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Superconducting nanowire single-photon detectors: A perspective on evolution, state-of-the-art, future developments, and applications

Special Collection: Non-Classical Light Emitters and Single-Photon Detectors

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ABSTRACT

Two decades after their demonstration, superconducting nanowire single-photon detectors (SNSPDs) have become indispensable tools for quantum photonics as well as for many other photon-starved applications. This invention has not only led to a burgeoning academic field with a wide range of applications but also triggered industrial efforts. Current state-of-the-art SNSPDs combine near-unity detection efficiency over a wide spectral range, low dark counts, short dead times, and picosecond time resolution. The present perspective discusses important milestones and progress of SNSPDs research, emerging applications, and future challenges and gives an outlook on technological developments required to bring SNSPDs to the next level: a photon-counting, fast time-tagging imaging, and multi-pixel technology that is also compatible with quantum photonic integrated circuits.

I. INTRODUCTION

A. Single-photon detection and the emergence of SNSPDs

Technologies operating at the single-photon level, the quantum of the electromagnetic field,[1] are crucial for communication, sensing, and computation.[2,3] Photons can encode information using different degrees of freedom including polarization, momentum, number state, energy, and time. For instance, quantum key distribution (QKD) was demonstrated over a distance exceeding 4600 km,[4] potentially forming the backbone of a quantum internet.[5] As crucial as the single-photon carriers, are the high-performance single-photon detectors to perform measurements on the quantum bits. They were instrumental in recent demonstration of large-scale Boson sampling,[6] showing a computational advantage over conventional supercomputers. Furthermore, in a number of other fields including bio-imaging, light detection and ranging (LiDAR),[7–9] optical time domain reflectometry (OTDR),[10,11] single-molecule detection,[12] semiconductor circuits inspection,[13] star light correlation spectroscopy,[14] diffuse optical tomography,[15] positron emission tomography (PET),[16] mass spectroscopy, and quantum metrology measurements,[17] single-photon/particle detectors are essential. For these applications, tremendous efforts have been made to produce single-photon detectors combining near unity system detection efficiencies (SDEs), low dark count rates (DCRs), short timing jitters, high maximum count rates, photon number resolution capabilities, and large active areas.

Single-photon avalanche diode (SPAD)[18,19] and photomultiplier tubes (PMTs)[20,21] were first used to detect single photons. However, combining high detection efficiency with high time-resolution and low noise in SPADs and PMTs remains a challenge. In addition, a limited spectral response (limited at 1100 nm for silicon) and afterpulsing further limit their use for quantum technologies. With two decades of development since their inception,[22] superconducting nanowire single-photon detectors (SNSPDs) offer unrivaled detection metrics with an unprecedented combination of performance, for a comparison of SPADs and PMTs with SNSPDs, see Ref. 23.

B. A brief history of SNSPDs development

Before the inception and maturity of SNSPDs, other superconducting devices such as Josephson-junctions,[24] superconducting quantum interference devices (SQUIDs),[25] hot electron bolometers,[26,27] and transition edge sensors (TESs)[28–30] already achieved high performances. The first demonstration of single-photon detection with current-biased superconducting microbridges was reported in 2001 at a wavelength of 0.81 μm.[22] The field of SNSPDs then underwent fast development and was driven by applications' requirements. In 2002, meandering nanowires were introduced to increase the active area.[31] In 2003, the first commercial use of SNSPD, for integrated circuit fault testing, was reported.[32] A key driver pushing SNSPD early development was quantum key distribution (QKD) that made commercialization viable. The first SNSPD based QKD was reported in 2006[33] and was followed by a world record 200 km QKD experiment[34] doubling the previous distance achieved with InGaAs SPADs and matched the loss threshold for space to ground QKD of 40 dB. Soon after these pioneering works, fiber-coupled SNSPDs reached a detection efficiency of 24% at 1550 nm (Ref. 35) and were further improved to 47% with antenna structures.[36] Optical cavities were integrated with SNSPDs to boost the detection efficiency to 57% at 1550 nm.[37] In 2012, by stacking two WSi SNSPDs and connecting them in parallel, the system detection efficiency (SDE) was improved to over 87%.[38] Another important development in 2011 and 2012 was the integration of SNSPDs with photonic waveguides,[39,40] which made high on-chip detection efficiency possible and delivered a key element to the toolbox of integrated quantum photonics (see Sec. III A). In 2013, WSi SNSPDs in an integrated cavity reached an SDE of 93% at 1550 nm,[41] 92%–93% SDE was subsequently demonstrated with other material platforms.[42,43] In 2020, three independent groups reported > 98% SDE based on three different material systems: MoSi with distributed Bragg reflectors,[44] dual-layer NbN meanders,[45] and NbTiN with a membrane cavity.[46]

Aside from a high detection efficiency, detectors with low dark count rates, i.e., undesired detection events generated without illumination or due to black-body radiation, are vital in many photon-starved applications. Early works[47] showed intrinsic dark counts to originate from vortices crossing the nanowire cross section, which may be triggered by thermal fluctuations or current-assisted unbinding of vortex-antivortex pairs.[48] Additionally, black-body radiation can be a major source of dark counts, especially for large area SNSPDs and particularly at longer wavelengths.[49] To suppress black-body induced dark counts, cold filters[50] or fibers with end-face coatings can be used.[51] It has also been shown that the dark count rate increases under illumination due to the suppression of switching current by incident light.[52] As of 2021, a dark count rate as low as 10^{-4} per second has been demonstrated,[50,53] further studies are required to determine the origin of the remaining dark counts.

