Fraunhofer

April 2026

Photon Detectors for Quantum Key Distribution – Technology Overview and Future Perspectives

Imprint

Photon Detectors for Quantum Key Distribution – Technology Overview and Future Perspectives

Report coordination

Fraunhofer Institute for Systems and Innovation Research ISI

Breslauer Strasse 48, 76139 Karlsruhe, Germany
Saeideh Shirinzadeh, saeideh.shirinzadeh@isi.fraunhofer.de

Responsible for content

Saeideh Shirinzadeh, Fraunhofer ISI, saeideh.shirinzadeh@isi.fraunhofer.de
Chie Endo, Fraunhofer ISI, chie.endo@isi.fraunhofer.de
Thorsten A. Goebel, Fraunhofer IOF, thorsten.albert.goebel@iof.fraunhofer.de
Thomas Schmaltz, Fraunhofer ISI, thomas.schmaltz@isi.fraunhofer.de
Lukas Weymann, Fraunhofer ISI, lukas.weymann@isi.fraunhofer.de

Contributing institutes

Fraunhofer Institute for Applied Optics and Precision Engineering IOF

Albert-Einstein-Str. 7, 07745 Jena
Thorsten A. Goebel, thorsten.albert.goebel@iof.fraunhofer.de

Compiled in the context of

Umbrella Project for Quantum Communication in Germany
(Schirmprojekt Quantenkommunikation Deutschland – SQuaD),
funded by the Federal Ministry of Research, Technology and Space
(Bundesministerium für Forschung, Technologie und Raumfahrt – BMFTR)

With funding from the:

Federal Ministry
of Research, Technology
and Space

Picture credits

Cover page: Heyko Stöber, Hohenstein

Published

April 2026

DOI

10.24406/publica-6629

License

Notes

Contents

List of Abbreviations

2DEG	Two-Dimensional Electron Gas
C-band	Telecom C-band (≈1550 nm)
CV-QKD	Continuous-Variable Quantum Key Distribution
CW	Continuous Wave
DCR	Dark Count Rate
DV-QKD	Discrete-Variable Quantum Key Distribution
G–M	Gifford–McMahon (cryocooler)
InGaAs/InP-SPAD	Indium Gallium Arsenide/Indium Phosphide Single-Photon Avalanche Diode
JT	Joule–Thomson (cooler)
KTP	Potassium Titanyl Phosphate
LiDAR	Light Detection And Ranging
LO	Local Oscillator
MCR	Maximum Counting Rate
MKID	Microwave Kinetic Inductance Detector
MoSi	Molybdenum Silicide
NbN	Niobium Nitride
NbTiN	Niobium Titanium Nitride (appears as Nb(Ti)N)
NIR	Nea-Infrared
O-band	Telecom O-band (≈1310 nm)
OCDE	On-Chip Detection Efficiency
PDE	Photon Detection Efficiency
PMT	Photomultiplier Tube
PNR	Photon Number Resolution
QBER	Quantum Bit Error Rate
QD cRTD	Quantum Dot Coupled Resonant Tunneling Diode
QDFET	Quantum Dot Field-Effect Transistor
QDs	Quantum Dots
QKD	Quantum Key Distribution
RSK	Secret Key Rate

RTD	Resonant Tunneling Diode
SDE	System Detection Efficiency
Si-SPAD	Silicon Single-Photon Avalanche Diode
SNSPD	Superconducting Nanowire Single-Photon Detector
SPD	Single-Photon Detector
SWaP	Size, Weight, and Power
TEC	Thermoelectric Cooler
TES	Transition Edge Sensor
VIS	Visible spectrum
WSi	Tungsten Silicide

Zusammenfassung und Kernergebnisse (German)

In diesem Bericht werden die technologischen Ansätze für Einzelphotonen-Detektoren (SPDs) für den Quantenschlüsselaustausch auf Basis diskreter Variablen (DV-QKD) beschrieben, mit besonderem Fokus auf:

