Topical Review

The potential and challenges of time-resolved single-photon detection based on current-carrying superconducting nanowires

Hengbin Zhang\textsuperscript{1,}*, Lin Xiao\textsuperscript{1}, Bingcheng Luo\textsuperscript{3}, Jianghua Guo\textsuperscript{4}, Labao Zhang\textsuperscript{5} and Jun Xie\textsuperscript{1,2,6}

\textsuperscript{1} Qian Xuesen Laboratory of Space Technology, Beijing 100094, People’s Republic of China
\textsuperscript{2} Beijing institute of Spacecraft System Engineering, Beijing 100094, People’s Republic of China
\textsuperscript{3} Department of Applied Physics, Northwestern Polytechnical University, Xi’an 710072, People’s Republic of China
\textsuperscript{4} School of Power and Mechanical Engineering, Wuhan University, Wuhan 430072, People’s Republic of China
\textsuperscript{5} Research Institute of Superconductor Electronics, Nanjing University, Nanjing 210093, People’s Republic of China

E-mail: xiejuncast001@163.com

Received 26 February 2019, revised 30 August 2019
Accepted for publication 4 September 2019
Published 14 October 2019

Abstract
Superconducting nanowire-based devices are being hailed as promising single-photon detectors that exhibit excellent combined properties. In particular, their unrivalled time-resolution ability has made these devices potentially revolutionary for the commercial ultrafast single-photon measurement and analysis fields. In this review, we present a detailed summary of the influencing factors and the intrinsic physical mechanism of the temporal resolution in superconducting nanowire single-photon detectors (SNSPDs). We elaborate on the two internal components of temporal resolution, the time response and time jitter, as well as on many measurement methods and device structure modifications attempted to exclude external interference, thus approaching the ultimate limits of time-resolved single photon detection. The investigation of the temporal resolution of SNSPDs not only sheds light on the intrinsic physical mechanism but also contributes to time-related practical engineering applications.

Keywords: temporal resolution, single photon detection, SNSPDs, timing jitter

(Some figures may appear in colour only in the online journal)

\textsuperscript{6} Author to whom any correspondence should be addressed.
1. Introduction

Light is one of the main carriers of information related to life’s activities. The conversion of light into electrical signals is crucial in the understanding of the intrinsic properties of materials and how to take advantage of them. With the extensive work that has been put into developing new photon detection methods, the detection limits have been pushed to the point where it is possible to detect a single photon. Over the past few decades, a number of techniques with sufficient sensitivity have been rapidly developed to detect single and few photons at room temperature without complex readouts, such as the use of avalanche photodiodes (APDs), photomultiplier tubes (PMTs), frequency up-conversion devices, quantum dot field-effect transistors (QDFETs) or single electron transistors. However, combining the overall performance parameters of these techniques to reach the stringent requirements of some optical quantum information applications remains a challenge. Due to the energy gap (meV) being three orders of magnitude lower than that in semiconductors (eV) and cryogenic operation environments (K or even mK), superconducting photon detectors have shown outstanding performance in terms of high sensitivity, low noise and a fast response. According to the different detection mechanisms and device structures, superconducting photon detectors can be classified into superconducting transition edge sensors (TESs), superconducting tunnel junctions (STJs), superconducting kinetic-inductive detectors (KIDs) and superconducting hot-electron bolometers (HEBs). Their ultimate limit detection abilities, such as ultralow dark counts, photon energy resolution, ultrahigh noise-equivalent power and high quantum efficiency, have enabled their widespread application in quantum precise sensing and quantum computing. However, their relatively poor timing performance, in terms of both the response speed and stability, has restricted their application in demanding timing-required fields, such as quantum communication (QC), laser ranging, photon counting and resolution and quantum mechanics experimental verification.

Over the last two decades, superconducting nanowire single-photon detectors (SNSPDs) have been of great interest for ultrafast practical applications. These devices can be patterned into ultrathin, submicrometre-wide meander types. They have shown very high quantum efficiency, negligible dark counts in single-photon detection and, in particular, an incomparable temporal resolution ability, orders of magnitude faster and more stable than that of existing single photodetectors. The detection scenario is relatively simple and can be phenomenologically sketched as follows: the nanostrip is biased just below its critical current, and when a photon irradiates the nanostrip, a localized resistive hot-electron cloud (called a hotspot) is created and triggers a voltage pulse that represents the signal of the incident photon event. The intrinsic response mechanism of SNSPDs to a single photon is complicated and can be roughly divided into three successive steps: photon absorption in the superconducting nanostrips, the generation of a hotspot and the output of a response pulse of the incidence event. Although the first and third stages are relatively well described, the dynamic mechanism responsible for the generation of the normal-conducting domain, which fundamentally determines the response properties of the SNSPDs, is still under debate. After photon absorption, the excited electrons will be thermalized and form the initial hotspot. The thermalization time of electrons is within a few picoseconds and is mainly dependent on the electron–phonon inelastic scattering. The ascending order of
the timescales is e–e inelastic scattering, electron diffusion, electron–phonon (e–p) interaction, phonon–electron (p–e) backflow interaction and phonon escape to the substrate. A diagram of the formation and evolution of hotspots is depicted in figure 1. The initial hot electron is rapidly cooled, mostly through e–e scattering, and a large number of copper pairs is taken apart into an electron bubble; a minor path of energy dissipation is through e–p scattering, and a relatively small amount of phonon bubble is generated. By e–p relaxation and e–e diffusion, the initial resistive hotspot is formed with comparable numbers of electrons and phonons. With further growth of the hotspot, some Cooper pairs are recombined, and the temperature of the hotspot starts to decline. After a sufficiently long timescale, an order of magnitude of approximately a nanosecond, the hotspot shrinks and ultimately disappears with the energy escape from the phonons to the substrate, and the Cooper pairs arrange in order again, waiting for the next photon to arrive.

With the fast development and broad application prospects of SNSPDs, the detection mechanism, device structures, properties and applications of this detector have been described in detail in a series of reviews [1–3]. However, in recent years, although many theoretical and experimental studies have explored the temporal resolution of SNSPDs and attempted to use new readout circuit schemes and multi-pixel arrays to realize higher maximum count rates and lower timing jitter, further improving the temporal resolution or even approaching the ultimate intrinsic limit is still challenging and is the basis of this review. The logic of this review is as follows. To comprehend the intrinsic physics of the temporal resolution and thereby guide further improvements for advanced applications, we will first review the current understanding of the detection mechanism in SNSPDs in section 2. Then, we present an overview of the time-related modern quantum optics applications of SNSPDs in section 3, both fundamental and practical. The main part of this paper will be section 4. The temporal resolution consists mainly of two parts: the response time and timing jitter, and the factors affecting both, are analysed in detail. The influences of the readout circuit and multi-pixel arrays on the temporal resolution of SNSPDs are also elaborated in section 4. In section 5, we summarize the new device structure of SNSPDs, including the superconducting nanowires, substrates and optically coupled structures. Finally, we end with a discussion and outlook on the further improvements and developments of temporal resolution in this field.

2. Operation mechanism of SNSPDs

Understanding the response mechanism of SNSPDs is vital in illuminating the intrinsic physics of the temporal resolution and thereby crucial to further improving devices for extremely timing-demanding advanced applications. Increasing evidence indicates the essential role of quantum mechanical-related behaviours in at least certain aspects of SNSPDs [3, 4]. Semenov and Gol’tsman first proposed the classical hotspot model to elucidate the detection mechanism of SNSPDs [5, 6]. The absorption of photons is assumed to generate numerous quasi-particles (QPs). The QP cloud has a radius larger than the superconducting coherence length ξ, and the normal-conducting core will then spread so that the current density around the normal core exceeds the critical current density, thus generating a voltage drop that represents the detection event. The time evolution of the number of QPs in the ξ-slab (nmax) as well as in the whole nanowire (rth) were both calculated for a 1000 nm wavelength photon absorbed in a TaN film, as shown in figure 2(a) [4]. The ξ-slab defines the minimum volume corresponding to the coherent length that has to switch from superconducting into the normal conducting state. Immediately after the photon absorption (t = 1 ps), the QPs are highly concentrated in a very small volume, leading to a significant suppression of superconductivity near the absorption site. Then at t = tmax = 2.6 ps, the maximum number of QPs in the ξ-slab is already reached. The total number of excess QPs in the complete strip continues to increase until t = rth = 10.5 ps, whereas a significant number of QPs has diffused out of the ξ-slab despite the relatively low diffusion coefficient Dqp at this low temperature, resulting in the faster drops of the concentration of QPs in the ξ-slab.

