Snowmass2021 - Letter of Interest

Superconducting Nanowire Single-Photon Detectors

Thematic Areas: (check all that apply □/■)

■ (IF1) Quantum Sensors
■ (IF2) Photon Detectors
■ (IF3) Solid State Detectors and Tracking
■ (CF1) Dark Matter: Particle Like
□ (Other) *[Please specify frontier/topical group]*

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Abstract: Superconducting nanowire single photon detectors (SNSPDs) have historically demonstrated exceptional performance in several key areas, such as system detection efficiency and dark count rates, making them indispensable for fundamental and technological research in quantum optics. However, recent (within the last 3 years) advances in material processing, device characterization, theoretical modeling, and fabrication techniques have not only pushed forward the performance of SNSPDs in their historical strengths, but made them increasingly competitive with (or, in some cases, superior to) conventional single-photon detectors in areas such as jitter, maximum count rates and active area. With focused and sufficiently funded collaborative research efforts, SNSPDs have the potential to provide transformative new capabilities to a wide variety of HEP experiments.

1 Background

Single-photon detectors based on superconducting nanowires (SSPDs or SNSPDs) have rapidly become the detector of choice for photonic quantum information science and technology. The table below summarizes the state-of-the-art performance for SNSPDs as well as anticipated progress that is likely to be achieved in the next five years. To be clear, the performance described in the table are for different devices, and is not currently possible to achieve in one device. However, with suitable investment in research and development, many of these detector metrics could be obtained simultaneously.

Parameter	SOA 2020	Goal by 2025
Efficiency	98% @ 1550nm	>80 % @10μm
Energy Threshold	0.125 eV (10 μm)	12.5 meV (100 μm)
Timing Jitter	2.7 ps	$<$ 1ps
Active Area	1 mm^2	100 cm^2
Max Count Rate	1.2 Gcps	100 Gcps
Pixel Count	1 kilopixel	16 megapixel
Operating Temperature	4.3K	25 K

The SNSPD response over a broad range of wavelengths with picosecond scale timing resolution and low dark count rates makes the technology attractive for HEP applications. For example, SNSPDs can be used to search for low-mass Dark Matter where it is critical for any detector to have (1) a high photon detection efficiency; (2) extremely low (on the order of 1 per day or lower) intrinsic false (or "dark") counts; and (3) low energy thresholds for infrared single photon detection. SNSPDs are the highest performing detectors available in all three metrics, and they are still far from reaching their fundamental limits. Other potential HEP applications of SNSPDs include exploiting their exceptional timing resolution in collider experiments and implementing large photodetector arrays for cosmological surveys at IR wavelengths. Furthermore, with advances in detector readout, one could imagine performing on-chip combination of signals from multiple nanowires, making a superconducting analog of the SSPM. This could enable a new class of photodetector for HEP applications that has a lower energy threshold and much lower dark count rate.

2 Objective and Plans

In the past few years, several applications have been proposed for SNSPDs in the field of low-mass DM detection. Some examples include optical haloscopes,[1] optical readout of cryogenic semiconductor targets,[2] electron recoil in superconduding nanowires,[3] resonant scattering and absorption in cryogenic molecular gases,[4] and, should the energy thresholds improve, axion detection. Likewise, the recent demonstration of sub-3ps timing resolution in specialized nanowires[5] and operation in high magnetic fields[6] may enable future HEP applications involving ultrafast timing in future high-luminosity colliders. And advances in the fabrication and readout of large nanowire detector arrays[7] provide a compelling technical foundation for low-noise high-efficience IR detector arrays that may be appropriate for cosmological surveys at longer wavelengths.