Einzelphotonen-Avalanche-Photodioden (SPADs) auf Basis von Silizium (Si-SPADs)
SPADs auf Basis von Indium-Gallium-Arsenid/Indium-Phosphid (InGaAs/InP-SPADs)
Supraleitende Nanodraht-Einzelphotonen-Detektoren (SNSPDs)

In dieser Studie werden Erkenntnisse aus der wissenschaftlichen Literatur und Experteneinschätzungen zusammengeführt, um die typische Leistung, Einsatzfähigkeit, Stand der Kommerzialisierung sowie die Eignung von Detektoren für QKD-Anwendungsfälle in Glasfaser-, Freistrahl- und Satellitenverbindungen mit Hinblick auf erzielbare Distanz und Schlüsselraten einzuordnen. Ein Kernergebnis ist der bestehende Trade-off zwischen Leistungsprofil und dem Betriebsaufwand und -kosten. SNSPDs bieten höchste Leistungsparameter, während SPAD-basierte Optionen (Si und InGaAs/InP) einen geringeren Kühlaufwand, geringere Kosten und einfachere Integration bieten.

Einzelphotonen-Detektoren stellen mit Hinblick auf die Systemperformanz aktuell die wohl wichtigste Komponente bei DV-QKD dar, da sie direkt die erreichbare sichere Schlüsselrate, die maximale Distanz und die Robustheit gegenüber Rauschen in realistischen Glasfaser-, Freistrahl- und Satellitenverbindungen beeinflussen. In den O-/C-Bändern (1310/1550 nm) ist die Kanaldämpfung in der Glasfaser im Vergleich zu anderen Spektralbereichen minimal (insbesondere im Vergleich zu kürzeren Wellenlängen, z. B. um 800 nm) und erhöht damit die erreichbaren Distanzen. In Freistrahlaufbauten und bei Satelliten der ersten Generation ermöglicht der Betrieb im sichtbaren/nahinfraroten Bereich (z. B. ≈800 nm oder 1550 nm) die Auslegung der Empfängereinheit auf einen Betrieb bei Raumtemperatur. Die praktische Implementierung des Temperaturmanagements in der Empfängereinheit umfasst grundsätzlich die Kühlung und Integration thermoelektrischer (TEC)-Module für InGaAs/InP-SPADs, der Kryotechnik für SNSPDs und einen stabilisierten Raumtemperaturbetrieb bei Si-SPADs.

Die drei relevanten Detektorfamilien spannen ein klares Spektrum an Fähigkeiten auf. Si-SPADs sind ausgereifte, kompakte Module mit hoher Effizienz und gutem Spektralbereich im Bereich ≈350–1000 nm, ideal für Freistrahl- und Kurzstrecken-Verbindungen. Ihre intrinsische spektrale Begrenzung macht sie für 1310/1550 nm-Glasfasern ungeeignet, sofern sie nicht mit entsprechenden Frequenzkonvertern kombiniert werden. InGaAs/InP-SPADs ermöglichen sie die direkte Detektion in den Telekom-Bändern und bleiben die praktische Wahl für Glasfaser- und Freistrahlverbindungen mit kleinen bis mittleren optischen Verlusten, jedoch bei aktuell verhältnismäßig geringer Detektionseffizienzen und erhöhten Rauschwerten. Weiterentwicklungen konzentrieren sich hier auf Effizienzsteigerungen bei zugleich niedrigem Rauschen sowie höhere nutzbare Zählraten durch optimiertes Gate-Verfahren und freilaufende Betriebsmethoden. SNSPDs liefern die höchste Performanz bei Effizienz, Dunkelzählraten, Jitter sowie Erholzeit und ermöglichen so potenziell größere Distanzen oder höhere Schlüsselraten. Der Betrieb der SNSPDs erfordert jedoch kryogene Kühlung und damit Systeme, deren Größe, Gewicht, Energieverbrauch und Kosten erheblich sind, wenngleich sie durch fortschreitende Verbesserungen bei der optischen Einkopplung, Arraystrukturen und kompaktere Kühlung stetig reduziert werden. Sogenannte „Up-conversion"-SPDs ergänzen dieses Bild, indem sie 1310/1550 nm-Photonen in den Detektionsbereich von Si-SPADs verschieben, um Si-ähnliche Performanz bei Raumtemperatur zu erreichen, wobei Konversionsverluste und pump-induziertes Rauschen die erreichbare Leistung begrenzen.