Although the hotspot model agrees with several experimental observations, such as the observed linear relation between the energy of incident photon and the detection threshold bias current [7], linear cut-off photon wavelength–nanowire width relation [8] and the detection threshold bias current–temperature dependence at lower temperatures of T/TC < 0.5 [9], this model predicts a downshift of the threshold bias current at higher temperatures of T/TC > 0.5 and cannot explain the photon absorption position of threshold bias current [10]. Furthermore, the hotspot model predicts a deterministic response: the detector responds to all photons of a particular energy, or it does not. It is contradictory to the experimental results that the count rates were exponentially decreased as the bias current was reduced below the threshold bias current [11]. Therefore, the detection signal may be triggered by some type of thermal activation or quantum mechanical behaviour. A candidate for these fluctuations is a vortex, which becomes increasingly important, even essential, to the formation of the initial resistive domain that triggers a detection event [12–14]. Below the Kosterlitz–Thouless topological transition, the vibration of vortex–antivortex pairs and pinned vortices or the thermal activation of magnetic Pearl vortices over the potential barrier will cause dissociation of pairs or vortex entry from one edge, resulting in dark and photon counts. Hence, the thermally excited hopping of magnetic vortices can be obviously affected by the thermal coupling of the superconducting nanowire [15, 16]. By increasing the strength of the thermal coupling of the NbN nanowire to the heat sink or using stacked multi-layer pancake SNSPDs, the dark count rate can be significantly suppressed due to the lower obstruction of the vortex movement across the nanowire potential barrier. The vortex-based model was further verified by a number of magnetic field transport measurements [17–20]. Recently, an experimental investigation of MoSi SNSPDs indicated that the detection model is also photon energy-dependent [21]. The detection of relatively high-energy photons (λ = 450 nm) obeys the hotspot model, and there is no vortex-induced behaviour, but for lower energy photons (λ = 1000 nm), it is probably related to vortex penetration from the edges of the film.
Another candidate for these quantum fluctuations is phase slip. In 2004, Engel et al ascribed the major source of dark counts to fluctuations in the superconducting order parameter [22]. Vodolazov et al described the suppression of the superconducting order parameter, in which a photon is absorbed, by solving the Ginzburg–Landau equation, and the results were coincident with recent experimental results [23]. Through the electronic transport characterization of a 4 nm thick NbN film below 6 K, Delacour et al found that no hotspot is formed and that phase slips are stable even at the lowest temperatures [24]. The electrical transport properties of NbTiN also revealed the superconducting phase slip phenomena and superconducting-insulator transitions for superconducting nanowires [25]. Very recently, Madan et al proposed that in 1D nanowires, the vortices must be replaced by fluctuating topological phase defects, and photon transitions between different dynamically stable states can be detected and manipulated by ultrashort laser pulses [26], as illustrated in figure 2(b). The right hand side panel plots the phase-slip evolution during one period in different locations along the nanowire using the 1D TDGL equations. The x,y coordinate axis correspond to the different locations along the wire and the time period. Adapted from [26]. CC BY 4.0.

Figure 2. (a) The calculated time evolution of the numbers of QPs for a 1000 nm wavelength photon absorbed by TaN SNSPDs. The marked τ_{qp}, t_{max} and τ_{th} represent the QP multiplication time, the maximum number of QPs in the slab of length equal to the coherence length and the time of the maximum total number of QPs in the complete superconducting strip, respectively. The x, y coordinate axis corresponds to the different positions across the nanowire in the transverse direction and longitudinal direction, respectively. Adapted from [4], with the permission of AIP Publishing. (b) Schematic representation of the order parameter ψ = |ψ|eiθ and resistance as a function of time during photon switching. Absorption of the pulse leads to a transient reduction in the order parameter, eventually resulting in a state with more PSCs and a higher resistance. The timing of the laser pulse and the phase slip configurations are indicated. The right panel plots the phase-slip evolution using the 1D-TDGL equations. The x,y coordinate axis correspond to the different locations along the wire and the time period. Adapted from [26]. CC BY 4.0.

3. Applications

3.1 Time-related applications

The unrivalled time-resolved ability of SNSPDs makes them the detector of choice in time-demanding fields, not only for fundamental research but also for system engineering applications. SNSPDs are widely used in quantum mechanics experimental verification. The Hadfield group first applied an SNSPD system to characterize an InGaAs quantum dot single photon source. They analysed the suitability of the twin SNSPD scheme for the characterization of single optically pumped, microcavity-coupled InGaAs QDs through Hanbury-Brown Twiss (HBT) interferometer measurement, which utilizes the correlation and anti-correlation effects in the intensities received by two detectors from a beam of particles, and a spontaneous emission lifetime of 370 ps and a second-order correlation function (g(2)) of 0.24 ± 0.03 [27] were obtained. Later, by directly integrating an SNSPD with a ridge waveguide, a single integrated photonic device was achieved and characterized by an average QD spontaneous emission timing jitter of only 72 ps [28]. Kahl et al realized a waveguide-integrated single photon spectrometer. Behaviours. However, increasing evidence supports the essential role of some types of quantum fluctuations, such as vortex and phase slip, in the detection mechanisms of SNSPDs.
capable of parallel multiple wavelength detection, which could image silicon vacancy colour centres in diamond nanoclusters [29].

In addition to the single photon source characterizations, SNSPDs can also improve the entangled photon pair generation and quantum state reconstruction with their low timing jitter, negligible dark count rate and inherent nonlinearities. By using SNSPDs at approximately 50 MHz count rates in a 5 ps timing window, a coincidence to accidental-coincidence ratio >80 and coherent interference fringe visibility >98% were obtained without any data post-processing [30]. In addition, fidelity in generating 780 and 1522 nm wavelength-entangled photon pairs as high as 0.93 ± 0.04 was achieved with SNSPD-based difference frequency conversion [31].

The excellent timing properties of SNSPDs are extremely desirable in the field of system engineering applications. The Yamamoto group first applied an SNSPD system to 200 km dispersion-shifted fibre-based quantum key distribution (QKD) with a 12.1 bit s⁻¹ secure key rate and a 42 dB channel loss, which was the first 10 GHz clock QKD system [32]. By using SNSPDs with lower dark counts of 0.01 cps, the length of the QKD increased to 336 km (72 dB loss), and the quantum bit error rate decreased to below 3%. To test the robustness of the QKD system to hacking attack, the SNSPD chip was blindly illuminated for a period of 1 ms, and the generated fake voltage pulse did not lead to a significantly elevated timing jitter, which proved the anti-attack ability of the SNSPD-based QKD system [33]. Recently, Pan’s group extended the measurement-device-independent QKD (MDIQKD) to over 404 km using ultralow-loss optical fibre and an optimized four-intensity decoy-state approach [34]. The schematic of the entire MDIQKD system is shown in figure 3(a), where the twin SNSPDs constitute a Bell state measurement device. This system achieved a new distance record for QKD and broke the traditional Bennett–Brassard protocol.

Another notable system engineering application of SNSPDs is remote and eye-safe laser ranging with low energy levels, which is strongly dependent on the time properties of the single-photon detector. Employing an SNSPD-based time-correlated single-photon counting (TCSPC) system, You’s group first demonstrated a 4 mm depth resolution for 115 m distance time-of-flight laser ranging at a 1550 nm wavelength [35]. Then, they conducted a satellite laser ranging (SLR) laboratory principle verification experiment at a 532 nm wavelength using the NbN SNSPD, and the equivalent depth ranging precision for the LARES satellite was 8 mm [36]. Practical space-to-ground laser ranging measurement based on SNSPDs has just become a reality at the Yunnan Observatory of China [37], as shown in figure 3(b). At a wavelength of 1064 nm, long-distance laser ranging of the target satellites Cryosat (1600 km), Ajisai (3100 km), and Glonass (19 500 km) was experimentally tested, with mean reflection

---

**Figure 3.** (a) Schematic of the MDIQKD system. Alice and Bob are two identical legitimate users, and the twin SNSPD constitutes a Bell state measurement device. Inset: the components of the MDIQKD setup. Adapted figure with permission from [34], Copyright 2016 by the American Physical Society. (b) Diagram of the SLR system based on SNSPDs as a photon detection module and the astronomical calibration and navigation system. Adapted with permission from [37]. © The Optical Society of America.
count rates of 1200 min⁻¹, 4200 min⁻¹, and 320 min⁻¹, respectively, which indicated the feasibility of remote laser ranging for satellites from low Earth orbit to geostationary Earth orbit using an SNSPD system. Moreover, optical coherence-domain reflectometry (OCDR), an optical technique that uses low-coherence light to capture micrometre resolution within optical scattering media, holds great potential for few-photon imaging applications. Mohan et al. first demonstrated an OCDR system that consisted of NbN SNSPDs and chirped periodically poled LiTaO₃ [38]. Due to the broadband wavelength region ranging from 700 to 1500 nm and the count rates being as high as 100 MHz, coherence-domain images for a variety of samples, such as a mirror, could be constructed. Taking advantage of the high efficiency and ultrafast temporal resolution of SNSPDs, Zhao et al. integrated SNSPDs into optical time domain reflectometry (OTDR) systems and achieved a 46.9 dB dynamic range corresponding to a 20 m two-point resolution and a 209.47 km sensing distance [39]. Recently, SNSPD-based systems have been widely extended to various fundamental research areas and practical applications, such as true random number generators (TRNGs) [40], optical near-field interaction characterization [41], single photon imagers [42] and dual-frequency Doppler lidars [43].

3.2. Multi-wavelength applications

SNSPDs are distinguished by their outstanding performance in the visible and near-infrared wavelengths. However, their application field can be extended to other wavelengths of photons, even to electrons and biomolecules, where the temporal resolution is also challenging but critical. At terahertz wavelengths, Valavanis et al. used antenna-coupled SNSPDs to measure nanosecond time-resolved photons from a terahertz quantum cascade laser, which cannot be accomplished using traditional bolometric or hot-electron detectors [44]. At ultraviolet wavelengths, Wollman et al. designed and fabricated ultraviolet SNSPDs with the combined properties of high quantum efficiency (>70%), negligible dark count rates (0.25 h⁻¹) and high timing resolution (sub-ns) [45]. Inderbitzin’s group first investigated the possibility of using SNSPDs for continuous photon detection at soft x-ray wavelengths. The device parameters and operation conditions of X-SNSPDs are quite different from those of infrared or optical SNSPDs. Generally, the superconducting film is much thicker (100 nm) to ensure acceptable quantum efficiency. Meanwhile, the tolerance to bias currents for an X-SNSPD spans a wide range. The device can respond to a single photon at a bias current as low as 1% Ic, and the negligible dark count rates are maintained as the bias current is increased to 99% Ic. Furthermore, the ultrafast rise and recovery of the bias current make the X-SNSPD susceptible to latching at all temperatures, which could be improved by modifying the device geometry [46, 47].

