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Progress and applications of superconducting-nanowire single-photon detectors

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Abstract:

Photon detectors connect optical and electrical systems by converting light to electrical signals. Single photon detectors detect single photons which measure ultra-weak light. Traditional semiconductor single-photon detectors suffer from high dark count rates, low infrared detection efficiency, and poor temporal resolution. Superconducting-nanowire single-photon detectors (SNSPDs) overcome these limitations using the hotspot effect. SNSPDs have created a solid foundation for optical technologies and become key in quantum information, LiDARs and Deep-Space Communications. This paper reviews working principles and performance metrics: system detection efficiency, dark count rate, recovery time, and timing jitter. The study summarizes applications in quantum information (quantum key distribution, optical quantum computing), single-photon LiDAR, and deep-space optical communication, replacing most single-photon avalanche diodes (SPADs). Recent experiments show that SNSPD-based systems can achieve meter-scale detection of sea fog, interplanetary laser communication over billions of kilometers, and boson sampling with 20 photons. Ongoing research is expected to improve performance in maximum count rate, system integration, and cryogenic operation, as well as to find applications in emerging fields such as environmental monitoring.

Keywords: superconducting-nanowire single-photon detectors, quantum information, light detection and ranging, deep-space communication.

1. Introduction

Single-photon detection has shifted the paradigm from measuring light as a continuous intensity to counting discrete photons. With the development of quantum optics, quantum communication and low-light imaging have been introduced to many experiments in quantum photonics; thus, the number of

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individual photons is counted rather than the total light intensity measured. Therefore, the degree to which it can be improved should be increased. The Single-Photon Avalanche Diode (SPAD) has been one of the main devices for many years in single-photon measurement technology. SPADs have some well-known problems. Silicon SPADs cannot sense infrared light. Yet other materials that can detect infrared also have a very high background noise, which is known as a dark count. In addition, they have poor performance at the important communication wavelengths of 1310 nm and 1550 nm, and the timing accuracy is relatively low. It will be difficult to realize long-distance quantum communication or deep-space links in the present day. SNSPD is therefore realized. The new devices have had an expansion in the spectrum and are now more accurate and efficient. First, the basic working principle of SNSPDs and its key performance indicators (timing jitter, recovery time, dark count rate, and system detection efficiency) is introduced and evaluated in section 2. Then, some typical applications of quantum information in single-photon LiDAR and deep-space optical communication have also been mentioned in section 3. Finally, the challenges and future prospects is discussed in section 4. This paper hopes to provide some references for future research of quantum photonics, optical sensors, other high-sensitivity communication technology, and so on.

2. Working Principles and Key Performance Indicators of SNSPDs

2.1 Working Principles of SNSPDs

An SNSPD consists of a thin superconducting strip, typically 50-100 nm in width and 5-10 nm thick, which is often arranged into a compact meander structure covering an area of, e.g., 10×10 μm². A bias current is applied to the nanowire, bringing it close to the critical current to ensure single-photon sensitivity. During the operation of the detector, it has to be placed into a low temperature environment (<4K) to keep the superconductivity of the material. As a visible or near-infrared photon is absorbed by the wire (Fig. 1. (II)), it breaks the Cooper pairs, leading to the creation of quasiparticles (Fig. 1. (III)). A non-superconducting area on the strip results from the local suppression of superconductivity since the bias current is already near the critical current. Therefore, the bias current will not flow in the nanowire and will instead pass through the outside circuit. The electronics will read the voltage change on the readout resistor after a photon strikes and then register it (Fig. 1(III)). After most of the current has been diverted, the quasiparticles recombine; at this time, the resistive region cools down (Fig. 1(IV)) and the nanowire re-enters the superconducting state (Fig. 1(I)). To increase the detection efficiency and time accuracy of SNSPDs, some methods have been employed to improve both, such as lensed fibers, thin-substrate back-side illumination, addition of nanowires to dispersed Bragg reflectors, etc.

