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ABSTRACT

Superconducting nanowires have emerged as a powerful tool for detecting single photons in the visible and near-infrared range with excellent device performance metrics. We outline challenges and future directions related to the up-scaling of nanowire devices and detector systems toward widespread applications in demanding real-world settings. Progress on achieving superconducting single-photon detectors with a large active area and an increasing number of pixels is reviewed, comparing the recent literature in terms of the reported key detector parameters. Furthermore, we summarize currently available readout and multiplexing schemes for multi-pixel detector arrays and discuss implications of the recently discovered microwire-based detector geometries.

Detecting light down to the single-photon level has enabled scientific discoveries and new technological applications. Although various types of detectors are available depending on the desired wavelength range, performance requirements, and operation conditions (see Ref. 1 for a comparison), the development of photosensitive devices remains an active field of research, pursuing the quest for achieving a single-photon detector with ideal characteristics. Photomultiplier tubes (PMTs) have the distinct advantage of offering large detection areas but show significant limitations related to their detector performance parameters, high operation voltages, and bulky packaging. Single-photon avalanche diode (SPAD) technology has considerably advanced in the past few decades and can be fully integrated with micro-optics as well as readout circuits. Various types of large-scale SPAD arrays have been reported, including kilopixel devices based on III–V semiconductors[2,3] and Si-based megapixel arrays.[4]

In terms of detector performance, superconducting nanowire single-photon detectors (SNSPDs)[5] stand out due to close-to-unity detection efficiency,[6] picosecond time resolution,[7] short recovery times down to the sub-nanosecond regime,[8] and low noise with milli-hertz dark count rates.[9] This technology has rapidly evolved from the first demonstration in 2001[10] to high-performance commercial products available to date, providing single-pixel detectors coupled to standard optical fibers in customized cryostats. Moreover, SNSPDs coupled to optical waveguides in photonic integrated circuits[11] have shown excellent capabilities for on-chip single-photon detection, which offers significant potential for the scalable realization of arrays with high integration density.

So far, SNSPDs have been primarily used in research and development, for instance, in the field of quantum optics where they attracted considerable attention for applications in quantum communication and quantum computing,[12] e.g., for the long-range distribution of quantum keys[13] and polarization entanglement.[14] Other applications include space communication,[15] fluorescence lifetime measurements,[16] singlet oxygen luminescence detection,[17,18] as well as light detection and ranging (LIDAR) with near-infrared photons, which has been employed for imaging objects,[19–21] for satellite ranging,[22] and for characterizing sea fog.[23] Although these demonstrations validate the high practical relevance of SNSPDs, further advances will be required to enable the widespread use of this photodetector technology in demanding industrial, clinical, or environmental settings. Similar to PMT and SPAD technologies, future developments will need to follow a trajectory that enables a drastic increase in the active area and number of pixels combined with improvements in terms of system-level integration. In this perspective, we summarize recent progress on the up-scaling of SNSPD devices and detector systems, providing an overview of the relevant readout and multiplexing schemes. Additionally, we share our viewpoint on key future developments that will allow for the adoption of SNSPDs in real-world applications beyond the optics laboratory.

Typical SNSPD devices offer active areas in the 10 μm diameter range allowing for efficient coupling to single-mode optical fibers (see Refs. 24 and 25 for considerations related to optical interfaces and coupling). They consist of a meandering nanowire (width on the order of 100 nm) fabricated from a superconducting thin film (thickness ~5–10 nm) with electron beam lithography and reactive ion etching. Due to the nanoscale geometries, the realization of SNSPDs covering large areas requires a high level of uniformity of the superconducting material and of the processing steps, which has limited the up-scaling and yield on the single-device level. This challenge has been addressed by continuous improvements in nanofabrication and material growth techniques. Magnetron sputtering is most commonly used to deposit nanocrystalline (e.g., NbN and NbTiN) and amorphous (e.g., WSi and MoSi) thin films. Excellent yield and reproducibility were also demonstrated for NbN thin films deposited by plasma-enhanced atomic layer deposition,[26] confirming the substantial potential of this deposition technique for upscaling SNSPD technology. Amorphous superconductors are often considered favorable in terms of uniformity for achieving SNSPDs with high yield and consistent properties; nevertheless, significant advances in up-scaling the active detector area have also been achieved for nanocrystalline materials.