High time resolution is one of the distinctive advantages of SNSPDs. Time jitter represents the time interval statistics between photons impinging the detector and the generation of the electrical detection signal. Early experimental works[54,55] showed that in addition to time jitter of the detector itself (briefly discussed in Sec. I C), several other experimental parameters such as electrical noise, fiber dispersion, and the accuracy of laser synchronization signals all contribute to the overall system time jitter. Experimentally, in 2006 a sub-30 ps time jitter was demonstrated by making SNSPDs from a 4 nm-thick NbN film.[56] In 2016, a timing jitter of 17.8 ps was achieved using an ultrafast time-correlated single-photon counting setup.[57] In 2017, by employing a cryogenic amplifier, a 14.8 ps jitter was demonstrated[42] with NbTiN SNSPDs. In the same year, by optimizing the experimental measurement setup, a 12 ps timing jitter was demonstrated with NbN SNSPDs.[58] Recently, the fiber-coupled SNSPD's timing jitter was pushed down to 7.7 ps.[59] As of April 2021, the best reported time jitter belongs to short straight nanowires and is <3 ps for NbN[60] and 4.8 ps for WSi.[61]

C. Understanding SNSPDs' performance optimization and trade-offs

To date, the theoretical understanding of the exact detection mechanism in SNSPDs is still under development. We discuss some of the leading models in Sec. II A. Here, we briefly hint at some basic observations to discuss the operation limits of SNSPDs.

Generally speaking, the detection efficiency of a SNSPD is influenced by two parameters: its optical absorption, i.e., what fraction of photons incident on the SNSPD is absorbed in the detector and the internal efficiency, the probability that an absorbed photon generates a measurable detection event. Small constrictions along the nanowires (due to nano-fabrication and/or variation in the superconducting film) were shown to be one limiting factor for the critical current as well as for the internal detection efficiency.[62,63] It was also demonstrated that bends in a meandering nanowire can lead to a noticeable reduction of the critical current as shown in Refs. 64–66; this current crowding issue can be addressed by optimizing the bend geometry[67] or with spiral SNSPDs.[68] As for the absorption efficiency, the optical absorption of typical superconductors used for SNSPD fabrication has been studied,[69] and the polarization dependence of SDE and nanowire designs (fill factor, linewidth, and device size) are well-understood and comprehensively discussed in Refs. 70 and 71. To minimize polarization dependence, three-dimensional architecture,[38] near-field optics,[72] dielectric capping layers,[73] or fractal-shape nanowires[74,75] were demonstrated.

The operation temperature dependence of SNSPDs is, at least experimentally, well understood: If the internal detection efficiency at a specific temperature and for a specific photon energy is unsaturated (no plateau in the detection rate vs bias current curve), the detection efficiency reduces as the temperature increases. Additionally, both intrinsic and blackbody induced dark counts are temperature dependent.[76] The former, independent of the applicable model or exact origin of DCR, is due to the fact that potential barriers (for example, for vortex crossing or vortex-antivortex depairing) or electron/photon interaction time constants are all temperature dependent. The intrinsic darkcount, for a fixed bias to switching current ratio, often increases with higher temperature. Extrinsic darkcount may decrease with temperature as the detection efficiency for photons (for example, long wavelength blackbody photons) is reduced as the temperature increases.[76] Therefore, in a system in which blackbody radiation is well filtered out, the signal to noise ratio (SNR) often decreases as the temperature is increased.

The timing properties of SNSPDs (recovery time and time jitter) have been thoroughly studied: Early on, the recovery time of NbN SNSPDs was found to be limited by their kinetic inductance,[77] revealing an intrinsic trade-off between large-area devices and fast recovery times. A more systematic electro-thermal model[78] was presented to better explain the detection dynamics with a practical solution to shorten recovery time by adding a resistor in series to SNSPDs. However, in the same work, it was demonstrated that there is a limit to reducing SNSPDs recovery times, this limit is dictated by electro-thermal feedback and hence depends on the substrate material, on the superconductor, temperature, bias, critical current, as well as on the SNSPD's kinetic inductance. While detectors with very fast electrical recovery time (<1 ns) have been demonstrated, it has also been shown that the electrical recovery time (extracted from the pulse traces) is not necessarily the same as the detector recovery time.[79] Alternatively, multi-pixel[56] and multi-element structures[80] were proposed and demonstrated to increase the active area without sacrificing time performance and even offering photon number resolution prospects.[81]

Since SNSPDs typically cover areas of hundreds of square micrometers and the electrical signal propagates through the detector with finite speed, photons detected at different locations generate detection pulses that reach the readout circuit at different times, leading to a geometrical jitter.[82] In 2017,[83] the influence of Fano fluctuations on timing jitter was also reported. In the same year, timing jitter caused by distributed electronic and geometric inhomogeneity of a superconducting nanowire[84] was analyzed. Also, vortex-crossing-induced jitter was systematically studied, and the theoretical limit of SNSPDs' intrinsic timing jitter was estimated to be around 1 ps.[85] Another study, based on the two-temperature model coupled with the modified time-dependent Ginzburg–Landau equation,[86] argued that photon absorption location on a current-carrying superconducting strip has direct influence on the minimal achievable time jitter. The minimum jitter was shown to depend on the critical temperature of the superconducting film. This was calculated to be of the order 0.8 ps for a nanowire with a width of 130 nm made from a typical NbN superconducting films with a critical temperature of 10 K. Narrower nanowires can potentially improve the minimum achievable jitter. If no other fundamental limitation for time jitter is discovered, ultimately, the time jitter would be limited by the dynamics of suppression of superconductivity (pair breaking) which depends on material, temperature, and the optical excitation density.[87]