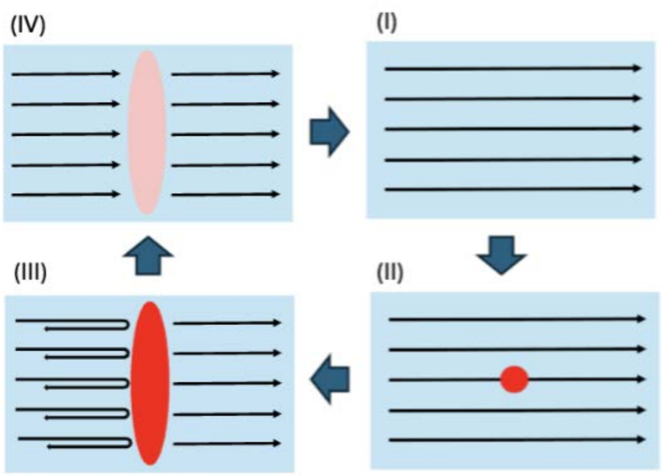

Fig. 1 Schematic of the hotspot formation and recovery process in an SNSPD

2.2 Key Performance Indicators

To assess the performance of an SNSPD, one needs to consider the following indicators. Basic metrics include the recovery time-it is the shortest interval needed before the detector can register another photon after a detection-timing jitter, which is the temporal time interval between a photon hitting the nanowire and the device generating a voltage pulse-and the spectral range, which defines the wavelengths over which the detector operates [1]. After being hit by a photon, SNSPD creates a hot spot in the current-biased superconducting strip. This generates an area that is locally non-superconducting and has thus become a resistor; therefore, a bias current needs to be passed around it, and a voltage pulse will appear. If the output pulse is due to random fluctuations or thermal noise in the device, and not because of light absorption, then it will be reported as an error. The frequency of such errors is called the dark count rate (DCR). The two kinds of dark counts are intrinsic dark counts and backdrop dark counts. The former are due to blackbody radiation, and the latter occur when the bias current is very close to the critical current of the nanowire. The two kinds of dark counts are reduced in different ways. In addition, there are also some indicators of efficiency. Coupling efficiency is the proportion of light from the fiber that reaches the nanowire. Absorption efficiency is the proportion of light that is absorbed by the nanowire. Quantum efficiency is the ratio of the number of electron-hole pairs to the number of incident photons. System detection efficiency (SDE) is thus the first indicator. SDE is a combined index of the three above efficiencies, which is the overall probability that a single photon hitting the detector can be detected [2].

3. Applications of SNSPD

3.1 SNSPD in Quantum Information

The combination of near-unity detection efficiency, low noise, low dark count rate, excellent timing jitter, and chip-integrable compact size has made SNSPDs the central component of quantum information experiments [3].

3.1.1 Quantum communication

Early quantum key distribution (QKD) investigations mostly employed InGaAs/InP single-photon avalanche diodes (SPADs). However, their limited detection efficiency and high dark count rate were unable to keep up with QKD's advancements. Moreover, a huge number of single-photon detectors must be directly integrated into a chip due to the increasing need for complicated quantum photonic circuits [4]. Although SNSPDs require cryogenic cooling, advances in on chip optical cavities, dielectric mirrors, and multilayer nanowire structures have improved their absorption efficiency and simplified integration with planar waveguides. In 2021, Xu et al. reported the fabrication of a single photon detector (SMSPD) with a photon detection efficiency of approximately 92.2% and a DCR of about 200 Hz at a wavelength of 1550 nm. Superconducting detectors are becoming more appealing for high-rate, chip-scale quantum communication systems due to the recent discovery of SMSPDs, which can be fabricated by standard photolithography, and demonstrates even better performance in detection efficiency [5]. Therefore, SNSPDs are now perfect candidates for such integration owing to their compact size and excellent detection accuracy and efficiency.

3.1.2 Quantum computation

Building an optical quantum computer requires photon detectors with near-unity system detection efficiency and photon-number-resolving capability. A 2019 study by Lu et al. and colleagues provides a clear example of SNSPD being the key technology to allow large-scale optical quantum experiments. Lu et al. employed photons to carry out "boson sampling," which is a difficult task for classical computers. The experimental setup involved three key elements: identical single photons, low-loss optical circuits, and near-perfect photon detectors. In practice, a quantum dot generated single photons, which were then split into 20 distinct paths using phase shifters and optical beam splitters. From there, the photons traveled through a sophisticated photonic device containing hundreds of mirrors and beam splitters. Finally, 60 SNSPDs captured every photon, recording all coincidences [6]. This experiment demonstrated the potential of SNSPDs for integration into bigger and more complicated systems by proving that they are capable of supporting large-scale optical quantum investigations.

