PIC). The PIC consists of an array of coupled waveguides fabricated on a silicon-on-insulator substrate (see Figure 1(b)). The waveguides then fan out to larger spacing for detector integration. The detector consists of a chain of detecting elements connected using 300-nm-wide delay lines. Each detecting element consists of 80-nm-wide, 5-nm-thick parallel NbN nanowires. Dielectric spacer and top metal ground are then fabricated on top of the nanowires to transform them into transmission lines with a group velocity less than $0.02c$ (c is the speed of light in vacuum). By injecting single or correlated photons into the PIC, we expect to map out the coincidence statistics efficiently using the integrated SNSPDs. This architecture may provide a viable solution for implementing a fully integrated large-scale photonic quantum processor.

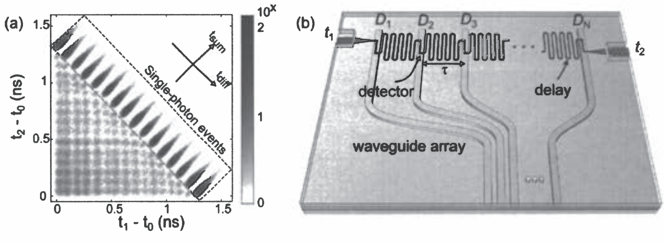

Figure 1: (a) Measurement result from a 16-element detector array (not integrated on waveguide). (b) Notional schematics of the delay-line-multiplexed SNSPD array on Si photonic integrated circuit.

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Broadband microfiber-coupled superconducting nanowire single-photon detector for visible and near-infrared light

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Superconducting nanowire single-photon detectors (SNSPDs) have enabled numerous experiments and applications, particularly in the fields of modern quantum optics and quantum communication. Two kinds of optical coupling methods have thus far been developed for SNSPDs: one produces standard fiber-coupled SNSPDs in which the photons vertically illuminate the meandered nanowires; the other produces waveguide-coupled SNSPDs in which nanowires are fabricated on the surface of a waveguide. A novel SNSPD coupled with microfiber (MF) was invented recently by placing MF atop superconducting NbN nanowires. The adiabatically tapered transmission from standard fiber to MF and evanescently photon absorption constitute a nearly lossless optical structure, indicating a potential high SDE characteristic of MF-coupled SNSPD. Previous work on MF-coupled SNSPD has shown system detection efficiency (SDE) of 20% at 1550 nm wavelength. In this work, we systematically analyzed the broadband property of MF-coupled SNSPD. By optimizing the diameter of the MF, the size of the NbN nanowires and the refractive index of the low-refractive-index adhesive used in the detector, our recent experimental results showed an unparallel broadband SDE over 30% from 532 nm to 1650 nm. The highest SDE reached 65% at 1250 nm and 40% SDE at 1550 nm wavelength. The characteristics of SDE dependence on the wavelength was proved to be consistent with the stimulation results.

Superconducting Nanowires: Progress and Promise

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Single-photon detectors are increasingly becoming an essential tool for a wide range of applications in physics, chemistry, biology, communications, medicine, and remote sensing. Ideally, a single photon detector generates a measurable signal only when a single photon is absorbed. Furthermore, the ideal detector would have 100% detection efficiency, no false positive (dark counts), and transform-limited timing resolution. There has been tremendous progress in the development of superconducting devices with nearly ideal performance. Recently, there has been significant effort to understand the fundamental limits in the performance of spackage superconducting nanowire detectors. There are also has been significant progress in packaging these detectors into systems that could be used in real-world applications. I will review the work presented in this workshop, and time-permitting discuss potential future possibilities.

Abstracts of Posters

(in alphabetical order)

High-Temperature Superconducting nano-meanders made by ion irradiation

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Superconducting nanowire single photon detectors (SNSPD) have shown unrivaled performances from telecommunication wavelength up to 10μm, including high quantum efficiency, high operating frequency, low dark count rate and small jitter[1]. Main SNSPD drawback is their operating temperature well below 4K since they are mostly made with low temperature superconducting thin films as Nb or NbN[2]. Indeed, they require complex cryogenics that limit technological applications. For this reason, it is desirable to implement such detectors using high temperature superconducting (HTS) materials. However this remains very challenging since superconducting properties in HTS thin films are very sensitive to nano-patterning process, generating oxygen out-diffusion and defects.

We will present the realization of 450μm-long, 30nm-thin and 100nm-wide CeO_2 capped $YBa_2Cu_3O_{7-x}$ nanowires[3] made by e-beam lithography and high-energy ion implantation[4-5]. DC measurements demonstrate that superconducting properties in nanowires, especially their critical current densities (j_C) and critical temperatures (T_C) are preserved compare to the raw YBCO thin-film. Large hysteresis in IV characteristic is a common feature of low-temperature SNSPDs which is a key requirement for hot-spot creation in SNSPDs. We recently reported hysteretic behavior in YBCO nanowires[3] that gives insight on the switching mechanism. The inductive part of the nanowires plays an important role in the reset dynamics of the detector, and might limit its detection rate. We studied the nanowire's inductance using a resonant method over a wide range of temperature up to T_C. The London penetration depth around 190nm extracted from the microwave measurement confirms that superconducting properties are conserved. Our ion irradiation technique paves the way for a suitable nanofabrication process of robust SNSPDs made of HTS materials.