D. Scope and content of this perspective

After summarizing the history and development of SNSPDs over the past two decades, we highlight the leading theories to explain the operation mechanism and provide the status quo and state-of-the-art in SNSPD technology (Sec. II). A selected number of current and potential future applications are discussed in Sec. III. Finally, we provide an outlook for future development (Sec. IV). For a more in-depth and technical review of SNSPD's working principle, intrinsic limitations, and design solutions, we refer the readers to Ref. 88.

II. SNSPD DETECTION MECHANISMS AND STATE-OF-THE-ART

A. SNSPD detection mechanisms

This section gives an overview of the leading physical models of the detection mechanisms in SNSPDs, providing a qualitative description to understand basic working principles and device physics. We consider the most common SNSPD implementation, based on a superconducting nanowire (width 50–100 nm) patterned from a thin film (thickness 5–10 nm) using a top-down nanofabrication process. The nanowire, often designed as a meandering structure, is "DC-biased" close to the device's critical current via a bias tee, and low noise amplifiers and counting electronics are used to detect single-photon events and register corresponding voltage pulses. A phenomenological model of the detection process was proposed in the initial reports on SNSPDs[22,89] and has been revised in the following two decades. To allow for quantitative modeling and design optimizations, the detection process[90] was divided into subsequent steps (see Fig. 1): (I) photon absorption; (II) creation of quasiparticles and phonons combined with their diffusion; (III) emergence of a non-superconducting nanowire segment; (IV) re-direction of bias current in readout circuitry, leading to a voltage pulse; and (V) detector recovery.

(I) The initial absorption of a single photon within the active detector area is well described by a classical electromagnetic theory. This allows for the use of established modeling tools[92] to optimize optical absorption in the superconducting layer for a desired wavelength range. The absorption of a visible or near-infrared photon results in (II) the formation and expansion of a cloud of quasiparticles, which is initiated by the relaxation of the photo-excited electron and followed by the creation, multiplication, and diffusion of quasiparticles and phonons. These processes are governed by electron-electron, electron-phonon, as well as phonon-phonon interactions and their characteristic timescales,[93] whereas the diffusion constants as well as the ratio of the heat capacities of electrons and phonons are crucial for the spatiotemporal relaxation dynamics. This downconversion process is modeled through deterministic kinetic equations for electrons and phonons[94] or through a stochastic loss of excitation energy into the

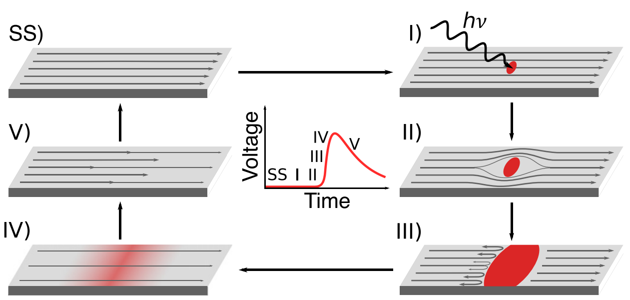

FIG. 1. Macroscopic explanation of the detection mechanism (based on Refs. 22, 78, and 89). In the steady state (SS), the superconducting thin-film strip is current biased. Photon absorption (I) leads to the creation of quasi-particles and phonons (II). This leads to the formation of a normal-conducting part of the strip (III). Redirection of the current toward the readout electronics allows a recovery of the superconducting state (IV), which leads to a return of the current (V) to its initial value. This reset dynamics is limited by the kinetic inductance of the device. Center: The voltage readout signal with each step labeled. Adapted with permission from Allmaras *et al.*, Nano Lett. **20**, 2163–2168 (2020). Copyright 2020 American Chemical Society.[91]

substrate.[83] An instability of the superconducting state emerges due to the quasiparticle cloud, linked with a local reduction of the superconducting order parameter, re-distribution of the current density, and lowering of the effective critical current density. Combining ideas from deterministic and stochastic models allows to describe a complete set of measurements qualitatively,[95,96] but these existing models require further developments to be able to fully describe the physical processes quantitatively. This instability can lead to a photon detection event, associated with (III) parts of the nanowire transitioning to a non-superconducting state. Following initial descriptions relying on a normal-conducting "hotspot," models of the SNSPD detection mechanism have been refined, underlining the importance of magnetic vortices.[47,97,98] For further details on the mechanisms governing the local emergence of a non-superconducting segment of the detector area, we refer to Engel *et al.*[90] Subsequently, the resistive region of the nanowire grows due to internal Joule heating.[78] The increasing resistance, on the order of several kΩ,[78] leads to (IV) the re-direction of the bias current from the nanowire toward the readout electronics. The circuit behavior can be described using lumped element models[99,100] or planar microwave simulations. Once the resistive area has sufficiently cooled down, (V) superconductivity is restored and the current flowing through the nanowire returns to its initial value, whereas the dynamics are governed by the kinetic inductance of the device.[77,78] In cases where the resistive domain does not cooldown rapidly enough, the detector latches due to thermal runaway and no further photons can be detected until the device is actively reset.[101]

While models for step (I), (IV), and (V) can be used to predict and develop successful designs, models for step (II) and (III) are missing such capabilities. The fluctuations beyond the initial downconversion cascade, the non-equilibrium state of electron-phonon baths, and the missing element of intrinsic dark counts are examples for open problems and challenges for the future.