In addition, SNSPDs can be used for the detection of ions with low kinetic energies [48]. The different responses observed for photons and atoms are due to the changed surface conditions of the detector. Nb0.7Ti0.3N SNSPDs demonstrated the ability for single electron detection, although the back-scattered electrons triggered some irregular events outside the active area of the device [49]. Detection of alpha- and beta-particles was also demonstrated, with unprecedented overall performance. The detection efficiency was close to unity, with excellent spatial resolution [50]. These detectors were blind to gamma rays from different sources, unlike the current macroscopic particle detectors.

Furthermore, the high timing accuracy of SNSPDs is promising for obtaining the mass spectra of biomolecules to characterize biomacromolecule systems. Using a large-area 200 × 200 μm² Nb nanostrip, time-of-flight mass spectrometry (TOF-MS) of angiotensin I and lysozyme was realized with a voltage pulse rise time and relaxation time of approximately 400 and 500 ps, respectively [51]. By introducing a time-to-digital converter, the count rate was increased, and hence, the mass spectra statistics were improved. Zen et al. utilized other superconducting materials, such asNb and YBCO, which have faster response times and similar response times at higher temperatures, respectively, compared to those of NbN. The relationship between SNSPD geometry and performance was investigated [52–55]. Casaburi et al. realized a TOF-MS system with a parallel strip-line configuration with a 2 × 2 mm² sensitive area for heavy biomolecules. They obtained a subnanosecond rise time and a few nanoseconds fall time with the keV energy range of molecular ions. Such parallel SNSPDs also enabled discrimination of the charge states of singly and doubly charged monomers and singly charged dimmers [56]. In conclusion, the outstanding temporal resolution has obviously expanded the application areas of SNSPDs not only to multi-wavelength photons but also to a wide variety of analytes.

4. The temporal resolution of SNSPDs

The temporal resolution of a single-photon detector is the minimal time interval between successively arriving photons, which can be distinguished in the response voltage pulse. For SNSPDs, differing definitions of temporal resolution are found in the literature, and we decomposed them into the response time and time jitter given by Sobolewski et al. [57, 58]. Considering the response time-induced temporal resolution, the subsequent photon will be lost if the detector has not recovered from the preceding incidental photon, and this temporal resolution is fundamentally determined by the intrinsic formation of the hotspot and the time evolution of the normal-conducting domain. The limitation of the time jitter originates from the uncertainty of the photon arrival time, which will give rise to indistinguishability or even errors in the time stamps of the photon sequence. Although the microscopic detection mechanism of SNSPDs is not absolutely clear, increasing evidence indicates that the temporal resolution is not only affected by the external operation conditions and device structure but also depends on the intrinsic physical mechanism and material parameters, such as the thermalization of QPs, energy transfer between the electrons and phonons, relaxation...
of hotspots, and the distribution of electronic and geometric inhomogeneities.

4.1. The response time

The response time is an essential factor that fundamentally determines the maximum count rates of SNSPDs and is mainly limited by the kinetic inductance and input impedance of read-out circuits [59]. From the voltage output, the response time consists of the rise time and fall time, i.e. \( t_{\text{response}} = t_{\text{rise}} + t_{\text{fall}} \). The rise time corresponds to the transition time of the nanowire from superconducting state to normal state, and the fall time refers to the converse transition, which frequently refers to relaxation time. Slysz et al measured the rise time, fall time and FWHM of the photon response signal of fibre-coupled NbN SNSPDs to be 250 ps, 5 ns and approximately 2.5 ns, respectively, which were limited by the meander high kinetic inductance [60]. Recently, Smirnov et al observed that the rise time of the voltage pulse nonlinearly increases from 150 ps to 400 ps with increasing meander nanowire length from 20 to 605 \( \mu \text{m} \) [61], as illustrated in figure 4(a), and they explained this phenomenon by taking into account the larger normal-conducting domain for longer nanowires and hence larger kinetic inductance \( L_k \).

Suzuki et al further confirmed the effects of kinetic inductance on the time resolution of SNSPD-based TOF-MS. Due to the smaller kinetic inductance with wider linewidth, the rise time and relaxation time for angiotensin 1 detection were 640 ps and 22 ns, respectively, for nanowires with 200 nm linewidths and were 360 ps and 9 ns, respectively, for nanowires with 300 nm linewidths [62]. Due to the direct proportion of the nanowire length to the detection efficiency, there is a trade-off between the kinetic inductance and the detection efficiency. To solve this problem, the kinetic inductance can be reduced through optical fibre coupling to a smaller active area, which can improve the timing performance of SNSPDs (relaxation time \(< 2 \text{ ns}, \text{ timing jitter } < 25 \text{ ps}) without sacrificing the detection efficiency [63].

Figure 4. The different response time-related characteristics of SNSPDs. (a) Experimental and theoretical rise time of the response signal as a function of nanowire length in a NbN SNSPD. Inset: Experimental and theoretical nanowire length dependence of the response time. Adapted from [61], with the permission of AIP Publishing. (b) Electron–phonon relaxation time measured from a hot-electron experiment for three TiN samples. The fitted solid line shows the T-3 temperature dependence of \( \tau_{ep} \). Adapted from [72], with the permission of AIP Publishing. (c) Time evolution of the injected energy going into the electronic system (\( E_e \)) under different \( \gamma \) and initial conditions. (Inset) The dynamics of \( E_e \) under an electron-bubble initial condition. The dashed lines indicate the linear dependence \( E_e = E_{\text{photon}}(1 - t/\tau_{\text{leak}}) \). Adapted with permission from [75], Copyright 2017 by the American Physical Society. (d) Normalized detection probability as a function of the pump-probe photon relaxation time for different bias currents. The solid lines indicate the Lorentzian fit of the measured curves. Adapted with permission from [79]. © The Optical Society of America.
which not only overcame the limitation of the kinetic inductance but also enhanced the detection efficiency by more than an order of magnitude [64].

However, if the response of the SNSPDs speeds up too rapidly, then joule heating will produce a self-heating hot-spot, resulting in the device being locked in a resistive state called latching [65]. By defining a damping coefficient \( \zeta = \frac{\tau_e}{\tau_p} \), where \( \tau_e \) is a thermal time constant and \( \tau_p \) is a recovery time constant, the latching effect is determined by the ratio of the electrical and thermal time constants and can be elucidated and is quantitatively consistent with a set of experimental results. To avoid latching, gated-mode operation of a bistable superconducting nanowire system was introduced, and a 625 MHz count rate was obtained with a large active area and a low dark count rate [66]. Similarly, Liu et al attributed the latching to improper bias of SNSPDs and adopted a quasi-constant-voltage bias approach to obtain a higher signal-to-noise ratio (SNR) and a smaller timing jitter without latching [67]. Annunziata et al investigated the intrinsic dynamics of latching in Nb SNSPDs and found that latching occurred when the hotspot cooling time was longer than the inductive time constant, which can be avoided by decreasing the temperature-dependent e–p inelastic scattering time [68]. However, the heat transfer cannot be enhanced infinitely; although the response time can be very rapid without latching, the nanowire will miss the photon because the excited hotspot will disappear too quickly to respond.

Although the response time is obviously limited by the large kinetic inductance and external readout circuits, the intrinsic generation and evolution dynamics of QPs determine the lower limit of the response time [5, 6, 69]. Lindgren et al first reported femtosecond time-resolved measurements with a YBCO microbridge [70]. Using pump-probe spectroscopy measurements and Rothwarf–Taylor theory, they measured and simulated the timing parameters, i.e. the electron thermalization time, e–p relaxation time, p–e scattering time and QP recombination time, to be 0.56, 1.1, 42 and 0.86 ps, respectively. A similar time-resolved measurement based on Hg-based high-temperature superconducting (HTS) implied that the Cooper pair breaking and formation processes are not limited by the phonon bottleneck [71]. Hence, the ultrafast electron thermalization time relative to the e–p interaction time of HTS indicated that the hot-electron process, as the primary determinant of the response time for HTS, totally dominated the early stages of electron relaxation.

In contrast to HTS thin film-based SNSPDs, the hotspot relaxation time \( \tau_{hs} \) in low-temperature superconducting material-based SNSPDs is determined primarily by the e–p interaction time, but the electron thermalization time cannot be totally neglected [6]. Kardakova et al directly measured the e–p relaxation time in disordered TiN films using the hot-electron experimental setup, which coincides with the T-3 relation for three samples with different thicknesses as illustrated in figure 4(b) [72]. The magnetoconductance measurements in 2D amorphous WSi films revealed \( \tau_{p-e} \) and \( \tau_{e-p} \) to be approximately 7 ps and 100 ps, respectively [73]. The ratio of the specific heat capacities of electrons and phonons, \( C_e/C_p \), equal to \( \tau_{p-e}/\tau_{e-p} \) within the two temperature models [74], was provided by optical photoresponse measurements and the kinetic-equation approach [75], as illustrated in figure 4(c). The time scale of the injected energy diffusion to the electronic and phonon system is dependent on coefficient \( \gamma \) from 1 to 100, where \( \gamma = \frac{8\pi^2 k_B^2}{\tau_{e-p} \tau_{p-e}} |T_e - T_p| \). For \( \gamma = 100 \), the majority of the injected energy has already shared between electrons and phonons subsystem by the time \( t \approx 0.001\tau_0 \), and this equilibrium time increases with a decrease of \( \gamma \). Hence, larger \( \tau_{e-p}/\tau_{p-e} \) and \( \tau_{p-e}/\tau_{e-p} \) ratios indicate that the photon energy is more efficiently confined in the electron subsystem and that a larger hotspot size (\( \sim 100 \text{ nm} \) in WSi [76] and \( \sim 23 \text{ nm} \) in NbN [77]) will occur.