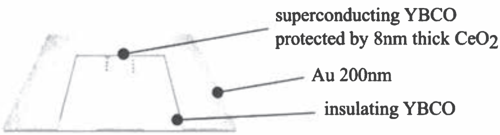

Figure 1 : Superconducting nanomeander embedded in a coplanar waveguide

Figure 2 : AFM picture of a nanomeander

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Superconducting Nanowire Single Photon Detectors with High Efficiency at High Count Rates and Low Jitter

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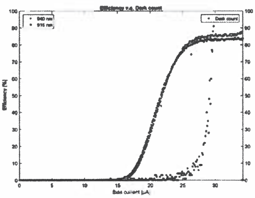
Superconducting nanowire single photon detectors (SNSPDs) are a fast developing technology [1]. Their unique merits of low timing jitter (<20 ps), short dead-time (<10 ns), high detection efficiency (>93 %) and broadband photon detection (UV-infrared) make them excellent candidates for various applications [2][3] like optical communication, laser ranging, and quantum information processing [4][5].

In this poster, we present a SNSPD working in strong saturation at 940 nm which shows count rates up to 80 MHz (limited by our laser) while maintaining > 85 % efficiency and a time jitter of 15 ps. To achieve these high numbers all at the same time special care was taken to design the shape of the superconducting meander, its substrate, and the electronics readout. To enhance absorption and hence the system efficiency, detectors were fabricated on a distributed Bragg-mirror. Saturated internal efficiency was achieved by patterning 70 nm wide meanders (filling factor of 0.5) on a 9-10 nm NbTiN film. Furthermore, a resistive network similar to [3] was used to guarantee a high detection efficiency at high count rate. Our device will enhance quantum optical experiments, high throughput optical communication for example in space communication, and remote sensing.



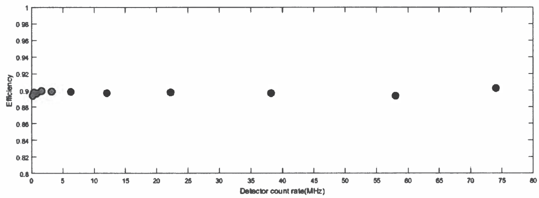


Fig. 1: Efficiency of a detector at 914/ 940nm. Fig. 2: Efficiency of a detector at different detection rate.

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Single-photon detection using suspended nano- and micro-scaled wires

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The use of superconducting-nanowire single photon detectors (SNSPDs) in the infrared spectral range is particularly of interest. However, reset time, efficiency, and possibly other parameters are likely strongly affected by thermal properties of the substrates. A variety of substrates have been used with nanowire detectors over the past years, but all provide a substantial thermal conduction path for the heat. To test the extreme case of near-zero heat removal into the substrate (so that all heat conducts along the wire instead), we have tested nanowire devices with the substrate entirely removed, i.e. a suspended nanowire.

In this work, we develop the technology of suspended superconducting nano- and microwires which allows the fabrication of nanowires in reproducible manner.

We systematically studied the thick NbN strips with widths from a few hundred nanometers to several microns. The detectors were optically characterized in the wide spectral range from optical to infrared wavelengths. Structures demonstrate saturation of detection efficiency under irradiation of photons with energy 0.8 eV.

A detailed analysis of the performance of suspended structures will be presented and the potential of suspended structures for different applications will be discussed.

A single-photon detector with NbN nanowire arrays and parallel readout

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Superconductor nanowire single photon detector (SNSPD)[1] with nanowires array and parallel readout is a powerful system, which not only inherited the merit of SNSPD, but also greatly improve the detection area and detection speed, and resolve the space, arriving time and the number of photon. These improved functions are of great significance in the applications of optical quantum computer, quantum communication, quantum imaging, astronomical exploration and so on. In this experiment, we proposed a SNSPD with 4 × 4 nanowire pixels array (as Figure 1) on Si_3N_4 buffer layer. The equivalent filling rate of detector is 98.5%. Assisted with light beam compression technology, the coupling fiber diameter is up to 300 μm and the system efficiency reached 60%. At the same time, the device can realize both photon number resolution and photon spatial resolution. The detected spatial distribution of light beam from multimode fiber and single-mode fiber is consistent with the theoretical prediction. A linear distribution between photon number and output pulse amplitude is observed, and the maximum number resolution of photon number is up to 16.

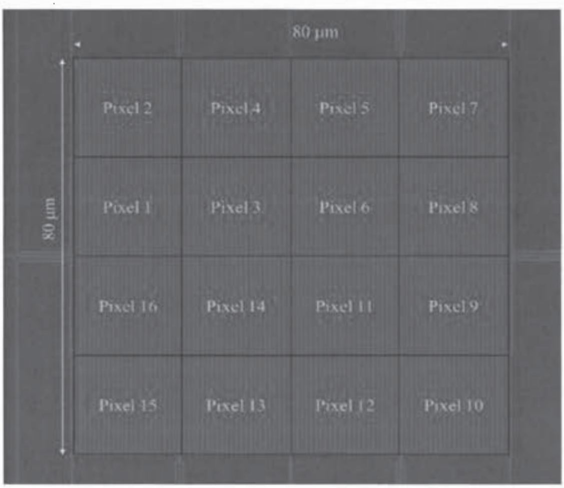

Figure 1: The SEM image of the 4×4 nanowires array

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Comparison of the detector properties between SNSPDs biased with microwave and direct currents