Active Area: Many of the DM detection applications discussed above require large sensor active areas to enable scaling to large target masses in experiments. The active areas of SNSPDs have grown steadily over the past several years from the order of the cross section of a single-mode optical fiber core (about 100 $\mu\mathrm{m}^2$) to kilopixel arrays with $\sim \mathrm{mm}^2$ active area.[7] The maximum nanowire length is subject to material inhomogeneity and geometrical imperfections. Recent developments in superconducting detector design and fabrication[8–10] have enabled few-micron-wide superconducting microwires that are potentially much more robust to many of these issues and can enable scaling to far greater active areas in the near future. We believe that it is physically possible to scale the SNSPD arrays to a level $>$10 megapixels (4096x4096), and an active area of $\sim$100 cm^2. To achieve this, significant research and development will be required both in nanofabrication process development and the development of novel cryogenic readout techniques, which will rely on a combination of on-chip multiplexing techniques, cryogenic readout electronics, and the scaling up of robust, low-cost cryogenic RF interconnects.

Dark Counts: Using our initial measurement of a background count once every 11 hours, we published a paper[3] illustrating the impact of a nanoscale detector on setting interesting dark matter limits. We have recently observed a lower background count rate of below 1 count per day. This is consistent with an event due to a cosmic ray muon. Unlike other superconducting sensors, the SNSPD require a localized deposition of heat to cause it to click. As a result, the SNSPD is much less sensitive to background counts due to energy deposited into the substrate and coupling into the device. We plan to explore novel device geometries to further reduce the sensitivity to background radiation. We also will explore device designs that will include an integrated cryogenic muon detector for local muon vetoing.

Energy Threshold To date, SNSPDs have been demonstrated with greater than 80% system efficiency over a wavelength range spanning from 313 nm to 1550 nm. Small area single-element SNSPDs have been demonstrated with saturated internal detection efficiency down to an energy threshold of 0.125 eV (10 μm^2)[11]. This has been achieved through optimization of the superconducting WSi material and the use of ultra-thin (2.5-3 nm) and ultra-narrow (50-70 nm) wires. We believe it is possible to continue reducing the energy threshold by a factor of ten. This will be pursued by exploring different alloy mixture ratios to control the superconducting gap energy and ultra-narrow nanowires to trap energy within the nanowire during the early stages of the detection process.

Timing Jitter Until recently, it has not been possible to probe the intrinsic limit of the timing resolution in SNSPD due to instrumental limitations, but recent progress has enabled demonstration of timing jitter as low as 2.7 ps FWHM for small active area devices suitable for waveguide coupling[5], while devices with active areas large enough for efficient fiber coupling have demonstrated system timing jitter of 8 ps[12]. Further improvements to the sub-ps level are expected to be physically possible and can be achieved in the next five years with sufficient investment. Key areas of research that are required to reach this goal are: studies of superconducting materials with fast energy relaxation times[13], development of scalable nanofabrication techniques to maintain a high fraction of depairing current for large-area devices[14], device-level microwave engineering to maintain high signal integrity[15], low-noise and low power-dissipation cryogenic amplifiers, and compatible time-tagging electronics capable of sub-ps timing accuracy. An important area of research is to develop large-area SNSPD pixels which still maintain few-ps timing jitter.

Maximum Count Rate With demonstrated intrinsic dark count rates as low as $\approx 10^{-5}\ s^{-1}$ and 3 dB saturation count rates above $10^7\ s^{-1}$, individual SNSPDs can have >100 dB of dynamic range. Nevertheless, the maximum count rate from a single SNSPD is determined by its reset time, which is typically limited by the hotspot thermal relaxation time (1-50 ns). To maximize the total count rate, it is necessary to have a large number of pixels. We have developed kilopixel SNSPD arrays with count rates approaching 1 Gcps[7], based on the row-column readout architecture which utilizes 2N readout lines for an NxN array. Through the use of emerging multiplexing techniques, such as the thermal row-column approach[16], as well as others, we believe that 16-megapixel arrays of SNSPDs will be capable of achieving 100 Gcps detection rates is within reach. Investment in on-chip readout circuitry will enable superior scaling of count rate with array size as well as a reduction of the number of readout lines coming out of the cryostat.

3 Summary

Single-photon detectors based on superconducting nanowires (SSPDs or SNSPDs) have demonstrated capabilities that is now capable of being used to discover new science in HEP experiments. Investment is needed to optimize the detector technology by developing new materials[17;18], fabrication techniques, superconducting electronics, and room temperature electronics for these applications.

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