In addition to the above intrinsic QP time scales, the relaxation time is also material-dependent and affected by the working conditions. The kinetic theoretical model and two-photon detection experiments based on pump-probe spectroscopy indicate that the \( \tau_{hs} \) of a WSi superconducting nanowire is proportional to the bias current, the temperature or the excitation energy [76, 78]. Ferrari et al systematically investigated the hotspot relaxation dynamics in NbN waveguide-integrated SNSPDs over a broad bias current range [79]. Using the near-infrared pump-probe technique operating in the two-photon regime, they observed a rapidly increasing relaxation time for higher bias currents, as illustrated in figure 4(d). With increasing the bias currents toward the departing current, the second incident photon can trigger a detection event even after relatively longer time interval of the absorption of the first photon. By extracting the HWHM of the Lorentzian fit of the measurement curve, a minimum relaxation time of approximately 22 ps was obtained when the bias current corresponded to 50% of the critical current. The bias current dependence of detector tomography is a criterion to estimate the photon detection regimes, which involves a short slab for conventional SNSPDs compared with other photon number resolution (PNR) detectors. In addition, the dependence of \( \tau_{hs} \) on the bath temperature, nanowire linewidth, substrate material and quality of the superconducting film was also systematically investigated for NbN SNSPDs [80]. In addition to the strong influence of the bias current, \( \tau_{hs} \) was also strongly affected by the substrates, such as Si, MgO, MgF\(_2\) and Al\(_2\)O\(_3\). The minimum and maximum \( \tau_{hs} \) values were 11.6 and 34.5 ps for the MgO (100) and Si (100) substrates, respectively. To summarize, the affecting factors of the response time of SNSPD are complicated. It is intrinsically determined by the QPs evolution and interaction process, such as electron diffusion, electron–phonon interaction, and e–e inelastic scattering and so on. In addition, the operation parameter, such as nanowire thickness, bias current, temperature, substrate and so on, significantly influence the response time of SNSPDs as summarized in table 1. Generally, the response process can be divided into two successive steps, the formation and relaxation of a hot-spot, which corresponds to the rise and fall time of the voltage pulse. The former is generally faster than the latter, but both are influenced by many intrinsic and operation parameters. We can synthetically design the specific parameters to further improve the response time in the future.
4.2. The timing jitter (response time stability)

The timing jitter is another key temporal resolution parameter that denotes the deviation of the arrival time of a single photon from an ideal periodic response voltage pulse and fundamentally limits the accurate determination of the photon arrival times in time correlation measurements. Especially for the time-tagged photon sequence, the fluctuation of the arrival time will result in errors and pose a fundamental limitation to the accuracy of time stamp-related experiments. Recently, many groups have reported lower timing jitter values, and the system jitter induced by the instruments has been thoroughly analysed and discussed [81, 82]. In the TCSPC measurement system, You et al derived the SNSPD system timing jitter as: 

$$j_{\text{system}} = \sqrt{j_{\text{intr}}^2 + j_{\text{SNR}}^2 + j_{\text{sync}}^2 + j_{\text{SPC}}^2},$$

where $j_{\text{intr}}$, $j_{\text{SNR}}$, $j_{\text{sync}}$ and $j_{\text{SPC}}$ are, respectively, the intrinsic jitter, the jitter induced by the low SNR, the jitter from the synchronization signal and the jitter from the TCSPC module. For NbN SNSPDs working at 1550 nm, the typical values of the last four factors are 5, 0.1, 4.0 and 7.6 ps, respectively. The factors $j_{\text{SNR}}$, $j_{\text{sync}}$ and $j_{\text{SPC}}$ are determined by readout circuits, which can be overcome in the future with the rapid development of low-noise cryogenic amplifiers; we will provide a detailed review of SNSPD-based readout circuits in section 4.4. However, the origin of the intrinsic timing jitter affects the underlying detection mechanism of SNSPDs, which remains elusive; recent simulation results estimated it to be approximately 1 ps [83], which is one order of magnitude smaller than the lowest measurement thus far.

The first intrinsic timing jitter is position-dependent timing jitter, which is induced from the different positions where the photon arrived at the nanowire, both longitudinally and transversely. Pearlman et al first proposed that transverse position-dependent photon absorption can contribute to the timing jitter. Owing to the smaller size hotspot that occurs when the photon is absorbed close to the edge of the stripe relative to the centre, the higher maximum temperature rise of electron $T_e$ will lead to a sharp increase in the delay time compared to when the photon strikes the nanowire centre [84]. Recently, Hu et al proposed that the position-dependent response time induced by the vortex-crossing process varied with the fluctuation of the cross-section of the nanowire where the photons are absorbed [83], as illustrated in figure 5(b), and they demonstrated the cross-section fluctuation-induced timing jitter by characterizing the dependence of the timing jitter on the bias current, the nanowire width and the polarization of the photon. It must be pointed out that the timing jitter induced by the uncertainty of the photon absorption along the transverse direction is tiny, less than 1 ps, and can be decreased by narrowing down the width of the nanowire, but its intrinsic characteristic makes it rather difficult to overcome.

Another type of position-dependent timing jitter is longitudinal. Berdiyorov et al confirmed the longitudinal spatially dependent of the photon response. The maximal sensitivity occurs when the photon acts on the centre of the nanowire, away from the turning point [85], as shown in figure 5(a). If we regard the superconducting nanowire as a transmission line, the contribution of the geometric jitter cannot be neglected, especially when the length and area of the SNSPD increase. When the size of the SNSPD device increases from $3 \times 3 \text{ mm}^2$ to $20 \times 20 \text{ mm}^2$, the variance in the differential propagation time increases from a few picoseconds to approximately 50 ps and can be suppressed by 20% using the differential cryogenic readout [86]. Sidorova et al systematically investigated the underlying physical mechanisms of the intrinsic timing jitter, and they divided the position-dependent jitter $j_{\text{local}}$ into $j_{\text{bend}}$ and $j_{\text{wire}}$, which correspond to the contributions of the bent and straight wire, respectively. As illustrated in figure 5(c), with decreasing photon energy and bias current, the detection scenario transitions from a deterministic regime to a probabilistic regime, where the intrinsic jitter is mainly determined by the straight parts of meanders and areas adjacent to the bends [87, 88]. Compared with the transverse position-dependent timing jitter, the longitudinal position-dependent timing jitter

![Table 1. Affecting factors and ultimate restrictions of temporal resolution.](image-url)
is greater and positive to the total length of the nanowire, but it can be suppressed by nanowire structure variance and new readout electronics, as stated in sections 4.3 and 4.4.

A distributed inhomogeneity, such as a defect or a constriction, is another cause of the intrinsic timing jitter. Experimental results have shown the strongly inhomogeneous nature of NbN films on the sub-100 nm scale [89], which has a significant influence on the performance of SNSPDs, such as the observed large detection efficiency fluctuation [90, 91] and reduced detection efficiency with a single defect or constriction [92]. Hortensius et al simulated electronic inhomogeneity- or disorder fluctuation-induced random local variations of the critical temperature along the nanowire [93], as illustrated in figure 5(d), which coincided with the stepwise pattern of the current–voltage curve. O’Connor et al proved that constrictions arising from device fabrication induced up to 20 ps of timing jitter from high- and low-sensitivity parts of the device [94]. Recently, combining the electro-thermal model with the Monte Carlo method, the effects of random electronic and geometric fluctuations were simulated, and the distributed inhomogeneity induced most of the total sub-15-ps timing jitter [95], as shown in figure 5(e). The inhomogeneity and localized constrictions generated different local properties of the hotspots, restricted the maximum bias current, slowed the thermal relaxation time and consequently increased the inhomogeneity-induced timing jitter. Some experiments demonstrated that the fluctuations in the SNSPD response are dominated by the distributed inhomogeneity for wide nanowires [96] (>90 nm) and are significantly influenced by Fano fluctuations for narrow nanowires [97] (<30 nm). By introducing artificial constrictions into nanowires, the factors affecting the inhomogeneity-induced timing jitter were investigated [98], and the results could be used to minimize the intrinsic timing jitter and shed light on its underlying mechanism.