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SNSPD-arrays became very important for applications requiring fast and effective detection of photons with high spectral, energy and timing resolution. However, to reduce the resulting system complexity and heat load of large arrays a multiplexing technique is necessary. As a possible solution, we proposed the Radio-Frequency Superconducting Nanowire Single-Photon Detector (RF-SNSPD) [1], which enables frequency-division multiplexing of the detector responses and bias currents. The RF-SNSPD uses a conventional SNSPD with its high kinetic inductance per unit length embedded into a resonant circuit. Operated at its resonant frequency, the oscillating microwave current is used to bias the nanowire close to the critical current. In this highly nonlinear regime the absorption of a single-photon is sufficient to create a normal conducting domain across the nanowire, which immediately changes the quality factor of the resonant circuit. Using this approach, we demonstrated single-photon detection of a 16-pixel RF-SNSPD array operated with only one microwave feed-line connecting the room-temperature electronics with the detector array [2].

Multiplexing of bias currents becomes possible, because the operating point of the detector is set via an oscillating microwave current instead of a direct current. We have fabricated a hybrid device which can be operated in both operating points and will present a comparison of the spectral detection properties measured in both cases. In addition, we show that the oscillating bias current gates the detector at twice its frequency, resulting in a phase dependence of the measured count rates to a modulated light signal close to the resonance frequency. This effect will be demonstrated in a synchronous detection of an optical signal modulated by a GHz carrier frequency.

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Resolving SNSPD dynamics in cw-measurements

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It has been shown that by carefully choosing the applied bias current the necessary number of photons to trigger a detection event in a superconducting nanobridge can be tuned [1]. We demonstrate in purely continuous-wave measurements on similar structures the interaction of more than 10 photons in one detection event.

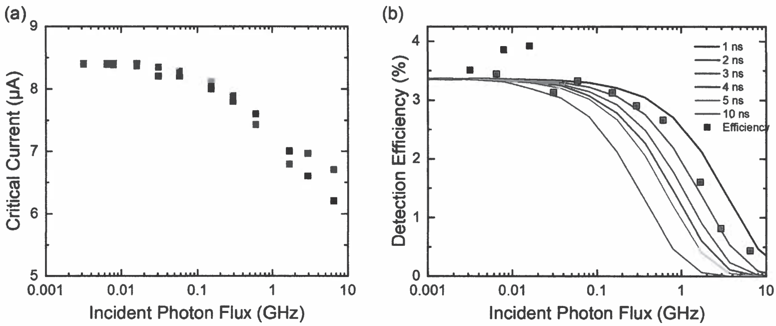

Figure 1: High photon flux behavior for an SNSPD of (a) the critical current and (b) the detection efficiency (black dots). Colored lines represent simulated detection efficiency for different SNSPD recovery times.

In similar measurements on large-area NbN SNSPDs on SiO_2 we demonstrate that one does not require fast electronical readout circuits or pump-probe-like excitation schemes [2] to resolve temporal dynamics. We are able to extract temporal coefficients from these cw measurements. At high photon fluxes both the critical current and the quantum efficiency of SNSPDs are reduced (fig. 1a and 1b). Here, the drop in bias current for the given recover due to an increasing dead time ratio. We use the bias current dependency of the detection efficiency to simulate the reduced detection efficiency of a photon event happening within the healing time of a previous event [2]. Fitting this simulation data for different electrical recovery times to the high photon flux measurement data reveals a recovery time of 2±0.5 ns for the $10x10\mu m^2$ SNSPD.

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Determination of the depairing current in superconducting nanowire single photon detectors

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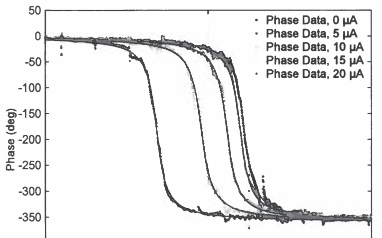
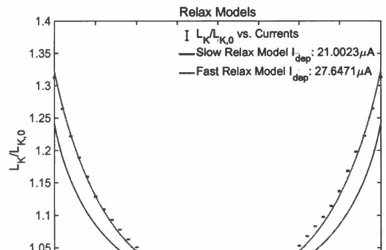
We estimate the depairing current of superconducting nanowire single-photon detectors[1] (SNSPDs) by studying the dependence of the kinetic inductance on the bias current. The kinetic inductance is determined by measuring the microwave resonance frequency of resonator-style nanowires[2]. Bias current dependent shifts in the measured resonant frequency correspond to a change in the kinetic inductance, which can be compared to theoretical predictions. We demonstrate that the fast relaxation model[3] described in the literature accurately matches the experimental data, as expected based on the short relaxation time of the superconductor compared to the resonant frequencies of the test devices. This method provides a valuable tool for directly determining the depairing current, since it minimizes reliance on externally measured values. Accurate measurement of the depairing current is extremely useful both for theoretically understanding the detection mechanism in SNSPDs and for estimating the quality of the nanowires and, ultimately, the yield of potentially large arrays. In this presentation, the quality of SNSPDs is analyzed at different temperatures, which is a critical aspect in designing higher-operating temperature SNSPD arrays interfaced with cryogenic CMOS (cryo-CMOS) readout. In this context, we present our progress in the integration of a scalable multi-channel cryo-CMOS front-end designed for large SNSPD arrays.