Folglich ist die Detektorauswahl szenarienabhängig. Für kosten- und platzsensitive Verbindungen mit moderater Reichweite oder im sichtbarem/NIR-Spektralbereich werden Si-SPADs bevorzugt.

Bei Telekom-Faserverbindungen mit Längen im städtischen Maßstab oder für kurzreichweitige Freistrahlstrecken haben InGaAs/InP-SPADs Vorteile („Up-Conversion"-SPDs als aufstrebende Alternative). Für High-End-, Langstrecken- oder Ultra-Hochraten-Systeme werden meist SNSPDs gewählt, sofern die zusätzlichen Kosten und Platzbedarfe für die benötigte Kryotechnik in Kauf genommen werden können. Diese Zusammenhänge offenbaren den übergreifenden Trade-off zwischen Leistung und Einsatzfähigkeit, der diesen Bericht strukturiert und der nachfolgenden Anwendungsfall-Zuordnung zugrunde liegt.

Kernaussagen zu Leistungs-Abwägungen

Die Leistungsdimensionen, die am wichtigsten sind, umfassen die Detektionseffizienz (echte Zählungen), Dunkelzählraten/Rauschen (falsche Zählungen), zeitliche Präzision (Jitter), Geschwindigkeit (mittlere Zählrate), Wellenlängenkompatibilität sowie Kühl-/Integrationsbedarf. Auf Basis dieser Kriterien variiert die Eignung je nach Verbindungstyp und Szenario:

Glasfaser (Telekom-Bänder, v. a. 1550 nm):

InGaAs/InP-SPADs: etablierte Detektortechnologie für kurze bis mittlere Distanzen und moderate Schlüsselraten.

SNSPDs: höchste Effizienz, ultra-niedriges Rauschen und Jitter; ermöglichen größte Reichweiten und höchste Schlüsselraten; der Kryobedarf erhöht jedoch Größe, Kosten und Komplexität.

„Up-Conversion"-SPDs: Telekom-Option bei Raumtemperatur; müssen Konversionsverluste und pumpinduziertes Rauschen kompensieren; versprechen eine Entwicklung zu Si-SPAD-ähnlicher Performance.

Freistrahl (sichtbar/NIR):

Si-SPADs: kompakt, Raumtemperaturbetrieb, hohe Effizienz im sichtbaren/NIR; gut geeignet für kurze bis mittlere Distanzen und relativ hohe Taktraten.

InGaAs/InP-SPADs: Option für NIR-Freistrahl (insb. um 1550 nm); erlauben einfache Multimode-Faserkopplung, was für Freistrahl-Empfänger mit großem Sichtfeld vorteilhaft ist, erfordern jedoch TEC-Kühlung und weisen höhere Rauschwerte als Si-SPADs auf

SNSPDs: für hochwertige Verbindungen, wenn Kryotechnik akzeptabel ist.

Satellit (800 / 1550nm):

SNSPDs: bevorzugte Wahl für Bodenstationen, um Empfindlichkeit und zeitliche Präzision zu maximieren; für hochwertige Verbindungen, wenn Kryotechnik akzeptabel ist.

Si-SPADs: für ≈800-nm-Terminals auf ressourcenbeschränkten Plattformen, bei denen Kryotechnik an Bord nicht realisierbar ist und solange etwas reduzierte Leistungsfähigkeit akzeptiert werden kann.

Zusammenfassung der Technologie-Roadmap

Kurz- bis mittelfristig (1–5 Jahre):

Grundlegende Messtechnik/Metrologie und Standardisierung von SPD-Kenngrößen verfügbar.

Si-SPADs: Verbesserungen bei Zeitauflösung, Afterpulsing-Kontrolle und Geschwindigkeit.