Finally, Fano fluctuations caused by the branching processes, which result in variations in the fractions of energy deposited between the subsystems, such as electrons and phonons, are known to determine the theoretical limit of spectral resolution and the noise characteristics of superconducting sensors, such as STJs and MKIDs. In 2017, Caloz et al characterized the bias current dependence of the detection probability for MoSi SNSPDs at the 750–2050 nm wavelength range and found results indicative of Fano fluctuations in the nonlinear energy–current relation [99]. Recently, Kozorezov et al proposed that especially in narrow nanowire SNSPDs, the Fano fluctuation-induced timing jitter overwhelmed the

Figure 5. The different factors affecting the timing jitter in SNSPDs. (a) Voltage response as a function of the photon absorption location near the inner corner. Adapted from [85], with the permission of AIP Publishing. (b) Schematic drawing of the cross-section uncertainty-induced timing jitter and local Josephson voltage variance in SNSPDs. The total output voltage is the photons absorbed at one edge of the nanowire ($x_0 = 45$ nm) or on the central line of the nanowire ($x_0 = 0$). Adapted from [83], with the permission of AIP Publishing. (c) Contributions to the local jitter from bends (triangles) and straight wires (circles) with varied bias current. Open and closed symbols correspond to wavelengths of 1560 and 800 nm, respectively. Adapted from with permission of [87], Copyright 2017 by the American Physical Society. (d) Simulation of the electronic inhomogeneity- or disorder fluctuation-induced random local variations of the critical temperature along the nanowire. © 2013 IEEE. Adapted, with permission, from [93]. (e) Simulation of the effect of random fluctuations in the width and thickness on the inhomogeneity-induced timing jitter. Adapted from [95], with the permission of AIP Publishing.
position-dependent response uncertainty and was the most notable factor in the width of the error function of the timing jitter [96]. It should be noted that Fano fluctuations determine the theoretical ultimate limit for the timing jitter of an SNSPD [100] and will be the last remaining challenge in advancing the performance of SNSPDs into a subpicosecond timing jitter.

4.3. Multiple array nanowire structures

The temporal resolution of generally meander-shaped SNSPDs is mutually exclusive with some other detector performance metrics, such as the quantum efficiency and dark counts. To overcome these limitations, some multiple array nanowire structures, such as the superconducting nanowire avalanche single-photon detectors (SNAPs), multi-element SNSPDs (MESNPDs) and the combination of both, are proposed. Ejrnæs et al first designed SNAPs with five parallel connection nanowires based on a cascade switching mechanism, which lowers the detector inductance compared with the same coverage area single-meander nanowire and reduces the response time to well below 1 ns [101]. The slow decrease in the signal pulse fall time to 7.8 ns for a detector area as large as 84 × 84 µm² permits a higher maximum count rate and fully exploits the available cooling power. However, the timing jitter values were comparable to conventional meander SNSPDs, even asymmetric ones, and 1.5 times larger at a high bias current of 235 µA. Later, the response time and timing jitter were further reduced to 200 ps and 54 ps with $N = 8$ [102] and 12 [103] parallel nanowires, respectively, as shown in figure 6(a). By further increasing $N$ to 24 parallel nanowires, the time-resolved hotspot evolution in SNSPDs was directly visualized, and a 1 ns time delay was observed between the maximum hotspot relaxation rate and the maximum hotspot expansion rate, which open a new approach to investigate the time-resolved physics mechanism of the hotspot for the future [104].

Additionally, to increase the number of parallel nanowires, a range of papers have studied temporal resolution improvement through narrowing the nanowire width of SNAPs. Marsili et al first reported SNAPs with ultranarrow (<30 nm) nanowires, which were shown to be more robust to constrictions and increased the voltage amplitude by a factor of four compared to the standard ~100 nm wide nanowire [97]. The reset time of such ultranarrow SNAPs could be sped up to approximately 1 ns at the expense of an unstable operating regime, a threshold bias current and afterpulsing [105]. However, the timing jitter of ultranarrow SNAPs is bias current-dependent. For a bias current close to the critical current, the timing jitter was comparable to that of conventional SNSPDs, sub-35 ps, while for a lower bias current, the most likely response time was prolonged, and the FWHM of the response time was broadened and disordered, thereby inducing a larger timing jitter [106].

Figure 6. Multiple element structures with better timing characteristics compared with those of traditional meander-shaped SNSPDs. Adapted from [103], with the permission of AIP Publishing. (a) Equivalent circuit diagram of the parallel structure detector, and timing characteristics of five- and twelve-parallel-nanowire devices. (b) Equivalent circuit of the $2 \times 3$-SNAP, and single-shot voltage patterns from a standard SNSPD, the series-3-SNAP, the $2 \times 2$-SNAP, the $2 \times 3$-SNAP, and the $3 \times 3$-SNAP. © 2017 IEEE. Adapted, with permission, from [112].
Recent investigations found that MESNSPD design significantly influences the temporal resolution of SNSPDs, including both the response time and timing jitter. Additionally, by combining an array of pixels through spatial or temporal multiplexing, SNSPDs can also have PNR ability [107, 108]. PNR ability is often researched using prototypes for quantum information applications, especially for linear optics quantum computation, and PNR is crucial for reducing errors. Dauler et al. first tested the high temporal performance of an MESNSPD with a sub-30-ps timing jitter. Four times the maximum count rate was achieved with PNR ability, which is suitable for second-order intensity correlation measurements without the requirement for a beam splitter [109]. By using nano-optical techniques and spatially separated pixels of parallel wires, the triggering regimes of single and multiple photons could be explicitly distinguished, demonstrating a faster timing response in the two-pixel trigger regime than the one-pixel regime. With each element fully integrated into an independent waveguide circuit, the $20 \times 12$ matrix of SNSPDs showed a 455-ps decay time with a $20 \mu m$ total nanowire length and an 18.4-ps jitter limited by the oscilloscope bandwidth of 6 GHz [110].

Recently, a novel design combined the advantages of SNAPs and multi-element series SNSPDs to improve the timing performance and the SNR. Miki et al. achieved a 7.65-fold improvement in the response speed compared with that of standard SNSPDs and a 68 ps timing jitter with two serially connected SNAPs (SC-2SNAPs) [111]. Based on this novel structure design, Cheng et al. fabricated five different designs, including standard SNSPDs, series-3-SNAPs, and three modified double-stage avalanche structures, $k \times m$-SNAPs ($k = 2, m = 2; k = 2, m = 3; k = 3, m = 3$), and compared the output voltage patterns of these five different designs, as shown in figure 6(b). The exponential decay times were proportional to $1/(k \times m)^2$ and were the fastest at 0.89 ns for the $3 \times 3$-SNAPs and slowest at 63.2 ns for the standard SNSPDs, which can be ascribed to the lack of choke inductors [112]. It is believed that a novel multiarray variant of the meander nanowire structure in the future should shed light on the detection mechanism and offer the possibility of further improving the temporal resolution of SNSPDs.

4.4. Relevant readout electronics

The timing performance of SNSPDs is greatly influenced by the readout electronics that sense and amplify the photon detection signal. Room temperature readout electronics are straightforward and easy to access. Zhao et al. increased the
count rate by four times and removed the circuit limits by adding a grounded capacitor to the conventional readout circuits [113]. A TCSPC circuit can also be integrated with SNSPDs [114, 115], which enables good arrival time accuracy close to the intrinsic timing jitter, as low as approximately 17 ps. Additionally, the time-tagged multiplexed readout of small SNSPD arrays based on TCSPC allows the high temporal and spatial resolution of single photon detection using only a narrow planar delay line [116]. A proof of concept experiment consisting of two detector elements validated the predictability and discrimination of two successive photons, as shown in figure 7(a). Recently, Doerner et al took advantage of KIDs and SNSPDs and introduced the concept of the radio-frequency superconducting nanowire single-photon detector (RF-SNSPD) [117, 118], which allows the convenient frequency division multiplexing of SNSPD arrays with only one feed line. The 16-pixel RF-SNSPD simultaneously possesses good temporal resolution and spatial resolution and PNR ability, and a single pixel requires only a bandwidth of 14 MHz, which presents promising prospects for large-scale array integration.

Due to the limited cooling power of the compact cryostat and the relatively large thermal conductivity of the room temperature connection lines, the large-scale array integration of SNSPDs has been severely restricted by room temperature readout electronics. Therefore, various low-noise cryogenic readout electronics have been developed. The improved readout electronics of the high-electron-mobility transistor (HEMT)-based readout technique integrated with an SNSPD detector and a high-load resistor have a photon-energy resolution ability and can discriminate dark pulses from actual photon pulses by comparing output pulse amplitude distributions [119, 120]. Compared with semiconductor amplifiers, superconducting single-flux-quantum (SFQ) circuits combine the advantages of microwatt power dissipation, GHz count rates, a sub-10- ps timing jitter and a large-scale array integration ability, which are especially suitable for multi-pixel SNSPD readout [121, 122]. The measured input pulse duration and timing jitter were 1.6 ns and 37 ps, respectively, which were both better than those of the conventional readout without an SFQ readout circuit. Recently, researchers integrated two SNSPDs with an SFQ circuit and achieved a 32.5 ps timing jitter for the entire coincidence detection system, which is approximately two times lower than that for the commercial TCSPC module, as illustrated in figure 7(b), and the results revealed Hong–Ou–Mandel interference with a weak coherent pulse [123]. In addition, adiabatic quantum flux parametron (AQFP) [124] and superconducting quantum interference device (SQUID)-based cryogenic circuits [125] were also promising alternatives to optimize the readout of an SNSPD output pulse.

5. New device structures of SNSPDs

The common micro-nano-processing procedure for SNSPDs is electron beam lithography (EBL) following reactive ion etching, which sets a limit for large-scale arrays. Beyer’s group first used optical lithography (OL) to fabricate a WSi SNSPD with 64 pixels [126]. Compared to EBL, the OL technique requires less time by over two orders of magnitude to fabricate the same structure and has a much lower cost. Another fabrication method utilizes an atomic force microscope [127], where the insulating niobium oxynitride lines are directly written with a voltage-biased tip; the filling factor of the superconducting meander line can be increased up to 80%. Recently, a new approach based on nonlinear femtosecond optical lithography was used to fabricate ultrathin NbN SNSPDs and realize a spatial resolution close to 50 nm for the formation of planar structures [128].