Larger circular single-pixel SNSPDs with diameters of 50 μm were fabricated and coupled to multimode optical fibers achieving system detection efficiencies exceeding 80% for 850 nm (NbN)[27] and 1550 nm (NbTiN),[28] while maintaining a low timing jitter below 20 ps in the latter case. The authors of Ref. 29 realized circular NbN-based single-pixel SNSPDs with a diameter of 100 μm coupled to a multimode fiber with 105 μm core diameter, resulting in a detection efficiency of 65% at 532 nm. An SNSPD device with an area of 400 × 400 μm^2 was reported in Ref. 30, exhibiting saturated intrinsic quantum efficiency at 1550 nm. Scaling up SNSPDs at the single-device level even further would be possible but is linked with long detector recovery times due to large kinetic inductance and, hence, limited suitability for high count rates. Consequently, large active area detectors have been realized with alternative device designs based on multi-pixel configurations (to be discussed in detail below) and on nanowire networks to reduce the kinetic inductance[31] (superconducting nanowire avalanche single-photon detectors, SNAPs). Large-area SNSPDs suitable for coupling to multimode optical fibers have important technological relevance in multiple application areas ranging from LIDAR to astronomy and biological imaging. As coupling optical instruments to multimode fibers is significantly less challenging than to single-mode fibers, SNSPD technology can be adopted for a much larger range of experiments, optical setups, and existing laboratory infrastructure. Furthermore, industrial use cases in demanding environments, where optical setups are subjected to, e.g., temperature variations and vibrations, will greatly benefit from employing multimode fibers in robust coupling schemes. As a result, we anticipate that SNSPDs will complement or replace other technologies for high-performance photodetector applications in the future, providing scientists and engineers with unmatched device performance metrics in wavelength regimes not accessible otherwise.

Figure 1(a) shows an SNSPD with 300 μm diameter and nine pixels, which in turn consists of two SNAP devices connected in series.[32] Using a 200 μm multimode fiber, a total system detection efficiency of 42% at 1064 nm was reported, achieving a maximum count rate exceeding 43 MHz. The implementation of superconducting single-photon detectors consisting of multiple pixels does not only alleviate the problem of long dead times for large active areas but also offers opportunities for enhanced functionality including correlation measurements, pseudo-photon number resolution (PNR), and imaging. The authors of Ref. 33 realized four-pixel multimode fiber-coupled detectors suitable for photon correlation experiments, demonstrated by measuring anti-bunching of photon emission from a quantum light source. PNR was shown via spatial multiplexing with multiple nanowires,[34] for instance, with a series array of 12 nanowire elements,[35] 16 interleaved nanowires interfaced individually,[36] and 24 nanowire pixels in a series configuration[37] for the simultaneous detection of up to 12, 16, and 24 photons, respectively. Electrical and optical crosstalk constitute additional challenges for multi-pixel configurations that need to be taken into account in the detector system design. Multi-element SNSPDs capable of crosstalk-free operation were demonstrated,[38,39] as well as four-element PNR detectors maintaining sub-30-ps timing resolution.[40]

The increasing number of pixels requires the development of multiplexing schemes to minimize the number of coaxial connections and, thereby, the heat load on the cryogenic system. The heat load of a single coaxial line to the 4 K stage of a closed cycle cryocooler is on the order of 1 mW,[41] which renders the realization of a kilopixel array consisting of individually connected SNSPDs unfeasible considering the cooling power of commercially available products. The use of cryogenic amplifiers that are commonly employed to reduce the SNSPD timing jitter further aggravates this problem. Moreover, such multiplexing schemes need to be compatible with the requirements of external readout electronics such as amplification, counting, and time-to-digital conversion modules.[42] Frequency multiplexing of 16-pixel SNSPDs has been reported, enabling the individual biasing and readout of each pixel employing only one common microwave feed line with a timing jitter of 59 ps.[43] In addition, Single Flux Quantum (SFQ) logic can be used to readout SNSPDs[44,45] and to encode spatial pixel information, which was shown for an array of 64 SNSPDs maintaining a timing jitter of 57 ps.[46] Figure 1(b) shows a kilopixel SNSPD array, the largest to date with 1.6 × 1.6 mm^2 area, which was used for single-photon imaging relying on a row-column readout scheme and 64-channel time-tagging electronics.[47] An alternative row-column readout scheme based on thermal coupling was proposed, mitigating the problem of current re-distribution within the array and requiring less wiring/circuit elements.[48] Figure 1(c) demonstrates time multiplexed readout with a nanowire delay line, resulting in single-photon imaging capabilities with ~590 effective pixels. The arrival time difference of the voltage pulses at both sides of the device is evaluated to extract the position of the photon detection event.[49] While current limitations for detecting multi-photon events need to be addressed in the future, the excellent scalability of SNSPD technology is highlighted by these examples. Furthermore, the recent demonstration of photonic SNSPD readout offers another promising prospect of operating a large number of pixels as optical fibers provide high bandwidth densities, minimized electromagnetic interference, and significantly reduced heat load to the cryostat due to their low thermal conductivity compared to coaxial cables.[50]