3.2 SNSPDs in LiDAR and Deep-Space Communication

In single-photon light detection and ranging (LiDAR), a laser pulse is fired at a target, and detectors record the photons that are reflected back. Atmospheric monitoring frequently makes use of this technique [7]. Semiconductor detectors (InGaAs/InP SPADs) are frequently used in traditional single-photon LiDAR systems. Despite their effectiveness, they are constrained by noise or excessive dark count rates, particularly at near-infrared wavelengths. In 2017, Spinosa et al. demonstrated that SNSPD-based LiDAR could detect sea fog at distances of 42.3-63.5 km and 53.2-74.2 km, far exceeding the performance of traditional APD-based systems [8]. At this wavelength, the NbN nanowire detector maintained single-photon sensitivity while traditional APD-based LiDARs failed due to high noise, achieving 80% quantum efficiency with dark counts <100 cps. Furthermore, due to the enormous distances involved, deep-space communications frequently encounter basic difficulties as signals become remarkably weak. NASA's Deep Space Optical Commu-

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nications (DSOC) experiment on the Psyche mission has demonstrated the effectiveness of SNSPD technology as a ground receiver for interplanetary laser communication. In the project, the foundation of the ground receiving terminal of Palomar Observatory's 200-inch Hale Telescope is a specially designed 64-pixel SNSPD array. The detector system achieves a peak system detection efficiency of 76%, a timing jitter below 120 ps, and a maximum count rate of approximately 1 Gcps. The technology demonstrated reliable optical communication from interplanetary distances, achieving more than six times greater timing precision than APD-based alternatives [9].

4. Challenges and Prospects

4.1 Challenges

A major obstacle to putting SNSPDs to practical use is their need for operating temperatures below 4 K. Maintaining such extreme cold requires bulky, expensive cryostats-either large freezers or liquid helium systems. This raises the detecting system's overall volume, power consumption, and construction costs significantly. Therefore, SNSPDs have not been applied to light and mobile devices yet, such as portable quantum key distribution terminals, airborne LiDAR and satellite receivers. Thus, the development of SNSPDs with higher working temperatures is an important research topic, even if novel superconducting materials still face challenges in processing and preparation processes. Moreover, there are also many challenges in the manufacture of SNSPDs. It demands the production of ultrathin (5-10 nm) and narrow (50-100 nm) superconducting nanowires across large areas, with array dimensions extending from $10 \times 10\ \mu m^2$ to several millimeters. Nanoscale imperfections-including pinholes, film thickness nonuniformity, and linewidth fluctuations-can cause localized current crowding, trigger premature hotspot formation, significantly elevate the dark count rate, or even completely suppress superconductivity. Therefore, the high-yield fabrication of large-scale array (such as 64-pixel, 256-pixel and above) is still a technical problem. Additionally, high-precision detectors must be positioned close to the optical coupling structure, for example, lensed fibers and integrated Bragg reflectors, which can also increase complexity in manufacturing.

4.2 Prospects

The core direction for SNSPD advancement focuses on photonic chip integration and hybrid cryogenic system optimization. Smaller system volume and simpler structural design can be achieved from breakthroughs in flip-chip bonding, waveguide-integrated SNSPDs, and multi-channel cryogenic electronics. In the meanwhile, environmental restrictions may be loosened by the development of high-temperature superconductors and cryogenic electronics such nanoscale cryogenic transistors, decreasing the barrier to practical application without compromising performance. To reduce the requirement for low-temperature environments, two-dimensional superconducting materials beyond conventional ones (e.g., niobium nitride and tungsten silicide)-such as niobium titanium nitride, tantalum nitride, and niobium diselenide-have become important research directions. These material advances will push SNSPDs beyond traditional applications into fields including single molecule fluorescence lifetime imaging, biosensing, non-destructive industrial testing, and dark matter detection. Miniaturization, ease of operation, and multifunctional integration are the goals of the new SNSPDs.

5. Conclusion

This paper systematically reviews the working principles, key performance metrics, and typical progress in applications of SNSPDs. The basic measuring metrics, such as system detection efficiency, dark count rate, recovery time, and timing jitter are analyzed. Compared with traditional semiconductor detectors such as SPADs, SNSPDs offer lower noise, higher detection efficiency, and more precise timing, thereby overcoming many practical limitations. In terms of applications, SNSPDs demonstrate outstanding weak light detection accuracy, which have been widely used in quantum information, LiDAR, and deep space optical communications. For quantum information processing, more reliable entanglement distribution and faster quantum key distribution is enabled through high SDE and low DCR. For deep space optical communications, the detector's high sensitivity and fast recovery allow reliable reception of weak laser pulses across vast distances without saturation. For LiDARs, even in photon-starved situations, the minimal timing jitter enhances ranging accuracy and depth resolution.

Future innovation will mainly proceed in two directions: further technological development and expansion into new application fields, driven by the growing demand for quantum information technologies. Despite the ongoing challenges such as system complexity and fabrication consistency, SNSPDs exhibit great potential for applications in biosensing, environmental monitoring and other emerging technologies.

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