Superconducting nanowires can be designed with a spiral shape and produce a profound effect on the timing jitter of the device. Compared with the conventional meander shape, spiral patterned nanowires can prevent the current crowding effect on sharp turns of the meander nanowire, and no polarization-sensitive and current crowding effect is observed in spiral SNSPDs [129]. Charaev et al investigated the influence of magnetic fields on the detection performance for different spiral-shaped nanowire structures [130]. The critical current and the photon and dark count rates in square spirals were all asymmetric with respect to the magnetic field direction; in contrast, circular spirals showed fully symmetric dependencies. Recently, these authors showed that the presence of bends in a superconducting nanowire can decrease the detection probability of low-energy photons. The nanowires were shaped as a meander, a double-spiral layout with an S-turn in the middle and a single-spiral layout without such a turn, and the largest and smallest cut-off wavelengths were found for the single-spiral layout and for the meander, respectively [131].

Recently, some novel pixel array structures have proven to be effective at enhancing the overall system performances of SNSPDs. Verma et al vertically stacked several WSi layers to form a tridimensional SNAP [132], which enhanced the system detection efficiency and reduced the polarization dependence compared to traditional planar SNSPDs. Later, these authors separated two meander nanowires by a thin insulating barrier, which could be utilized to improve the system performance through a thermal avalanche process [133]. Recently, Florya et al investigated the sandwich structure of a thin amorphous silicon layer intercalated into three superconducting amorphous tungsten silicide layers [134], and both the avalanche and arm-trigger regimes were illustrated. Heat propagation processes in the three-layer detection pixel were simulated after the absorption of a single photon with energy of 1–1000 eV [135]. By connecting up to 70 narrow superconducting strips in parallel, a maximum of seven subsequent incident photons can be resolved using interarrival time analysis [136]. The multiple parallel structure of nanowires significantly influences the timing performance of SNSPDs, which we discussed in section 4.3.

The photon coupling methods also fundamentally determine the overall properties, including the time parameters. Unlike the ordinary cavity-integrated or fibre-coupled approaches, Akhlaghi et al integrated a U-shaped NbTiN nanowire with a silicon-on-insulator waveguide and embedded it into an asymmetric nanobeam cavity, achieving a near
unity on-chip quantum efficiency and a 55 ps timing jitter performance for 1545 nm wavelength photons [137]. You’s group demonstrated a 100 µm diameter active area SNSPD with a distributed Bragg reflector acting as an optical cavity coupled with a 105 µm multi-mode optical fibre [138], which increased the count rates by one order of magnitude, from 1 to 10 MHz. Generally, a higher detection efficiency and lower timing jitter cannot be accomplished in one SNSPD structure. However, by embedding the nanowires in a racetrack resonator, the photons were trapped in the cavity, and the interaction time was increased with only a 1 µm nanowire length [139]. This novel structure improves the temporal resolution without sacrificing the possible detection efficiency. Alternatively, by illuminating a superconducting nanowire with front-side-coupled 1D silver or gold optical nanoantennae in free space, the system detection efficiency can be enhanced by 50% to 130% without losing the timing performance [140, 141]. Recently, some progress based on alternative materials has demonstrated excellent performances with both detection efficiency and timing jitter take into account [142–145], due to the typically lower critical currents. To better balance the absorption efficiency with the length of SNSPDs, Lu et al. introduced an asymmetric metal-insulator-metal subwavelength concentric ring grating structure and achieved 99.6% absorption of the energy using a filling factor as sparse as 0.2 in the nanowire arrangement [146]. The plasmonic nature of a superconducting layer [147] and non-periodic dielectric multilayers [148] were also utilized to enhance the surface absorption of incident optical photons. To reduce the polarization sensitivity of SNSPDs, high refractive index compensation materials [149] and a SiN, dielectric layer [150] were capped on NbN-based SNSPDs, and a polarization sensitivity below 0.1 was realized at both 1.31 and 1.55 µm wavelengths. Recently, Cheng et al. separated the optical path and electrical path on the opposite sides of the chip by using a back-illuminated detector structure, which achieved a high performance comparable to that obtained when using metal reflectors or distributed Bragg reflectors while exhibiting more potential for compact multi-channel integration applications [151]. There is no doubt that with various novel device structures appearing in the near future, the overall system properties of SNSPDs will reach a new height.

6. Conclusion

Single-photon detectors have evolved considerably in the past few decades, opening up new avenues in quantum physics research and quantum optical technologies. The use of SNSPDs is a powerful new approach that allows simultaneous high efficiency, negligible dark counts, high speed and low jitter detection of a single photon from the microwave to x-ray broadband, and even of particles or biomolecules. In this review, we focused on the temporal resolution of SNSPDs, whose mechanism is not thoroughly understood, therefore restricting further precision improvements for timing-related applications, such as QC and laser ranging. In table 1, we provide a comprehensive summary of the affecting factors and the intrinsic physical mechanism of the temporal resolution in SNSPDs, both internal and external. We must note that the parallel development of measurement techniques and device structures is crucial in revealing the intrinsic temporal resolution limited by the photon detection mechanism itself, which has been masked by instrumental aspects. Just before this review was submitted, successive papers reported the latest research on the temporal resolution for straight nanowires using a new dual-readout technique, and a sub-3ps timing jitter was realized in SNSPDs [152]. We are convinced that with improved experimental methods and device structures, the remaining restriction on the temporal resolution must be a relevant internal mechanism that is challenging but intriguing and deserving of intensive studies. Ultimately, the investigation into the temporal resolution of SNSPDs not only contributes to practical engineering applications but also sheds light on the intrinsic physical mechanism of such detectors and other superconducting detectors.

Acknowledgments

This work was funded by the National Key R&D Program of China (2017YFB0503300) from the Ministry of Science and Technology.

ORCID iDs

Hengbin Zhang https://orcid.org/0000-0002-6197-5122

References

[1] Natarajan C M, Tanner M G and Hadfield R H 2012 Superconducting nanowire single-photon detectors: physics and applications Supercond. Sci. Technol. 25 063001
[2] Dauler F A, Grein M E, Kerman A J, Marsili F, Miki S, Nam S W, Shaw M D, Terai H, Verma V B and Yamashita T 2014 Review of superconducting nanowire single-photon detector system design options and demonstrated performance Opt. Eng. 53 081907
[3] Engel A, Renema J J, Il’in K and Semenov A 2015 Detection mechanism of superconducting nanowire single-photon detectors Supercond. Sci. Technol. 28 114003
[4] Engel A and Schilling A 2013 Numerical analysis of detection-mechanism models of superconducting nanowire single-photon detector J. Appl. Phys. 114 214501
[5] Gol’tsmans G N, Okunev O, Chulkova G, Lipatov A, Semenov A, Smirnov K, Voronov B, Dzardanov A, Williams C and Sobolewski R 2001 Picosecond superconducting single-photon optical detector Appl. Phys. Lett. 79 705–7
[6] Semenov A D, Gol’tsmans G N and Sobolewski R 2002 Hot-electron effect in superconductors and its applications for radiation sensors Supercond. Sci. Technol. 15 R1–16
[7] Renema J J, Frucci G, Zhou Z, Mattioli F, Gaggero A, Leonri R, de Dood M J A, Fiore A and van Exter M P 2013 Universal response curve for nanowire superconducting single-photon detectors Phys. Rev. B 87 174526
[8] Lusche R, Semenov A, Il’in K, Siegel M, Korneeva Y, Trifonov A, Korneev A, Goltsman G, Vodolazov D and Huebers H W 2014 Effect of the wire width on the intrinsic
Topical Review

[9] Engel A, Inderbitzin K, Schilling A, Lusche R, Semenov A, Huebers H-W, Henrich D, Hotherr M, Il’i in K and Siegel M 2013 Temperature-dependence of detection efficiency in NbN and TaN SNSPD IEEE Trans. Appl. Supercond. 23 2300505

[10] Renema J J et al 2015 Position-dependent local detection efficiency in a nanowire superconducting single-photon detector Nano Lett. 15 4541–5

[11] Verevkin A, Zhang J, Sobolewski R, Akunev O, Chulkova G, Korneev A, Smirnov K, Gol’tsmann G N and Semenov A 2002 Detection efficiency of large-active-area NbN single-photon superconducting detectors in the ultraviolet to near-infrared range Appl. Phys. Lett. 80 4687–9

[12] Semenov A D et al 2007 An energy-resolving superconducting nanowire photon counter Supercond. Sci. Technol. 20 919–24

[13] Kitaygorsky J J et al 2007 Dark counts in nanostructured NbN superconducting single-photon detectors and bridges IEEE Trans. Appl. Supercond. 17 275–8

[14] Renema J J et al 2014 Experimental test of theories of the detection mechanism in a nanowire superconducting single-photon detector Phys. Rev. Lett. 112 117604

[15] Hotherr M, Ball L, Il’i in K, Semenov A, Huebers H W and Siegel M 2012 Dark count suppression in superconducting nanowire single photon detectors J. Low Temp. Phys. 167 822–6

[16] Salim A J, Eftekharian A and Majedi A H 2014 High quantum efficiency and low dark count rate in multi-layer superconducting nanowire single-photon detectors J. Appl. Phys. 115 054514