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Towards combining superconducting nanowires and silicon photonics

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Silicon photonics is a rapidly progressing technology that enables dense on-chip integration of advanced optical functions and systems suitable for low-cost mass production. In particular, the combination of silicon photonics with superconducting nanowire technology [1] can lead to compact single-photon sensors that have high efficiency, high speed, high timing resolution, and low dark count rates, paving the way for complex quantum optical computers and simulators [2,3]. Pursuing this combination is natural for VTT, as it already offers mature foundry-level services in both silicon photonics [4] and superconducting thin film technology [5].

As a first step towards this goal, we have fabricated and measured transport characteristics of narrow superconducting silicide nanowires. For these nanowires, the particular interest has been the dimension dependence of the superconducting properties, namely the fluctuation affected transport [6]. Recently we have also grown thin superconducting TiN films with atomic layer deposition. This technique enables highly accurate thickness control of the wires and excellent step-coverage on high aspect ratio structures. In order to ensure integration with silicon photonics, all the tested materials were chose to be compatible with the high temperatures typically required in silicon processes.

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Countermeasure against detector blinding attack in QKD using multi-pixel SNSPD

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In the recent years, interest in superconducting nanowires single photon detectors (SNSPDs) grew significantly. Their high detection efficiency, low jitter and low dark count rate makes them a promising technology for various applications domains requiring high performances single photon detectors like quantum key distribution. A recent experiment allowed the exchange of a secret key between two parties separated by up to more than 400 km of ultra-low loss fiber using MoSi SNSPDs [1]. However, these detectors (similarly to avalanche photo-diodes) can open loopholes in a QKD system allowing a malicious third party, Eve, to get some information on the exchanged key. Detector blinding attack is an attack where Eve tries to control Bob's detectors using bright light. In this way, she can measure the photons coming from Alice and reproduce her outcome on Bob's side introducing no error. The control of different kinds of SNSPDs have been demonstrated in Ref. [2].
As a countermeasure to this attack, we propose to use multi-pixel SNSPDs (MP-SNSPDs) as shown on Fig. 1. Each pixel is individually sensitive to the blinding attack. As shown on Fig. 2, Eve can control the click probability of each pixel. But, the four pixels being illuminated by a single fiber, we assume Eve has no possibility to target only one pixel at a time i.e. she cannot choose the click probability of each pixel independently. Under this assumption, the photon statistics of weak coherent pulses (WCP) will be disturbed by the blinding attack. Monitoring the statistics with MP-SNSPD can give Alice and Bob information on Eve's knowledge of the exchanged key.

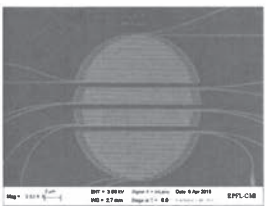

Figure 1 : SNSPD divided into four independent pixels.

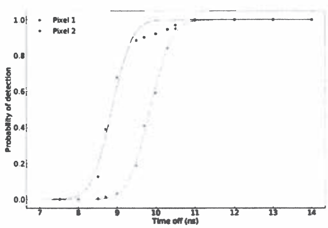

Figure 2 : Click probability of two pixels depending on the extinction time when Eve is doing the attack.

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Improvement of Time Correlated Single-Photon Counting with ultra-high time resolution

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Superconducting Nanowire Single Photon Detectors (SNSPDs) are sensitive, fast and low noise [1]. We propose the implementation of large-area SNSPDs coupled to multimode fibers. Optical coupling will benefit, but two major issues arise [3]: higher kinetic inductance affecting recovery time and a challenging fabrication process. Our approach is to characterize the new–generation detectors by measuring photons count-rate versus wavelength with diffraction grating based spectroscopy.

In addition, we aim at the development of a fully integrated setup for the characterization of Single Photon Sources (SPS) by means of Hanbury Brown-Twiss Interferometry (HBTI), Time-Resolved Photoluminescence Spectroscopy (TR-PL) and Entanglement measurements. The optimization of both measurement framework and system detection parameters (i.e. efficiency, spectral filtering and time jitter) will enable to resolve SPS properties with unprecedented resolution. Indeed, bad system jitter hinders the chance to resolve the dip in the second order correlation function g2(t=0) from an ideal SPS with perfect antibunching behavior as seen by convoluting its g2(t=0) with a Gaussian distributed error related to the system time resolution [2].

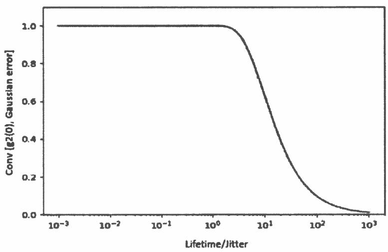

Figure 1 convolution between g2(t=0) and system jitter Gaussian distributed error.