B. State-of-the-art SNSPDs

In the section below, we discuss advances with regard to the superconducting materials used for production of SNSPDs, nanofabrication, multi-pixel detectors, the nano- and micro-wire SNSPDs, wavelength range, state-of-the-art performance, and characterization of SNSPDs that has led to detectors with > 98% SDE.[44,46,102]

1. Superconducting materials and nano-fabrication of SNSPDs

SNSPDs have been made out of dozens of superconductors. The material selection for the superconducting film can be based on various factors, but the motivations for specific choices can mainly be divided into two groups: optical properties such as absorption at different wavelengths and superconducting properties such as critical temperature and critical current density. In practice, other parameters may also be taken into account, for example, for photons with higher energy the use of higher critical temperature superconductors might be preferred to simplify the cryo-cooling system while for mid-infrared detectors (beyond 2–3 μm), low-gap amorphous superconductors such as MoSi and WSi have so far been the main option. In Table I, we present an overview of some leading results based on different superconducting materials. In addition to the highlighted superconducting materials in Table I, another important class of superconducting materials that have been subject of research are the high Tc superconductors. High-Tc SNSPDs are a topic of long-standing discussions with reports of dark counts[103] and signatures of single-photon operation[104] on the one hand and skepticism[105] on the other hand. Therefore, further studies are required to understand the limits and potentially unlock the use of these promising platforms.

Production of high performance SNSPDs involves various nanofabrication technologies. Starting from a commercial substrate (typically silicon), the first fabrication step involves the deposition of a distributed Bragg reflector to enhance the optical absorption. (Metal based reflectors are also possible[42,46] but less common and nanoantennas can also be integrated[117,118] to enhance optical absorption.) A superconducting thin film (typically 4–10 nm) is then deposited on top of the mirror layer. The electrical contacts are formed by means of optical or e-beam lithography, metal deposition (evaporation or sputtering), and liftoff. The nanowire detector can be formed using a single

TABLE I. Overview of some SNSPD leading works on different material platforms.

Material	Efficiency/time jitter	Temperature	Wavelength
NbN (Refs. 43 and 45)	92%–98.2%/40–106.1 ps	0.8–2.1 K	1550–1590 nm[a]
NbTiN (Refs. 42 and 46)	92%–99.5%/14.8–34 ps	2.5–2.8 K	1290–1500 nm[b]
WSi (Refs. 41 and 44)	93%–98%/150 ps	120 mK–< 2 K[c]	1550 nm
MoGe (Ref. 106)	20%/69–187 ps	250 mk–2.5 K	1550 nm
MoRe (Ref. 107)	—/—	9.7 K	—
MoSi (Refs. 108–110)	80%–87% /26–76 ps	0.8–1.2 K[d]	1550 nm
NbRe (Ref. 111)	—/35 ps	2.8 K	500–1550 nm
NbTiN (Ref. 76)	15%–82% /30–70 ps	2.5–6.2 K	400–1550 nm
NbSi (Ref. 112)	—/—	300 mK	1100–1900 nm
TaN (Ref. 113)	—/—	0.6–2 K	600–1700 nm
MgB_2 (Refs. 114–116)	—/—	3–5 K	Visible

[a]Optimal performance at < 1 K while an SDE of 90%–95% was achieved at 2.1 K. Time jitter depends on temperature and design. Errobar for 98.2% efficiency was ±1%.
[b]Errorbar for 99.5% efficiency was (−2.07, +0.5)%.
[c]Operation up to ~2 K possible at the cost of higher time jitter,[41] temperature and jitter measurements are not mentioned in Ref. 44. Errorbar for efficiency measurements was ±0.5%.
[d]In Ref. 109, an operating temperature of 2.3 K was demonstrated with added cost of higher time jitter and lower internal efficiency saturation.

electron-beam lithography step followed by reactive ion etching. For detector packaging and to achieve stable and efficient operation, coupling to an optical fiber is crucial, which is typically done with self-aligned schemes requiring additional lithographic steps combined with deep etching of the substrate (micro-machining using a Bosch process). The complete process is illustrated in Fig. 2.

Deposition of the superconducting layer is a crucial step, and its quality has a direct impact on the detector performance. This is typically performed by magnetron sputtering and can yield nanocrystalline or amorphous layers. Excellent deposition uniformity and nanofabrication processes are required to ensure manufacturing of devices with reproducible and consistent superconducting properties. In this regard, amorphous materials such as WSi and MoSi as well as optimized crystalline films with relatively larger thicknesses (8–12 nm)[59,119] are considered more forgiving and thus favorable for high-yield detector fabrication. In addition, plasma-enhanced atomic layer deposition[120,121] and single-crystalline molecular beam epitaxy[122] growth of NbN were recently demonstrated as viable and potentially high-yield alternatives for SNSPD fabrication.