„Up-Conversion"-SPDs: besser integrierte, rauschärmere Module, die an die Wettbewerbsfähigkeit aktueller InGaAs/InP-SPADs heranreichen.

InGaAs/InP-SPADs: Effizienzgewinne bei niedrigem Rauschen; Fortschritte beim Hochgeschwindigkeitsbetrieb.

SNSPDs: verbesserte Integration einschließlich optischer Einkopplung und höherer Kanaldichte/Arrays; schrittweise Reduktionen von Größe, Gewicht und Leistungsaufnahme der Kryosysteme durch optimierte Systeme.

Langfristig (~10 Jahre):

Si-SPADs mit hohen Zählraten und weiter reduzierten Rauschwerten im sichtbaren/NIR.
„Up-Conversion"-SPDs mit Si-SPAD-ähnlicher Effizienz, Totzeiten unter 100 ns und geringem Rauschen.
InGaAs/InP-SPADs: stetige, aber herausfordernde Optimierung; orientiert an Marktnachfrage; zunehmend auch als integrierte SPAD-Arrays in einem Modul verfügbar.
SNSPDs: sehr hohe Effizienz in den Telekom-Bändern, ultra-niedriges Rauschen/Jitter, Mehr-pixel-Arrays mit aggregierten Zählraten im GHz-Bereich; Kryosysteme werden kompakter und effizienter.

Letztlich sollte die Detektorauswahl für QKD von der angestrebten oder erforderlichen Reichweite und Schlüsselrate geleitet werden, abgewogen gegenüber Kosten, Kühlung und Integrationsbeschränkungen. Auf dieser Grundlage können QKD-Betreiber Detektoren passend zu ihren Anforderungen auswählen und den Rollout verlässlicher QKD-Dienste über Faser-, Freistrahl- und Satellitennetze beschleunigen.

Executive Summary

This report describes and discusses single-photon detector (SPD) options for discrete-variable quantum key distribution (DV-QKD), focusing on:

Silicon single-photon avalanche diodes (Si-SPADs)
Indium gallium arsenide/indium phosphide SPADs (InGaAs/InP-SPADs)
Superconducting nanowire single-photon detectors (SNSPDs)

The report synthesizes scientific literature and expert insights on performance, deployability, as well as commercial maturity and adoption, and maps detector suitability to QKD use cases across fiber, free-space, and satellite links according to distance and key rate needs. The central finding is the tradeoff between detector performance and operational overhead and cost. SNSPDs set the performance ceiling, while SPAD-based options (Si and InGaAs/InP) offer simpler thermal management, lower cost, and easier integration.

Single-photon detectors are the decisive component in DV-QKD as their performance directly limits the secure key rate, maximum distance, and robustness against noise across realistic fiber, free-space, and satellite links. In fiber, operation in the O/C bands (1310/1550 nm) minimizes channel loss compared to operation in other spectral regions (in particular at shorter wavelengths, e.g., around 800 nm) and therefore extends reachable distances. In free space and first-generation satellites, operation around the visible/near-infrared (NIR) (typ. ≈800 nm or 1550 nm) enables compact receivers that can be operated at room temperature. Practical deployment hinges on cooling and integration of thermoelectric (TEC) modules for InGaAs/InP-SPADs or cryogenics for SNSPDs versus room-temperature operation for Si-SPADs detectors.

At a high level, the three leading detector technologies span a clear spectrum of capabilities. Si-SPADs are mature, compact modules with high efficiency and good timing resolution across ≈350–1000 nm, which are ideal for free-space and short-range links. Their intrinsic spectral limit makes them unsuitable for 1310/1550 nm fiber-based communication, unless paired with frequency up-conversion. InGaAs/InP-SPADs provide direct telecom-band detection and remain the practical choice for fiber and free-space links with small-to-moderate optical loss, but currently they have low detection efficiencies and higher noise. Progress in this area focuses on efficiency at low noise and higher usable count rates via optimized gating and free-running operation. SNSPDs deliver the highest performance in efficiency, dark counts, jitter, and recovery speed, which potentially enable longer distances or higher key rates. However, operating SNSPDs require cryogenic systems whose size, weight, power, and cost are considerable, although these are steadily improving through better optical coupling, arrays, and more compact coolers. Up-conversion SPDs complement this landscape by shifting 1310/1550 nm photons into the Si-SPAD band, targeting Si-like performance at room temperature, while conversion loss and pump-induced noise from additional components limit the achievable performance.