While device upscaling has been proven to be challenging but feasible for wavelengths up to the telecom range, the realization of SNSPDs operating further in the infrared places even more stringent requirements on material growth and nanofabrication. Detectors

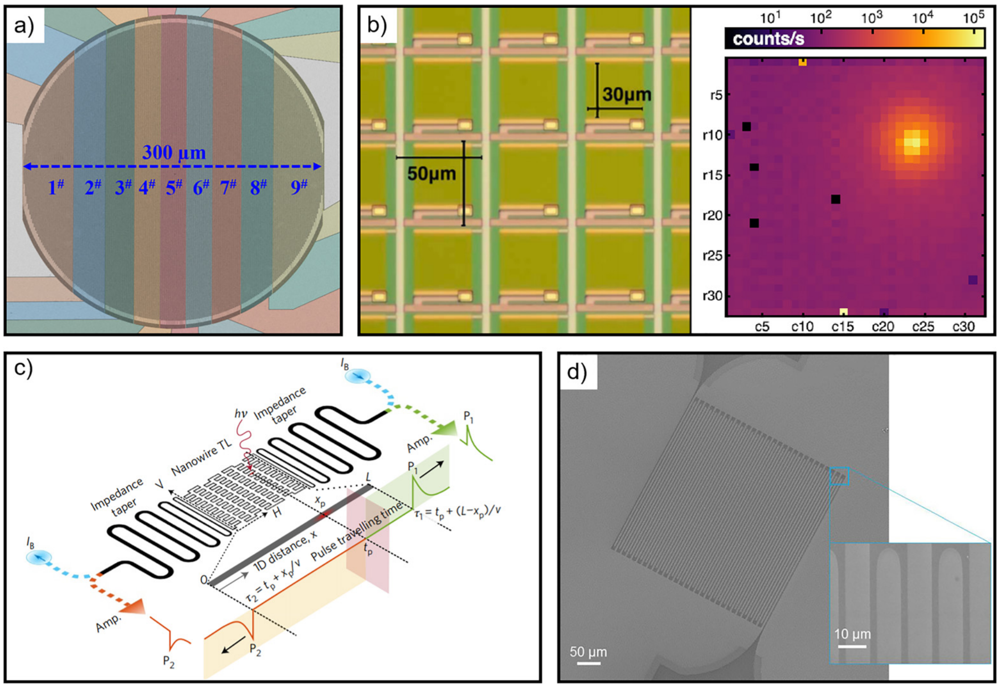

FIG. 1. (a) Superconducting nanowire single-photon detector (SNSPD) device with a 300 μm diameter and nine pixels, suitable for coupling to multimode optical fibers with a large core diameter combined with high maximum count rates. Reproduced with permission from Zhang *et al.*, AIP Adv. **9**, 075214 (2019). Copyright 2019 Author(s), licensed under a Creative Commons Attribution (CC BY) License. (b) SNSPD array with 1024 pixels and 1.6×1.6 mm^2 area realized in a row-column multiplexing architecture. A 64-channel time-tagging readout was implemented and imaging of a focused laser spot was demonstrated. Reproduced with permission from Wollman *et al.*, Opt. Express **27**, 35279–35289 (2019). Copyright 2019 Optical Society of America. (c) Superconducting nanowire delay line for single-photon imaging resolving $\sim$590 effective pixels. Reproduced with permission from Zhao *et al.*, Nat. Photonics **11**, 247–251 (2017). Copyright 2017 Springer Nature. (d) Large-area SNSPD based on 3 μm microwire with a 400×400 μm^2 active area. Reproduced with permission from Charaev *et al.*, Appl. Phys. Lett. **116**, 242603 (2020). Copyright 2020 AIP Publishing LLC.