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Intensity interferometry for the 21st century

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Intensity interferometry is a technique pioneered by Hanbury Brown and Twiss in the 1950s, which consists in inferring the diameter of a star by measuring the spatial intensity correlation function with two separated telescopes [1]. After impressive success in the 1960s-1970s [2], this technique was abandoned because of its poor sensitivity, in particular compared to direct ("amplitude") interferometry. However, intensity interferometry presents the important advantage to be much easier to implement. This fact, as well as the progress achieved in photon detectors and associated digital electronics, have sparked a renewed interest in intensity interferometry involving several research groups worldwide (see [3, 4] for recent reviews).

I will present the current status of our project towards the revival of intensity interferometry [5, 6], and I will discuss the technical requirements to push forward this method. In particular, superconducting nanowire single-photon detectors may well be the best technology for this application. Thanks to a very high quantum efficiency and a low timing jitter, the signal-to-noise ratio of the correlation measurement could be significantly improved compared to existing setups.

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Nanowire single-photon detectors made from atomic layer deposited NbN thin films

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Typically, Superconducting Nanowire Single-Photon Detectors (SNSPDs) are patterned from NbN thin films which have been deposited by sputtering technique. Sputtering suffers from poor thickness control and the need for high temperatures above 1100 K, making it hard to handle in wafer-scale processing.
Using atomic layer deposition (ALD) rather than sputtering for the deposition of NbN, precise thickness control and good film homogeneity over a large area can be achieved[1,2]. Other advantages of ALD include chemically saturated surfaces (and thus, in principle, thin films less prone to degradation) and the possibility to conformally cover also non-planar surfaces.
However, early investigations indicated reduced values of T_C and J_C compared to sputtered films, the latter being particularly critical for the application in SNSPDs.
In order to increase these values, the influence of various fabrication parameters has been investigated, including the substrate material and the ALD cycle number which directly corresponds to the film thickness.
A critical temperature, T_C, of 11.3 K and a critical current density, J_C, of 5.2 MA/cm^2 have been measured on a 100 nm-wide meandered nanowire with a total length of 110 µm and a film thickness of 10 nm. The obtained critical current density has been put into relation to the de-pairing critical-current density theoretically predicted by different models.
Other film properties like the electron-diffusion coefficient and Ginzburg-Landau coherence length were measured and have been taken into account to compare both deposition methods.
Finally, we report on the actual SNSPD characteristics such as count rate, dark-count rate, and timing jitter and their recent improvements by optimizing the ALD deposition and patterning parameters.

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Improvement of the critical temperature of NbTiN films on III-nitride substrates

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In this work, we study the impact of using III-nitride semiconductors (GaN, AlN) as substrates for ultrathin (11 nm) superconducting films of NbTiN deposited by reactive magnetron sputtering. The resulting NbTiN layers are (111)-oriented, fully relaxed, and they keep an epitaxial relation with the substrate. The higher critical superconducting temperature (Tc = 11.8 K) was obtained on AlN-on-sapphire, which was the substrate with smaller lattice mismatch with NbTiN. We attribute this improvement to a reduction of the NbTiN roughness, which appears associated to the relaxation of the lattice misfit with the substrate. On AlN-on-sapphire, superconducting nanowire single photon detectors (SNSPDs) were fabricated and tested, obtaining external quantum efficiencies that are in excellent agreement with theoretical calculations.
Keywords: NbTiN, superconductor, GaN, AlN, single photon detector.

Alternative designs for amorphous MoSi superconducting nanowire single-photon detectors

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Superconducting nanowire single-photon detectors (SNSPDs) [1] are a key technology for optical quantum information processing. Their low dark count rate, fast response time, small jitter, and high system detection efficiency (SDE) favors their use in various demanding quantum optics applications such as high-speed or long-distance quantum key distribution, quantum networking, device-independent quantum information processing and deep-space optical communication.

SNSPDs are subject to various limitations related to their design. Meander-based SNSPDs designs usually exhibit a polarization-dependent detection efficiency due to the geometry of the nanowire meander. The meander also impacts electronical parameters of the detector. Typically, the length of the wire limits the maximum count rate by creating a large kinetic inductance, and sharp meander turns locally increase the current density in the wire. This limits the maximum bias current used in the device through the switching current and/or the latching current.

In this poster, we will present alternate designs intended to study and overcome both optical and electronical limitations of SNSPDs in amorphous molybdenum silicide [2]. The influence of the nanowire geometry on the detector performances will be discussed. Solutions to improve the count rate, maximum biasing current, and reduce polarization dependence will be presented.

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Superconductor to resistive state switching by multiple fluctuation events in NbTiN SSPD

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The investigation of phase slip phenomena in quasi-2D superconductors has recently become a particularly interesting topic as the practical use of quasi-2D superconducting strips as single photon detectors (SSPD) has grown[1]. Murphy et al. reports quantum, thermal and multiple phase-slips events as generators of dark counts in SSPD made of NbN quasi-2D strips[2]. In this work, we investigate phase-slip events in 2D NbTiN strips, a material of great interest and widely used in SSPD applications due to its low dark counts rate[3]. We measure the switching current distributions in a range of temperatures from 4.2 K down to 0.3 K and observe that the standard deviations of switching distributions σ shows a non monotonous dependence on temperature and it exhibits an extended region of temperatures where multiple-phase-slip events occurs. In fact, for a typical NbTiN SSPD operation temperature, the dark counts are due to multiple-phase-slip events.
Furthermore, we find that the observed multiple coincident events switching can be explained by a single physical phenomenon.