Consequently, detector selection is scenario-driven. Cost- and footprint-sensitive links with modest reach or visible/NIR operation favor Si-SPADs. Telecom-fiber links at metropolitan scales as well as short free-space links favor InGaAs/InP-SPADs (with up-conversion as an emerging alternative), and premium, long-distance or ultra-high-rate systems select SNSPDs, where cryogenics are acceptable. These choices highlight the fundamental trade-off between performance and deployability that underpins this report and the use-case mapping that follows.

Key takeaways on performance trade-offs

Performance dimensions that matter most include detection efficiency (true counts), dark counts/noise (false counts), timing precision (jitter), speed (sustained count rate), wavelength compatibility and cooling/integration needs. Applying these criteria, detector suitability varies by link type and scenario:

<u>Fiber (Telecom bands, primarily 1550 nm):</u>

InGaAs/InP-SPADs: established SPD technology for short–mid distances and moderate key rates.
SNSPDs: highest efficiency, ultra-low noise and jitter; enable the longest reach and highest key rates; yet their need for cryogenics drives size, cost and complexity.
Up-conversion SPDs: room-temperature telecom option; need to compensate for conversion losses and pump-induced noise.
<u>Free-space (visible/near-infrared):</u>
Si-SPADs: compact, room-temperature, high efficiency in the visible/near-infrared (NIR); well suited for short–mid distances and relatively high clock rates.
InGaAs/InP-SPADs: option for NIR free-space links (especially around 1550 nm); support straightforward multimode-fiber coupling, which is attractive for receivers with a large field of view, but require TEC cooling and present higher noise levels than Si-SPADs.
SNSPDs: selected for premium links when cryogenics are acceptable.

<u>Satellite (800 / 1550nm):</u>

SNSPDs: preferred choice for ground stations to maximize sensitivity and timing; for premium links where cryogenics are acceptable.
Si-SPADs for ≈800 nm terminals on resource-constrained platforms, where onboard cryogenics are not viable and somewhat reduced performance is acceptable.

Technology roadmap highlights

<u>Near to mid-term (1-5 years):</u>

Basic metrology and standardization of SPD characteristics become available.
Si-SPADs: improvements in timing resolution, afterpulsing control and speed.
Up-conversion SPDs: better-integrated, lower-noise modules approaching competitiveness with current InGaAs/InP-SPADs.
InGaAs/InP-SPADs: efficiency gains at low noise; progress on high-speed operation.
SNSPDs: improved integration including optical coupling and higher channel density/arrays; incremental reductions in cryogenic size, weight, and power with more compact systems.

<u>Long term (~10 years):</u>

Si-SPADs allowing high count rates with further noise reductions in the visible/NIR.
Up-conversion SPDs approaching Si-SPAD-like efficiency with sub-100 ns dead time and low noise.
InGaAs/InP-SPADs: steady but challenging optimization; market demand will be decisive, with a growing availability of integrated SPAD arrays within single modules.
SNSPDs: very high efficiency at telecom bands, ultra-low noise/jitter, multi-pixel arrays with aggregate GHz-level count rates; cryogenic systems become more compact and efficient.

Ultimately, detector choice for QKD should be guided by the required distance and key rate, while also considering cost, cooling, and integration constraints. With these foundations, QKD operators can match detectors to fulfil requirements and accelerate the rollout of dependable QKD services across fiber, free-space, and satellite networks.

1 Introduction

Secure communication networks are beginning to incorporate quantum key distribution (QKD) outside of laboratory settings, from metropolitan fiber links to free space and early satellite demonstrations. In these systems, the detectors that register individual photons are a decisive element. They determine to a large degree how far a link can operate, how quickly secret keys can be established, and how robustly the key exchange is conducted in the presence of imperfections and noise.