capable of detecting wavelengths of 2 μm and beyond are commonly linked with small nanowire widths down to 30 nm.[51] It remains an open question how the current device technology needs to be improved to achieve large-scale SNSPDs for mid-infrared detection; thus, future developments will rely not only on technological advances but also on new fundamental insights into the detector working principles. The recent demonstration of superconducting single-photon detectors based on microwires[52] came as a surprise to the scientific community and has questioned prevailing paradigms on the detection process. The following reports[53,54] showed large-area detectors with saturated intrinsic quantum efficiencies at telecom wavelengths [Ref. 53: $400 \times 400 \mu m^2$; Ref. 54: 362×362 μm^2, see Fig. 1(d)] and microstrip structures with comparatively low timing jitter around 40 ps.[55] While microwire-based devices seem to critically rely on superconducting thin films with tailored properties, they are highly appealing from an industrial perspective as they could be realized with high-throughput optical lithography systems. In addition, the properties of microwire devices will likely allow the community to learn more about the physics of SNSPDs, which will be crucial for the rational design of large-scale superconducting single-photon detectors operating far in the mid-infrared.

To conclude, recent years have shown significant progress in developing SNSPD devices and systems with increased active areas and pixel numbers, which is summarized in Fig. 2 and Table I. These

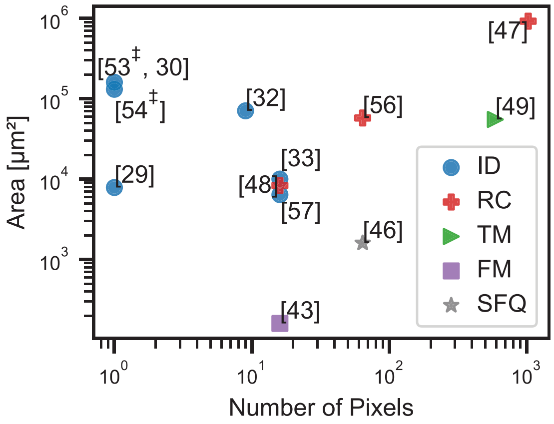

FIG. 2. Large-area and multi-pixel superconducting single-photon detectors are compared by the number of pixels and total detection area. Microwire-based devices are marked with ‡. The devices are color-coded by their readout scheme: individual device readout (ID), row-column readout (RC), time multiplexing (TM), frequency multiplexing (FM), and SFQ-based logic (SFQ). Further details are tabulated in Table I.

TABLE I. Literature review of large-area and multi-pixel superconducting single-photon detector devices. Summary of the material, number of pixels N_{pixel}, detector area *A* (total/per pixel), readout scheme, wavelength λ, system detection efficiency *SDE*, and timing jitter τ. The listed readout schemes are individual device readout (ID), row-column readout (RC), time multiplexing (TM), frequency multiplexing (FM), and SFQ-based logic (SFQ). Single-pixel microwire-based devices are marked with $1^{\ddagger}$ in the column N_{pixel}.

Mater.	N_{pixel}	A_{pixel} (μm^2)	A_{total} (μm^2)	Readout	λ (nm)	SDE (%)	τ (ps)	References
WSi	1024	900	9.2×10^5	RC	1550	8	250	47
MoSi	$1^{\ddagger}$	1.6×10^5	1.6×10^5	ID	1550	…	…	53
WSi	1	1.6×10^5	1.6×10^5	ID	1550	…	…	30
WSi	$1^{\ddagger}$	1.3×10^5	1.3×10^5	ID	1550	…	…	54
NbN	9	7.9×10^3	0.7×10^5	ID	1064	42	207	32
WSi	64	900	57.6×10^3	RC	1550	3	…	56
NbN	590	…	55.2×10^3	TM	1550	…	50	49
NbTiN	16	625	10×10^3	ID	670	…	23	33
WSi	16	520	8.3×10^3	RC	1550	…	<300	48
NbN	1	7.8×10^3	7.8×10^3	ID	532	65	82	29
NbN	16	400	6.4×10^3	ID	1064	46	92	57
NbTiN	64	25	1.6×10^3	SFQ	1550	…	57	46
NbN	16	$\sim$10	$\sim$160	FM	1550	2–10	59	43

developments were enabled by combined effort in nanofabrication, materials science, device design, photonics engineering, and cryogenics. Future improvements in multiplexing and readout schemes will allow for the operation of massive numbers of pixels while preserving near-ideal detector performances. We expect multiple emerging applications to benefit from further advances in large-scale superconducting single-photon detector systems due to their unmatched performances for detection and imaging over a large spectral range. In addition to their high industrial relevance, SNSPDs with a large active detection area will serve as essential tools for scientists tackling unsolved fundamental questions in quantum optics and beyond, such as the detection of dark matter.[30]

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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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