[17] Renema J J et al 2015 The effect of magnetic field on the intrinsic detection efficiency of superconducting single-photon detectors Appl. Phys. Lett. 106 092602

[18] Vodolazov D Y, Korneeva Y P, Semenov A V, Korneev A A and Gol’tsmann G N 2015 Vortex-assisted mechanism of photon counting in a superconducting nanowire single-photon detector revealed by external magnetic field Phys. Rev. B 92 104503

[19] Zhang X, Engel A, Wang Q, Shilling A, Semenov A, Sidorova M, Huebers H W, Charaev E, Il’i n K and Siegel M 2016 Characteristics of superconducting tungsten silicide W2Si1-x for single photon detection Phys. Rev. B 94 174509

[20] Nasti U, Parlati L, Erijmaa M, Cristiano R, Taino T, Myoren H, Sobolewski R and Pepe G 2015 Thermal fluctuations in superconductor/ferromagnet nanostripes Phys. Rev. B 92 014501

[21] Korneev A A et al 2015 Characterization of MoSi superconducting single-photon detectors in the magnetic field IEEE Trans. Appl. Supercond. 25 2200504

[22] Engel A, Semenov A, Huebers H W, Il’i n K and Siegel M 2004 Superconducting single-photon detector for the visible and infrared spectral range J. Mod. Opt. 51 1459–66

[23] Vodolazov D Y 2014 Current dependence of the red boundary of superconducting single-photon detectors in the modified hot-spot model Phys. Rev. B 90 054519

[24] Delacour C, Pannetier B, Villegier J C and Bouchiat V 2012 Quantum and thermal phase slips in superconducting niobium nitride (NbN) ultrathin crystalline nanowire: application to single photon detection Nano Lett. 12 3501–6

[25] Makise K, Terai H, Tominari Y, Tanaka S and Shinozaki B 2016 Duality picture of superconductor-insulator transitions on superconducting nanowire Sci. Rep. 6 27001

[26] Madan I, Buh J, Baranov V V, Kabanov V V, Mrzel A and Mihailovic D 2018 Nonequilibrium optical control of dynamical states in superconducting nanowire circuits Sci. Adv. 4 eaao0043

[27] Hadfield R H, Stevens M J, Mirin R P and Nam S W 2007 Single-photon source characterization with twin infrared-sensitive superconducting single-photon detectors J. Appl. Phys. 101 103104

[28] Reithmaier G, Lichtmannecker S, Reichert T, Hasch P, Mueller K, Bichler M, Gross R and Finley J J 2013 On-chip time resolved detection of quantum dot emission using integrated superconducting single photon detectors Sci. Rep. 3 1901

[29] Kahl O, Ferrari S, Kovalyuk V, Vetter A, Lewes-Malandrakis G, Nebra C, Korneev A, Gol’tsmann G and Pernice W 2017 Spectrally multiplexed single-photon detection with hybrid superconducting nanophotonic circuits Optica 4 557–62

[30] Liang C, Lee K F, Medic M, Kumar P, Hadfield R H and Nam S W 2007 Characterization of fiber-generated entangled photon pairs with superconducting single-photon detectors Opt. Express 15 1322–7

[31] Ikuta R et al 2013 High-fidelity conversion of photonic quantum information to telecommunication wavelength with superconducting single-photon detectors Phys. Rev. A 87 010301

[32] Takesue H, Nam S W, Zhang Q, Hadfield R H, Honjo T, Tamaki K and Yamamoto Y 2007 Quantum key distribution over a 40 dB channel loss using superconducting single-photon detectors Nat. Photon. 1 343–8

[33] Tanner M G, Makarov V and Hadfield R H 2014 Optimised quantum hacking of superconducting nanowire single-photon detectors Opt. Express 22 6734–48

[34] Yin H-L et al 2016 Measurement-device-independent quantum key distribution over a 404 km optical fiber Phys. Rev. Lett. 117 190501

[35] Chen S et al 2013 Time-of-flight laser ranging and imaging at 1550nm using low-jitter superconducting nanowire single-photon detection system Appl. Opt. 52 3241–5

[36] Li H et al 2016 Superconducting nanowire single photon detector at 532 nm and demonstration in satellite laser ranging Opt. Express 24 3535–42

[37] Xue L et al 2016 Satellite laser ranging using superconducting nanowire single-photon detectors at 1064nm wavelength Opt. Lett. 41 3648–51

[38] Mohan N, Minaeva O, Gol’tsmann G N, Nasr M B, Saleh B E A, Sergienko A V and Teich M C 2008 Photon-counting optical coherence-domain reflectometry using superconducting single-photon detectors Opt. Express 16 18118–30

[39] Zhao Q et al 2015 Long-haul and high-resolution optical time domain reflectometry using superconducting nanowire single-photon detectors Sci. Rep. 5 10441

[40] He Y et al 2016 Bias-free true random number generation using superconducting nanowire single-photon detectors Supercond. Sci. Technol. 29 085005

[41] Luszcz K, Bonvin E and Novotny L 2018 Optical near-field mapping with a superconducting nanowire photon detector Appl. Phys. Lett. 113 011103

[42] Zhao Q, Zhu D, Calandri A, Dale A E, McCaughan A N, Bellal F, Wang H Z, Santavicca D F and Berggren K K 2017 Single-photon imager based on a superconducting nanowire delay line Nat. Photon. 11 247

[43] Zhangguan M, Xia H, Wang C, Qiu J, Lin S, Dou X, Zhang Q and Pan J-W 2017 Dual-frequency Doppler lidar for wind detection with a superconducting nanowire single-photon detector Opt. Lett. 42 3541–4

[44] Valavanis A et al 2013 Time-resolved measurement of pulse-to-pulse heating effects in a terahertz quantum cascade laser using an NbN superconducting detector Appl. Phys. Lett. 103 061120

[45] Wollman E E et al 2017 UV superconducting nanowire single-photon detectors with high efficiency, low noise, and 4 K operating temperature Opt. Express 25 26792–801
[46] Inderbitzin K, Engel A and Schilling A 2013 Soft x-ray single-photon detection with superconducting tantalum nitide and niobium nanowires IEEE Trans. Appl. Supercond. 23 2200505

[47] Zhang X, Wang Q and Schilling A 2016 Superconducting single x-ray photon detector based on W0.8Si0.2 AIP Adv. 6 115104

[48] Cristiano R, Ejrnaes M, Casaburi A, Zen N and Ohkubo M 2015 Superconducting nano-strip particle detectors Supercond. Sci. Technol. 28 124004

[49] Rosticher M, Ladan F R, Maneval J P, Dorenbos S N, Zijlstra T, Klapwijk T M, Zwiller V, Lupascu A and Nogues G 2010 A high efficiency superconducting nanowire single electron detector Appl. Phys. Lett. 97 183106

[50] Azzouz H, Dorenbos S N, De Vries D, Urena E B and Vetter A 2007 Fibre-coupled, single photon detector J. Phys. D: Appl. Phys. 39 255

[51] Inderbitzin K, Engel A and Schilling A 2013 Soft x-ray single-photon detection with superconducting tantalum nitide and niobium nanowires IEEE Trans. Appl. Supercond. 23 2200505

[52] Kerman A J, Yang J K W, Molnar R J, Dauler E A and Berggren K K 2009 Electrothermal feedback in superconducting nanowire single-photon detectors Phys. Rev. B 79 100509

[53] Akhlaghi M K and Majedi A H 2012 Gated mode superconducting single photon detectors Opt. Express 20 1608–16

[54] Liu D-K, Chen S-J, You L-X, Wang Y-L, Miki S, Wang Z, Xie X-M and Jiang M-H 2012 Nonlatching superconducting nanowire single-photon detection with quasi-constant-voltage bias Appl. Phys. Express 5 125202

[55] Annunziata A J et al 2010 Reset dynamics and latching in niobium superconducting nanowire single-photon detectors J. Appl. Phys. 108 084507

[56] Zhang J, Slysz W, Pearlman A, Verevkin A, Sobolewski R, Okunev O, Chulkova G and Ohkubo M 2008 Time delay of resistive-state formation in superconducting stripes excited by single optical photons Phys. Rev. B 67 132508

[57] Lindgren M, Currie M, Williams C, Hsiang T Y, Fauchet P M, Sobolewski R, Moffat S H, Hughes R A, Preston J S and Hegmann F A 1999 Intrinsic picosecond response times of Y–Ba–Cu–O superconducting photodetectors Appl. Phys. Lett. 74 853–5

[58] Li X, Xu Y, Chromik S, Sirbik V, Odier P, De Barros D and Sobolewski R 2005 Time-resolved carrier dynamics in Hg-based high-temperature superconducting photodetectors IEEE Trans. Appl. Supercond. 15 622–5

[59] Kardakova A, Finkel M, Morozov D, Kovalyuk V, An P, Dunscombe C, Tarkhov M, Mauskopf P, Klapwijk T M and Goltsman G 2013 The electron–phonon relaxation time in thin superconducting titanium nitride films Appl. Phys. Lett. 103 252602

[60] Zhang X, Lita A E, Sidorova M, Verma V B, Wang Q, Sae Woo N, Semenov A and Schilling A 2018 Superconducting fluctuations and characteristic time scales in amorphous WSi Phys. Rev. B 97 174502

[61] Perrin N and Vanneste C 1983 Response of superconducting films to a periodic optical irradiation Phys. Rev. B 28 5150–9