In this report, our focus is discrete-variable QKD (DV-QKD), where single-photon counting determines key distribution performance, costs and security margin. The analysis concentrates on the detector families most practical for DV-QKD including silicon SPADs in the visible/NIR, InGaAs/InP-SPADs for telecom wavelengths, frequency up-conversion detectors that shift 1310/1550 nm photons into the Si-SPAD band, and superconducting nanowire detectors operated at cryogenic temperatures covering a broad frequency range. KPIs are analyzed as correlated variables that influence quantum bit error rate, usable clock speeds, and distance under realistic noise and loss conditions.

We frame the analysis around deployment contexts central to QKD, including fiber links in the 1310 and 1550 nm bands, free-space urban links, and visible or NIR satellite terminals. We investigate which detector characteristics are required to meet specific distance and key rate targets, how cooling and integration with thermoelectric or cryogenic systems constrain deployability, and which implementation choices best align detector capabilities with real world operating conditions.

We discuss the challenges that most strongly limit progress, including regulatory requirements, operational constraints, and production issues such as material quality and process yield. The roadmap translates these challenges into milestones with near-term, mid-term, and long-term steps. It outlines expected enhancement of KPIs and technology development trajectories through approximately 2040.

The report is structured as follows. Chapter 2 introduces the methods used to conduct this study. Chapter 3 examines detector technologies based on the literature and expert perspectives, providing assessments of commercially available devices. Chapter 4 presents the technology roadmap, including KPI analysis, challenges, mapping of single photon detector (SPD) devices to QKD scenarios, future perspectives and development paths. Chapter 5 provides the conclusions of this study.

2 Methods

The following methods were used to gather information on different detector technologies, KPIs, commercialization aspects, their applications in QKD, as well as their paths for further development to create the technology roadmap.

Desk research

As a first step, information on the various technologies studied in this report has been collected from the scientific literature and commercial device datasheet. As a first objective, desk research focused on investigating SPD technologies and their technical characteristics. The selected SPD technologies were further studied for their applications in QKD, KPIs of commercially available devices, as well as their advantages and shortcomings. The information provided within this step was validated and further elaborated by the next steps of the adopted methodology. The review of relevant literature and technical reports continued through the end of the study to keep track of the latest research and industry developments.

Expert interviews

Interviews were conducted with SPD and QKD experts from research and industry alongside desk research to characterize focus technologies and important KPIs, their range for each SPD type and application in various QKD scenarios. The interviews also addressed the technical characteristics of the selected technologies, the evolution of KPIs over time, technology development paths, market and industry barriers and scenarios towards widespread QKD utilization of products.

Interviews were also conducted to prepare for the discussion workshops. This enabled target stakeholders from research and industry to become familiar with the objectives of the study and deeper analyses to be conducted during the workshop. Additionally, the interviews enabled the roadmap team to organize workshop sessions with selected groups of relevant stakeholders for specific discussions based on their areas of expertise.

Workshop

A discussion workshop was held with experts from universities, research and technology organizations and SPD manufacturers, QKD companies and national metrology institutes. In the online workshop, various technical aspects of SPD technologies under focus were discussed including current KPIs, challenges and potential future developments for different technologies. By combining different discussion formats a high involvement of the invited stakeholders was achieved. The results of the workshop verified and complemented the information gathered in the previous steps of this methodology.

3 Detector Technologies used for QKD

In this section, we explore the important role of detector technologies in QKD, focusing on DV-QKD and Single-Photon Detectors (SPDs). SPDs, critical for the accurate detection of single photons, are categorized into various types, among which Superconducting Nanowire Single-Photon Detectors (SNSPDs) and Single-Photon Avalanche Diodes (SPADs) stand out due to their unique characteristics and performance metrics. This section will provide a comprehensive overview of these detectors, delving into their operational principles, advantages, and the implications of their performance on the efficiency of QKD systems.