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Initiative Towards Establishment of Single Photon Based Metrology For Quantum Information Sciences & Technologies

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CSIR-National Physical Laboratory (CSIR-NPL) is the custodian of "National Standards" by act of Parliament with a responsibility of the dissemination of traceability to the country and perform routinely International inter-comparisons for establishing measurement equivalence with leading NMIs of the world. The lab recently initiated R&D activities on superconducting nanowires based single photon detector (SNSPD) due to its potential in variety of applications which includes quantum key distribution (QKD), optical quantum computing, imaging of infrared photoemission for defect analysis in CMOS circuitry, LIDAR, on-chip quantum optics etc. Quantum optical information processing technologies in particular, require fast single photon detectors with improved detector performance in terms of its figure of merit at telecom wavelength range.

CSIR-NPL is currently engaged in developing necessary expertise for fabrication, testing and evaluation of superconducting nanowires and designing of visible and infrared photon detectors. The Initiative towards this direction however, ultimately aims to establish single photon detection based quantum metrology infrastructure for assisting standardizations in the field of quantum information sciences & technologies.

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Superconductivity in the presence of microwaves: Full phase diagram

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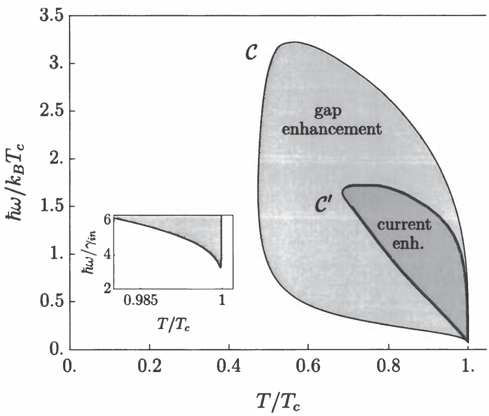
We address the problem of non-equilibrium superconductivity in the presence of microwave irradiation. Using contemporary analytical methods, we refine the old Eliashberg theory and generalize it to arbitrary temperatures T and frequencies ω. Microwave radiation is shown to stimulate superconductivity in a bounded region in the (ω, T) plane. In particular, for $T < 0.47\ T_c$ and for $\omega > 3.3$ Tc superconductivity is always suppressed by a weak *ac* driving. We also study the supercurrent in the presence of microwave irradiation and establish the criterion for the critical current enhancement. Our results can be qualitatively interpreted in terms of the interplay between the kinetic ("stimulation" vs. "heating") and spectral ("depairing") effects of the microwaves.



Phase diagram of a superconductor under weak microwave driving at the frequency ω (the inelastic relaxation rate γ_{in}/T_c = 0.02). Gap enhancement is observed inside the curve C. The region of the critical current enhancement is bounded by the curve C'. Inset: zoom of the gap enhancement region near T_c, showing the minimal frequency $\omega_{min,min} = 3.23\ \gamma_{in}$.

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A testbed for mid infrared single photon detection with SNSPDs

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Superconducting nanowire single photon detectors (SNSPDs) exhibit high detection efficiencies, low dark count rates, high maximum count rates and low timing jitter making them an ideal choice for high sensitivity photon detection applications such as quantum key distribution, space-to-ground communication and single photon remote sensing [1]. A key area of research in SNSPDs is enhancing their efficiency into the mid infrared. Sensitivity has been shown for wavelengths up to 5000nm [2] and there is growing interest in applications such as remote sensing of greenhouse gas in the atmosphere [3] which require efficient detectors at these longer wavelengths.

Our work here focuses on construction of a mid infrared testbed for development and characterisation of these new detectors. We generate sub-ps pulses of mid infrared photons at wavelengths up to 4200nm wavelengths using an optical parametric oscillator (OPO) from Chromacity Ltd. This photon source is then attenuated down to single photon level in free space before being fibre coupled and delivered to the input of a cryostat operating at 350mK. Blackbody radiation from components at room temperature coupling into the fibre is a challenge for detectors operating in the mid infrared so we have deployed a cold filtering setup within the cryostat to ensure this unwanted radiation is kept to a minimum.

We demonstrate this setup using niobium titanium nitride (NbTiN) detectors with integrated optical cavity optimised to enhance detection at 2300nm and achieve a timing jitter of <90ps FWHM. We are now carrying out fully calibrated detection efficiency measurements. Our testbed will allow exploration of novel detector design in a variety of superconducting materials and allow us to compare and evaluate the performance of these new detectors. It is hoped that this will lead to development of an efficient and fast detector for use in mid infrared photon counting applications such as single photon LIDAR.