2. Wavelength range

SNSPDs have been demonstrated to operate from the x-ray to the mid-infrared wavelength range. In 2012, soft x-ray detection was demonstrated.[123] In contrast to the standard detection mechanism, where photons are absorbed in the meander, for x-ray detection the absorbance in thin superconducting layers with thicknesses around 10 nm is low and absorption in the substrate plays a major role.[124,125] Due to the significant higher particle energy, x-ray detectors can have saturated intrinsic efficiency at considerably larger geometrical

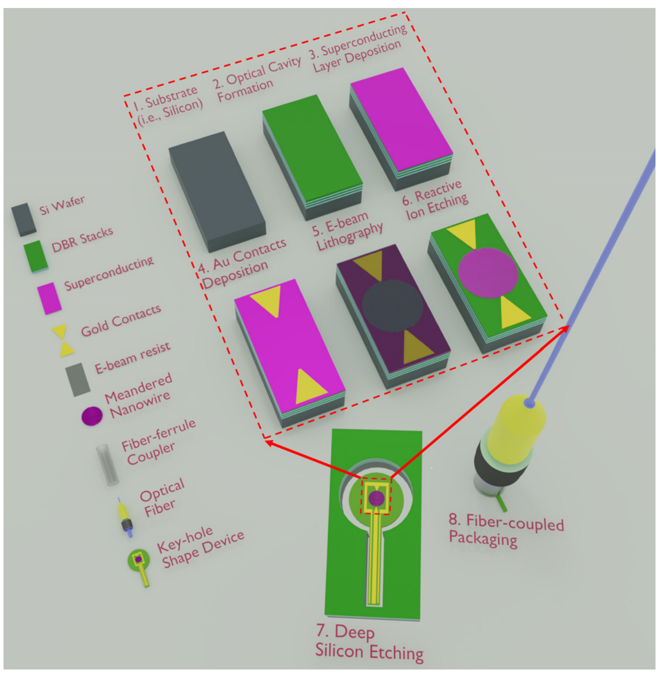

FIG. 2. Illustration of the process flow for fabricating SNSPDs from a bare silicon substrate to a fiber-coupled device. For details see main text.

parameters, which can increase x-ray absorption in the superconductor to a few percent.[126,127] SNSPDs for UV photons have reached efficiencies of >85%, dark count rates of 0.25 counts per hour and timing jitter < 60 ps.[128] By engineering film deposition to optimize energy sensitivity, WSi detectors were shown with a saturated internal efficiency at 10μm[129] in 2020. Although beyond the scope of single-photon detection, it is worth mentioning that SNSPD structures can also be used to detect α and β particles.[130]

3. Multipixel SNSPDs

In systems with a small number of superconducting single-photon detectors such as fiber-coupled multi-pixel arrays,[59] a straightforward way to address individual detection channels is through spatial multiplexing of the biasing and RF detection signals through several coaxial lines. As multi-pixel arrays scale in size, a limit on the number of coaxial lines is set by the cryostat cooling power.[131] Multi-pixel readout techniques for SNSPDs are under development, a row-column readout of pixels for a 32×32 detector-array using only 64 electrical connections was demonstrated.[132] This method is very attractive as the number of required RF lines is only $2N$, for arrays consisting of N^2 detectors, though this approach does not allow for simultaneous readout of all pixels. Time-domain multiplexing is another approach, where a single superconducting transmission line is used to address several detectors on the same chip.[133–137] One of the main challenges of this approach is the fast propagation speed of the electrical signal in the superconducting transmission-lines, approaching the speed of light, which limits the possibility for dense packing of detectors.[134] Dispersion engineering was recently used to reduce group velocity of the detection signal in the superconducting transmission-line by orders of magnitude. Both planar and multi-layered structures were used to control the group velocity of the detection signals.[133,135–137] Another promising route for scalable readout of multi-pixel SNSPDs is the use of single flux quantum (SFQ) logic.[138–143] Frequency multiplexing was also demonstrated for SNSPDs,[144] where several resonant cavities operating at different radio frequencies are coupled to individual detectors on a single transmission-line. For the latter, a challenge in large scale systems is the complexity involved with matching resonant frequencies of the cavities to the driving radio frequency tones. Alternatively, amplitude coding of the detection signals of SNSPDs provides another approach for multiplexing.[145,146] The advantage is the simplicity of fabrication and readout method using a voltage division circuit. On the other hand, the drawback is the need for on-chip resistors to set different amplitude levels, which dissipate heat, and additionally the size of the array is limited by the leakage current in different branches.[136]

4. Nanowire vs microwire detectors

SNSPDs have typical nanowires widths in the range of 40–120 nm. These devices show exceptional performance but require complex nanofabrication. Recently, detectors with wide micrometer lines were reported: Superconducting microstrip single-photon detectors (SMSPDs).[147] These devices have, compared to SNSPDs, far larger critical currents and lower kinetic inductance, making them suitable for the fabrication of large-area detectors as shown in a number of recent works.[148–151] For example, Ref. 149 demonstrates devices with meander widths of 1 and 3 μm and active areas up to 400×400 μm^2

with excellent light detection in micro-strips fabricated by conventional optical lithography.[151] Additionally, very recently, high performance single-photon detection (SDE > 90%) was demonstrated.[68] Since this a relatively new research direction, there are limited reports on time resolution;[152] wavelength limits and high count-rate performances are yet to be reported.