[62] Vodolazov D Y 2017 Single-photon detection by a dirty superconducting nanowire single-photon detector IEEE Trans. Appl. Supercond. 27 8739–87

[63] Marsili F et al 2016 Hotspot relaxation dynamics in a current-carrying superconductor Phys. Rev. B 93 094518

[64] Renema J J, Gaudio R, Wang Q, Gaggero A, Mattioli F, Leoni R, van Exter M P, Fiore A and de Dood M J A 2017 Probing the hotspot interaction length in NbN nanowire superconducting single photon detectors Appl. Phys. Lett. 110 233103

[65] Koszorezov A G et al 2015 Quasiparticle recombination in hotspots in superconducting current-carrying nanowires Phys. Rev. B 92 064504

[66] Ferrari S, Kovalyuk V, Hartmann W, Vetter A, Kahl O, Lee C, Korneev A, Rockstuhl C, Gol’tsman G and Pernice W 2017 Hot-spot relaxation time current dependence in niobium nitride waveguide-integrated superconducting nanowire single-photon detectors Opt. Express 25 8739–50

[67] Zhang L, You L, Wu H, Gu C, Cheng Y and Hu X 2017 Vortex-crossing-induced timing jitter of superconducting nanowire single-photon detectors Appl. Phys. Lett. 111 062603

[68] Zhang J, Slysz W, Pearlman A, Verevkin A, Sobolewski R, Okunev O, Chulkova G and Gol’tsman G N 2003 Time delay of resistive-state formation in superconducting stripes excited by single optical photons Phys. Rev. B 67 132508
[84] Pearlman A et al 2005 Gigahertz counting rates of NbN single-photon detectors for quantum communications IEEE Trans. Appl. Supercond. 15 579–82

[85] Berdiyorov G R, Milosevic M V and Peeters F M 2012 Spatially dependent sensitivity of superconducting meanders as single-photon detectors Appl. Phys. Lett. 100 262603

[86] Calandrì N, Zhao Q-Y, Zhu D, Dane A and Berggren K K 2016 Superconducting nanowire detector jitter limited by detector geometry Appl. Phys. Lett. 109 152601

[87] Sidorova M, Semenov A, Huebers H-W, Charaev I, Kuzmin A, Doerner S and Siegel M 2017 Physical mechanisms of timing jitter in photon detection by current-carrying superconducting nanowires Phys. Rev. B 96 184504

[88] Sidorova M, Semenov A, Huebers H-W, Charaev I, Kuzmin A, Doerner S, Ilin K, Siegel M, Charaev I and Vodolazov D 2018 Timing jitter in photon detection by straight superconducting nanowires: effect of magnetic field and photon flux Phys. Rev. B 98 134504

[89] Gandhi R, Hoog K P M O, Zhou Z, Sahin D and Fiore A 2014 Inhomogeneous critical current in nanowire superconducting single-photon detectors Appl. Phys. Lett. 105 222602

[90] Kerman A J, Dauler E A, Yang J K W, Rosford K M, Anant V, Berggren K K, Gol’tsman G N and Voronov B M 2007 Constriction-limited detection efficiency of superconducting nanowire single-photon detectors Appl. Phys. Lett. 90 101110

[91] Zotova A N 2016 The contribution of bands and constrictions of a superconducting film to the photon detection by a single-photon superconducting detector J. Exp. Theor. Phys. 122 818–22

[92] Hadfield R H, Dalgalno P A, O’Connor J A, Ramsay E, Warburton R J, Gansen E J, Baek B, Stevens M J, Mirin R P and Nam S W 2007 Submicrometer photoresponse mapping of nanowire superconducting single-photon detectors Appl. Phys. Lett. 90 201116

[93] Hortensius H L, Driesen E F C and Klappwijk T M 2013 Possible indications of electronic inhomogeneities in superconducting nanowire detectors IEEE Trans. Appl. Supercond. 23 2200705

[94] O’Connor J A, Tanner M G, Natrajan C M, Buller G S, Warburton R J, Miki S, Wang Z, Nam S W and Hadfield R H 2011 Spatial dependence of output pulse delay in a niobium nitride nanowire superconducting single-photon detector Appl. Phys. Lett. 98 201116

[95] Cheng Y, Gu C and Hu X 2017 Inhomogeneity-induced timing jitter of superconducting nanowire single-photon detectors Appl. Phys. Lett. 111 062604

[96] Kozorezov A G, Lambert C, Marsili F, Stevens M J, Verma V B, Allmaras J P, Shaw M D, Mirin R P and Nam S W 2017 Fano fluctuations in superconducting–nanowire–single-photon detectors Phys. Rev. B 96 054507

[97] Marsili F, Najafi F, Dauler E, Belloni F, Hu X, Csete M, Molnar R J and Berggren K K 2013 Single-photon detectors based on ultranarrow superconducting nanowires Nano Lett. 13 2048–53

[98] Zhang L et al 2014 Characterization of superconducting nanowire single-photon detector with artificial constrictions AIP Adv. 4 067114

[99] Caloz M, Korn B, Timoney N, Weiss M, Gariglio S, Warburton R J, Schoenenger C, Renema J, Zbinden H and Bussieres F 2017 Optically probing the detection mechanism in a molybdenum silicide superconducting nanowire single-photon detector Appl. Phys. Lett. 110 083106

[100] Allmaras J P, Kozorezov A G, Korzh B A, Berggren K K and Shaw M D 2019 Intrinsic timing jitter and latency in superconducting nanowire single-photon detectors Phys. Rev. Appl. 11 034062

[101] Ejrnaes M et al 2019 Timing jitter of cascade switch superconducting nanowire single photon detectors Appl. Phys. Lett. 95 132503

[102] Zhao Q, McLaughan A N, Dane A E, Najafi F, Bellei F, De Fazio D, Sunter K A, Ivry Y and Berggren K K 2014 Eight-fold signal amplification of a superconducting nanowire single-photon detector using a multiple-avalanche architecture Opt. Express 22 24574–81

[103] Tarkhov M et al 2008 Ultrafast reset time of superconducting single photon detectors Appl. Phys. Lett. 92 241112

[104] Ejrnaes M, Casaburi A, Mattioli F, Leoni R, Pagano S and Cristiano R 2010 Time-resolved observation of fast hotspot dynamics in superconducting nanowires Phys. Rev. B 81 132503

[105] Marsili F, Najafi F, Dauler E, Molnar R J and Berggren K K 2012 Afterpulsing and instability in superconducting nanowire avalanche photodetectors Appl. Phys. Lett. 100 112601

[106] Najafi F, Marsili F, Dauler E, Molnar R J and Berggren K K 2012 Timing performance of 30 nm-wide superconducting nanowire avalanche photodetectors Appl. Phys. Lett. 100 152602

[107] Divochiy A et al 2008 Superconducting nanowire–number-resolving detector at telecommunication wavelengths Nat. Photon. 2 302–6

[108] Kobayashi T, Ikuta R, Yasaki S, Miki S, Yamashita T, Terai H, Yamamoto T, Koashi M and Imoto N 2016 Frequency-domain Hong–Ou–Mandel interference Nat. Photon. 10 441

[109] Dauler E A, Stevens M J, Baek B, Molnar R J, Hamilton S A, Mirin R P, Nam S W and Berggren K K 2008 Measuring intensity correlations with a two-element superconducting nanowire single-photon detector Phys. Rev. A 78 053826

[110] Schuck C, Perrnice W H P, Minaeva O, Li M, Gol’tsman G, Sergienko A V and Tang H X 2013 Matrix of integrated superconducting single-photon detectors with high timing resolution IEEE Trans. Appl. Supercond. 23 2201007

[111] Miki S, Yabuno M, Yamashita T and Terai H 2017 Stable, high-performance operation of a fiber-coupled superconducting nanowire avalanche photon detector Opt. Express 25 6796–804

[112] Cheng R, Poot M, Guo X, Fan L and Tang H X 2017 Large-area superconducting nanowire single-photon detector with double-stage avalanche structure IEEE Trans. Appl. Supercond. 27 2200805

[113] Zhao Q, Jia T, Gu M, Wan C, Zhang L, Xu W, Kang L, Chen J and Wu P 2014 Counting rate enhancements in superconducting nanowire single-photon detectors with improved readout circuits Opt. Lett. 39 1869–72

[114] Shcheslavskiy V, Morozov P, Divochiy A, Vakhitomin Y, Smirnov K and Becker W 2016 Ultrafast time measurements by time-correlated single photon counting coupled with superconducting single photon detector Rev. Sci. Instrum. 87 053117

[115] Wu J, You L, Chen S, Li H, He Y, Lv C, Wang Z and Xie X 2017 Improving the timing jitter of a superconducting nanowire single-photon detector system Appl. Opt. 56 2195–200

[116] Hofherr M, Arndt M, Il’i in K, Henrich D, Siegel M, Toussaint J, May T and Meyer H G 2013 Time-tagged multiplexing of serially biased superconducting nanowire single-photon detectors IEEE Trans. Appl. Supercond. 23 2501205

[117] Doerner S, Kuzmin A, Wuensch S, Ilin K and Siegel M 2016 Operation of superconducting nanowire single-photon detectors embedded in lumped-element resonant circuits IEEE Trans. Appl. Supercond. 26 2200205

[118] Doerner S, Kuzmin A, Wuensch S, Charaev I, Boes F, Zwick T and Siegel M 2017 Frequency-multiplexed bias and readout of a 16-pixel superconducting nanowire single-photon detector array Appl. Phys. Lett. 111 032603