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High Coupling Efficiency into Lithium Niobate Waveguides at Cryogenic Temperatures

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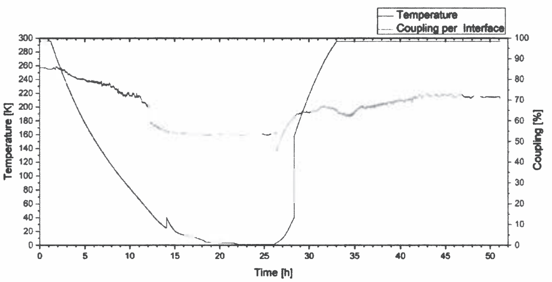
Lithium niobate is an important platform for integrated optics given its high second-order nonlinearity and electro-optic properties [1]. In this material are high-speed electro-optic modulation and polarization conversion even at cryogenic temperatures realizable. Superconducting detectors and other quantum optic devices are operated at cryogenic temperatures [2]. For the characterization and stable operation of these devices is the coupling efficiency from an outside source into the device an important figure of merit [3].

In this work are titanium in-diffused lithium niobate waveguides pigtailed with single mode fibres. The theoretical maximal coupling efficiency from fibre to waveguide is around 93% which is calculated by the mode overlap. In this developed method were mode overlaps of up to 85% at room temperature and 55% at cryogenic temperatures realized. The mode overlap of pigtailed samples were calculated by subtracting the system losses from the total through coupling and averaging over the device surfaces.

The coupling stability was achieved by building customized ferrules which support the fibre at the coupling surface. These ferrules are made of the same base material as the waveguides in order to match the thermal expansion coefficient. This work enables the development of modular cryogenic compatible components that can be readily interpreted into existing fibre-based optic networks.



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Singlet oxygen luminescence detection with SNSPDs

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The detection of a single photon at 1270 nm wavelength allows the direct monitoring of Singlet Oxygen ($^1O_2$), an excited state of the oxygen molecule central to biological and physiological processes. Singlet Oxygen Luminescence Dosimetry (SOLD) is a powerful direct monitoring technique for photodynamic therapy in the treatment of cancer [1]. However, the direct detection of $^1O_2$ emission at 1270 nm wavelength is extremely challenging as the $^1O_2 \rightarrow {}^3O_2$ transition in biological media has very low probability and short lifetime due to high reactivity of singlet oxygen with biomolecules. Recent advances in high efficiency infrared single photon detectors such as the Superconducting Nanowire Single Photon Detector (SNSPD), are important innovations in the development of a practical SOLD system for eventual clinical use [2, 3]. Here we present a compact fiber coupled SOLD system, using a supercontinuum pump source to precisely target exact photosensitizer absorption peak wavelengths and a SNSPD for detection (Figure 1a) [4]. Both pump laser and SNSPD detector are intrinsically fiber coupled making them ideally suited for the development of practical singlet oxygen sensor head (Figure 1b).

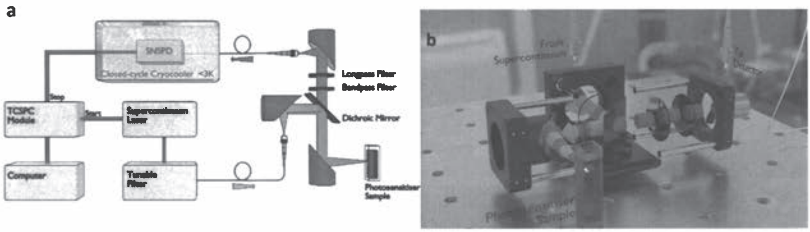

Figure 1: a) Block diagram of the experimental setup implementing a supercontinuum laser source and SNSPD, b) Schematic of the singlet oxygen sensor head.

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Bolometric Response of Ultra-Thin High-T_c Superconducting Nanowires on Transparent Substrate

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Low temperature superconductors have shown outstanding potential for realizing efficient single-photon detection at ultra-low noise levels with high timing accuracy [1]. Most state-of-the art superconducting single-photon detectors (SNSPDs) rely on NbN, NbTiN or WSi nanowires either as stand-alone units with an optical fiber interface or as waveguide-integrated devices. Despite their attractive performance characteristics such low-Tc SNSPDs require cryogenic environments for operation at temperatures below 4K. Employing high-Tc superconductors instead would alleviate the refrigeration conditions, e.g. to liquid nitrogen cooling, and thus significantly broadens the application space of SNSPDs. The photo-response of high-Tc material systems further promises new insights into the superconducting dynamics underlying the detection process. Here we show progress towards the realization of high-Tc bolometers fabricated from ultra-thin yttrium barium copper oxide (YBCO) films on a strontium titanate (STO) substrate (Figure 1), which is well suited as a wave-guiding material [2]. We employ focused ion beam milling for the fabrication of high-quality YBCO nanowires [3] with effective width down to 40 nm and critical current densities of above 64 MA/cm^2 (4 K). As a first step the bolometric response at liquid nitrogen temperatures was shown with nanowire responsivities of 104 mV/W. The electrical characterization of nanowires at 4 K reveals complex vortex dynamics that result in hysteretic voltage switching (Figure 2), which forms the basis of the single-photon detection mechanism. Recent experimental [4] and theoretical [5] studies suggest that single photon detection is indeed possible in high-Tc nanowires if they can be biased close to the depairing current, thus opening interesting prospects for future work on integrated YBCO-SNSPDs.

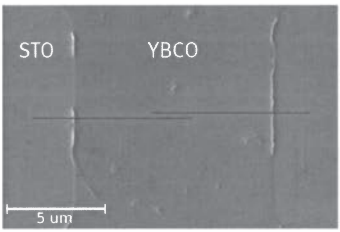

Figure 1: Colorized scanning electron micrograph after FIB milling a 8 nm thin YBCO film sample (purple) on STO substrate (green).