III. SNSPD APPLICATIONS

In this section, we review a non-exhaustive number of established and emerging applications of SNSPDs.

A. Quantum optics, information processing, quantum communication, and integrated quantum photonics

SNSPDs have been the detectors of choice in landmark quantum information processing experiments, i.e., on large scale boson sampling[6] and record breaking quantum communication experiments.[153–155] Also high performance SNSPDs played a major role in the loophole-free test of local realism based on Bell experiment.[156] A recent promising direction for application of SNSPDs in quantum information promising is its integration with ion-trap.[157] For an up-to-date review on the use of SNSPDs in quantum technologies, we refer to Ref. 105.

Complex quantum photonics integrated circuits require many on-chip single-photon detectors. SNSPD in traveling wave geometry,[39,40] with its outstanding performance and small footprint, serves as an excellent candidate for this function in photonic integrated circuits. Waveguide-integrated SNSPDs have already been used for on-chip single qubit quantum optics experiments,[158,159] to demonstrate on-chip two qubit quantum interference,[160] and for on-chip secure quantum communication.[161] SNSPDs were integrated in different nano-photonics platforms such as Si,[40,162–168] SiN,[158–160,169–174] GaAs,[39,174–177] AlN,[174,178] $LiNbO_3$,[174,179,180] Ta_2O_5,[181] and diamond.[182,183] In Ref. 184, the performance of most of these earlier SNSPD nano-photonics platforms is reviewed. Integrated SNSPDs have also demonstrated sub-nanosecond recovery time.[165,181] Another important aspect in sophisticated integrated quantum photonics circuitry is the reliability of photonics elements. It has been shown[173] that by fabricating traveling wave SNSPDs buried under photonic waveguides, one can determinedly ensure that only the best performing detectors are integrated. Further development of integrated SNSPDs, as envisioned in Sec. IV B can significantly enhance the role of SNSPDs in future quantum nanophotonics circuits.

B. Light detection and ranging (LIDAR)

LIDAR is an optical measurement technique for studying environmental parameters such as the atmosphere, vegetation, as well as remote objects. The detector performance influences the resolution, acquisition time, and maximum range. It has been shown that SNSPDs outperform conventional Geiger-mode avalanche photodiodes both in low noise environments and, under appropriate operation, in noisy (high background) environments.[7,8] SNSPDs were used for measuring sea fog in an area 180-km in diameter.[185] Kilometer-range, high resolution imaging at telecom wavelength has also been demonstrated.[186] Another promising direction with encouraging recent results is single-photon LIDAR beyond 2000 nm, a wavelength range with both reduced solar flux and atmospheric absorption.[9]

C. Mass spectrometry

SNSPDs offer excellent potential for applications in the field of mass spectrometry, where impacts of single ions can be measured. They show exceptional sensitivity and, additionally, operate at a convenient (particularly considering the size and the heat load of common mass spectrometry chambers) temperature of 2–5 K that is within the operating temperature range of relatively inexpensive Gifford-McMahon and pulsed-tube cryostats. The feasibility of sub-nanosecond detection using these detectors has already been demonstrated.[12,187] In Addition, a proof of principle for detection of neutral and low energy particles was demonstrated.[188,189] Superconducting nanowire detectors do not rely on the secondary electron mechanism, and their detection mechanism is based on the creation of high energy quasiparticles by the impact, allowing for 100% detection efficiency even for macromolecules.[190] While SNSPDs offer excellent performances, until recently their active area had been limited. With the development of SNSPD arrays (employing any of several existing multiplexing techniques), kilo-pixel detectors have been introduced[132] that can cover much larger areas, and by interfacing SNSPD arrays and cryogenically cooled electronics (see Sec. IV A), even larger arrays are expected to become available.

D. Diffuse correlation spectroscopy

Biological tissues are strongly diffusive media. Diffused optical imaging is a functional medical imaging modality that uses the lower attenuation of near-infrared light to probe physiological parameters in the tissue such as oxy- and deoxyhemoglobin.[15] The light transport in these tissues is mainly dominated by scattering, and it has been shown that achievable resolution (the half-width of the point-spread function) scales with thickness.[191] Recently, SNSPDs have been considered for improving the performance of diffuse correlation spectroscopy.[192]

E. Optical time domain reflectometry (OTDR)

To identify the position of losses and scattering along optical fiber networks, reflection of a laser pulse is measured and timing yields information on the fault position.[193] The ability to operate at the single-photon level, with the outstanding time resolution and low dark counts of SNSPDs, allows for OTDR measurements to be carried out over the longest possible distances and yield cm resolution.[10,11,194] Additionally, OTDR can be used to implement fiber-optic distributed Raman sensor for absolute temperature measurements.[195,196]

F. Future applications

In neuromorphic computing, SNSPDs were recently proposed both as a direct platform for neuromorphic computing[197,198] and in conjunction with on-chip semiconducting photon sources.[199,200] Neuromorphic computing is the discipline that produces neural-inspired computational platforms and architectures. Carver Mead in the late 1980s has come a long way and has had important results such as beating humans in the game of Go.[201]

In astronomy, SNSPDs are finding uses for exoplanet transit spectroscopy, in deep space optical communication, as well as in the search for dark matter. Detecting such particles places stringent requirements on the detector, SNSPDs have been shown to be suitable candidates for direct detection of dark-matter particles from the halo of milky way directly creating an excitation in a detector on Earth of sub-GeV particles.[53] Another application is wideband optical communication to satellites. The limited power available on satellites places stringent requirements on the downlink detectors, with yet stronger requirements if the emitter is further away, as for a deep space probe. These requirements have shed light on SNSPDs[202–206] for downlink, and possibly for uplink.

Nearly 70 years after the pioneering intensity correlation experiments by Hanbury-Brown and Twiss,[207] there is a growing interest in temporal correlation spectroscopy to achieve a high angular resolution in studies of celestial light sources with star light correlation spectroscopy. Temporal intensity interferometry in comparison with conventional direct interferometry has the advantages of having a simplified implementation. This is because no light recombination or physical delay lines are needed and as a result the correlation will be insensitive to environmental turbulences. Recently, using avalanche photodiodes with an active area of 100 μm^2, time jitter of 500 ps and integrating for 70.5 h, temporal intensity interferometry (photon bunching) experiments were carried on three bright stars. Currently available SNSPD technology readily offers $\sim$5 folds improvements of SNR as compared to Ref.14. Future SNSPD developments will push the boundaries of this field even further.

Advances in single-photon detection at mid-infrared wavelengths[208,209] have led to a growing interest in mid-infrared spectroscopy with SNSPDs.[210,211] Recently, Wollman *et al.*,[212] for the origins space telescope concept, studied the potentials of SNSPDs as a tool to probe bio-signatures in exoplanets atmospheres: using a mid-infrared spectrometer, they will study small spectral changes in a star light due to the absorption or emission from a transiting exoplanet atmosphere. The wavelengths range from 2.8 to 20 μm is of particular interest, because it contains absorption lines of many important molecules vital for life; SNSPD based sensors are promising candidates for exoplanet transit spectroscopy.

Positron emission tomography (PET)[16] is a routinely used functional imaging technology to visualize changes in metabolic and physiological activities as well as chemical regional composition inside the body. PET is an important tool in cancer therapy and with the help of radiotracers, it can retrieve quantitative information about location and concentration of tumor cells. The high time-resolution of SNSPDs integrated with scintillators[213] will allow to reach the 10-picosecond PET challenge.[214,215] Combining SNSPDs with various types of scintillators (particularly cryogenic scintillators) is an exciting research field for SNSPD and PET but also for the broader high-energy physics community.

In biomedical imaging, SNSPDs open new possiblities: the weak emission from oxygen singlet at 1270 nm can readily be measured, operation further in the infrared allows for deeper imaging in biological samples where scattering is lower and specific molecules can be tracked.

For some quantum computation implementations, an important challenge is to funnel large amounts of data in and out of cryostats operating at mK temperatures with limited cooling power. This limits the classical approach of using coaxial lines, the use of optical fibers to communicate at the single-photon level using SNSPDs with systems operating at mK offers the prospects of a very large data bandwidth with very low thermal loads.

IV. OUTLOOK

After a review of current and future applications of SNSPDs in Sec. III, we present two important envisioned SNSPD developments that could further boost the impact of SNSPDs in science and technology.

A. Large SNSPD arrays with integrated cryogenic electronics

Addressing the readout challenge of large SNSPD arrays, i.e., accessing and processing large amounts of data generated at cryogenic temperatures, is imperative for high-end imaging applications. As discussed in Sec. II B 3, each readout technique has specific advantages and disadvantages. We envision future large-scale systems with hybrid cryogenic RF readout techniques utilizing different readout schemes in different sub-systems. Additionally, dispersion engineering is a powerful tool that can be used to tailor the properties of the superconducting transmission lines for better footprints or to boost the operating bandwidth.[216,217]

For applications requiring large SNSPD arrays (e.g., high resolution imaging and spectroscopy), it is essential to integrate cryogenic readout circuits close to the SNSPD and separate them from processing units (comparators, counters, time to digital converters, and digital processing units) operating at higher temperatures. Connections among these units must have high RF transmission while providing high thermal isolation (i.e., low thermal conduction, see, for example, Ref. 218). Such an envisioned system is illustrated in Fig. 3: The array sensor is connected via superconducting transmission lines to the pixel addressing and pulse pre-amplification electronics (illustrated as addressing and analog amplifiers in the figure) within the first cryogenic stage. Low thermal conductivity coaxial links are used to connect the first cryogenic stage to the second stage (30–50 K). The second cryogenic stage is where further complex processing are performed which may include (but be not limited to) triggering, pulse counting, time to digital converters for time stamping, data compression, and serializers able to handle the large data stream. We foresee successful implementation of large area, high density imaging sensors such as the one shown in Fig. 3 can bring about a step change to many imaging applications discussed in Sec. III. A further step could be the integration of such a sensor in compact cryo-coolers,[219] making it even more attractive for applications, where size and power consumption are important decision-making factors such as equipment integrated in satellites.