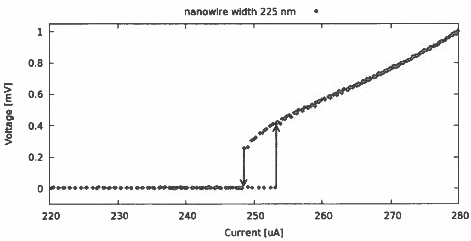

Figure 2: I-V-characteristic of a YBCO nanowire of thickness 4.5 nm.

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SNSPDs for space observatories from the UV to the mid-IR: opportunities and challenges

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In preparation for the 2020 Astrophysics Decadal Survey, four possible mission concepts are currently being studied for a NASA-led space observatory to follow the James Webb Space Telescope (JWST) and the Wide-Field Infrared Survey Telescope (WFIRST). The science goals of this next generation of large-class space telescopes will ultimately be limited by detector performance, and so gaps in detector technology are currently being identified. For two of the proposed mission concepts, the Large Ultraviolet, Optical, and Infrared surveyor (LUVOIR) and the infrared Origins Space Telescope (OST), SNSPDs can provide considerable advantages over conventional detectors due to their ultra-low intrinsic dark count rates, high detection efficiency, high dynamic range, and flexible optical design. For space observatories, flying a cryocooler for superconducting detectors requires an increase in cost and risk, but such systems are a possibility for large-class missions, and there are existing cryocoolers with flight heritage. ESA's Herschel and Planck observatories included cryogenic systems operating at 300 mK and at 100 mK, and NASA's JWST has an instrument operating at 7 K. Additionally, the OST mission concept already includes a cooled telescope and energy-resolving superconducting detectors operating at 100 mK.

In the past several years, advances have been made towards optimizing SNSPDs for ultraviolet and infrared wavelengths as well as in scaling SNSPD arrays to larger formats. However, considerable development is necessary before SNSPD arrays can meet all the detector requirements of these large-scale missions. In this presentation, I will discuss the properties of SNSPDs that make them well-suited for use in future space observatories, focusing on mid-infrared detectors for the OST mission concept and ultraviolet detectors for LUVOIR. I will also cover the unique challenges of using SNSPDs for astrophysics applications that will need to be addressed before SNSPDs can be considered for one of these missions and provide a potential roadmap for detector development.

Deposition of NbTiN superconducting thin films on a wide variety of substrates, and the influence of the Nb/Ti ratio on their critical temperature and critical current densities

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The invention[1] and development of superconducting nanowires single photon detectors (SSPDs) opened the way to high efficiency detection of single photons in the infra-red, with low noise level and high time resolution.

Alongside Niobium Nitride NbN, which has been used and widely investigated by the pioneers of SSPDs, different materials have been tested in order to achieve the best single photon detectors. Amorphous materials have shown to be a material family allowing for easy deposition on a wide variety of substrates, and opening the way for high detection efficiency[2]. However, these materials offer somewhat limited capabilities in term of time resolution.

Our group has been focusing on a material similar to NbN, with Niobium Titanium Nitride NbTiN. This material offers the possibility to reach high detection efficiency (up to 94% system detection efficiency at 1550 nm), low noise (down to < 0.1 Hz), high count rates (over 150 MHz) without sacrificing the time resolution (timing jitter < 10 ps)[3] of the detector.

In this poster we show our recent progress characterisation of NbTiN and on its deposition on a wide range of substrates. The deposition with reactive magnetron co-sputtering from two separate targets of Nb and Ti allows us to tune and optimise the composition of the films. Furthermore, we show the systematic study of the Nb/Ti ratio influence on the critical temperature of the films and on the critical current densities obtained for detectors made from these films.

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Fractal superconducting nanowire single-photon detectors with reduced polarization sensitivity

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We demonstrated a fractal superconducting nanowire single-photon detector, achieved the maximum device efficiency of 67%, and reduced the polarization sensitivity down to 1.1. We used the space-filling fractal curves as the geometries for the SNSPDs [1]. In the context of polarization-insensitive SNSPDs, a major advantage of the fractal SNSPDs is that the reduced polarization sensitivity could be maintained for high-order spatial modes of multi-mode optical fibers, for example, TE_{01} and TM_{01} modes.

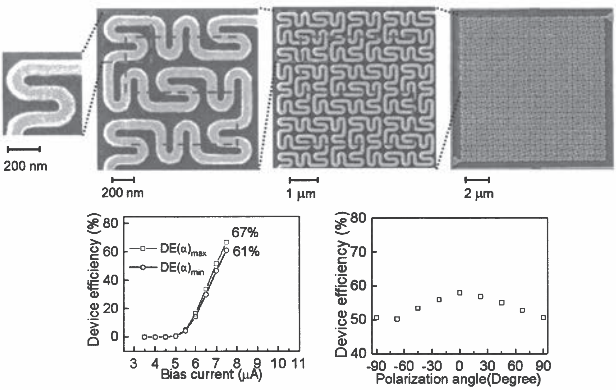

Figure 1: Device structure of the fractal superconducting nanowire single-photon detector and its device efficiency and polarization dependence.

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