B. SNSPD-based re-configurable integrated quantum photonics

Using SNSPDs for conditional reconfiguration of quantum photonics circuits based on detection events, as illustrated in Fig. 4, can facilitate quantum communication schemes such as teleportation, entanglement swapping, and quantum repeaters. Such schemes rely on performing a (Bell-state) measurement on a photonic qubit, then feed-forward the resulting detection electrical signal to conditionally modify another photonic qubit on the same or a different chip. This comes as a challenge though, the timescale for the voltage signal of SNSPDs is on the order of nanoseconds, necessitating delaying optical signals on the chip by a similar timescale to allow for conditional reconfiguration of the circuit based on detection events. To overcome

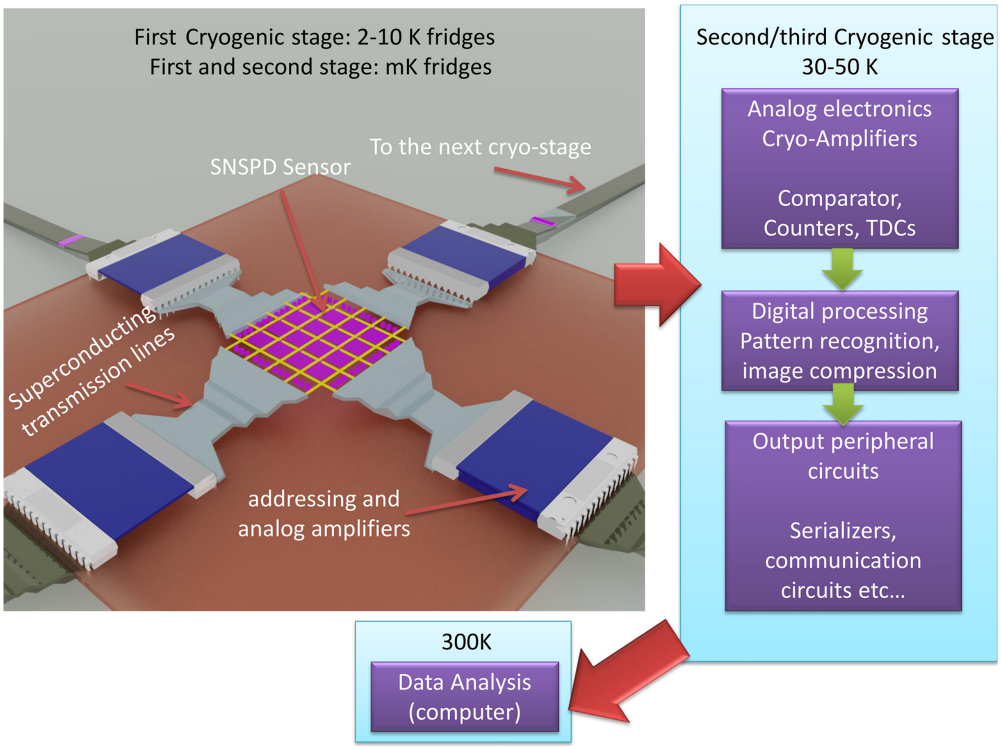

FIG. 3. Concept illustration of a large SNSPD based imaging sensor: the pixels are addressed, and the SNSPD pulses are amplified using the first cryogenic stage readout circuitry connected to the sensor via superconducting transmission lines. The pre-amplified analog signals are then passed to the second cryogenic stage for further processing which includes pulse counting, time to digital converters (TDC), data compression, and finally serializers. A processing unit at room temperature receives and analyzes the pre-processed data.

such a challenge, ultra-fast on-chip SNSPDs must be implemented, in combination with heat-free fast re-configurable photonic circuits and ultra-low loss optical delay lines to match the electrical signal delay. An important step toward such a goal was recently demonstrated by realizing waveguide integrated SNSPDs with thin-film lithium niobate circuits, which can deliver the needed modulation for fast routing of single photons on-chip.[220] Another interesting application for such re-configurable circuits is quantum simulators for implementing sampling problems, quantum transport simulations, or disordered quantum systems. The integration of efficient sources and detectors with low-loss optical waveguides on the same chip will significantly advance the scalability prospects for photonic quantum simulators.

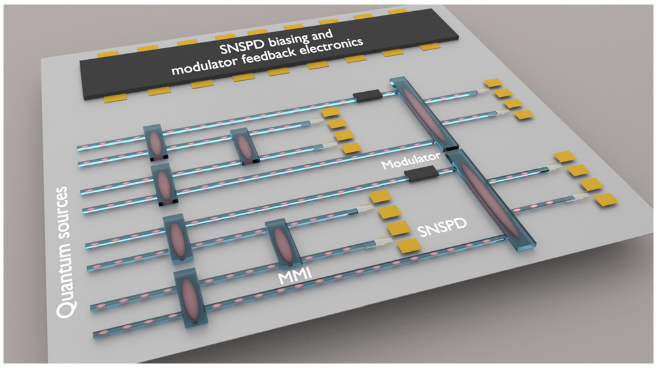

FIG. 4. Concept illustration of a single-photon reconfigurable quantum photonic circuit consisting of quantum sources, beam splitters that are implemented here using multimode interferometers (MMI), electro-optic modulators, and SNSPDs. Detection signals from quantum interference outcome between different qubits are processed by the feedback-electronics module to apply qubit rotations on-chip.

V. CONCLUSION

In this perspective, we reviewed the evolution of SNSPDs, the state-of-the-art, working mechanisms, fabrication methods, material platforms, readout schemes, applications, and disruptive enabled technologies. Our goal is to provide a dynamic multidisciplinary picture targeted toward both the community of SNSPD researchers and scientists working on overlapping lines of research, where this technology can have important impact. An outlook for future developments of SNSPD is also provided along with two key envisioned enabling developments to boost the impact of SNSPD in science and technology.

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DATA AVAILABILITY

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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