3.1 Introduction to Quantum Key Distribution and the Role of Detectors

Quantum key distribution represents an approach for secure communication, utilizing the principles of quantum mechanics to ensure that cryptographic keys are exchanged securely between two parties, commonly referred to as Alice and Bob. QKD can be categorized into two primary types prepare-and-measure QKD and entanglement-based QKD (Schmaltz et al. 2025; Schmaltz et al. 2024).

In prepare-and-measure DV-QKD, information is processed by first preparing quantum states and then measuring them. Here, Alice prepares single photons in specific quantum states, encodes information onto them, and transmits these photons to Bob. Upon receiving the photons, Bob utilizes single photon detectors and, depending on the type of encoding, other components such as polarizers decode the quantum information, allowing both parties to generate a shared secret key. Alice and Bob also use an authenticated classical channel to exchange limited information about their measurement and outcomes for post processing, error correction, and privacy amplification, without revealing the key itself. The inherent security of this method lies in the principles of quantum mechanics, such as superposition and the no-cloning theorem. Any attempt by an eavesdropper to intercept the photons will disturb their states, leading to detectable errors in the measurements. Various approaches for prepare-and-measure QKD are possible, however, all relying on single photon detectors. Thus, single photon detectors are crucial for accurately measuring qubit states and identifying potential eavesdropping.

In contrast, entanglement-based QKD utilizes pairs of entangled photons, which exhibit strong correlations regardless of the distance separating them. In entanglement-based QKD, a source generates entangled photon pairs, distributing one photon to Alice and the other to Bob. Both parties then analyze and measure their respective photons using single photon detectors. The security of this method is based on the property that any measurement on one photon instantaneously affects the state of the other, making any interference detectable. Single photon detectors play an essential role here by allowing Alice and Bob to verify the entanglement and generate a secure key based on their measurement results.

Transmission Pathways in QKD: Fiber, Free Space, and Satellite

The implementation of QKD can be achieved through various transmission pathways, including fiber optics, free-space communication, and satellite links. Each method has its distinct advantages and challenges, particularly regarding the wavelengths of the transmitted photons and the efficiency of single photon detectors.

In fiber optics, the telecom O-band (around 1310 nm) and the C-band (around 1550 nm) are commonly used due to their minimal dispersion and attenuation, respectively (Heindel et al. 2023).

These wavelengths are ideal for long-distance communication, ensuring that the quantum states remain coherent as they travel through the fiber. Consequently, single photon detectors must be sensitive to these specific wavelengths to accurately measure the transmitted photons.

Free-space optical communication transmits optical signals through the atmosphere rather than through fiber and can be used when installing or accessing fiber is not practical. For these applications, wavelengths of around 850 nm or 1550nm are generally preferred due to low atmospheric absorption and availability of components (Orsucci et al.), and the first quantum satellites operate around 800 nm (Heindel et al. 2023). However, atmospheric conditions can introduce challenges, such as turbulence and absorption, which may impact the detection of single photons. Here, single photon detectors must be optimized to operate effectively in varying environmental conditions.

Satellite-based QKD is at an early development stage but represents a promising way for establishing secure communication links over long distances. By utilizing satellite QKD, single photons can be transmitted across far distances, overcoming some of the limitations faced by terrestrial networks. The successful operation of such systems relies heavily on the performance of single photon detectors, which must be capable of detecting photons transmitted via satellite links.

Among the various transmission ways, fiber-based QKD is the most commonly implemented form of quantum communication. In this system, photons travel from a photon source to a detector through optical fibers. The efficiency of this transmission depends on the inherent loss or dispersion within the fiber and the effective fiber coupling techniques, which ensure that photons are efficiently injected into the fiber and reach the detector with minimal loss.

Fiber coupling is crucial for maximizing the number of photons that enter the fiber. This process often involves aligning the photon source with the fiber core using specialized optics, ensuring that photons are transmitted effectively. The use of waveguides further enhances the ability to direct photons along specific paths, optimizing their journey to the detector.

Within fiber optics, the choice between single-mode and multi-mode fibers significantly impacts the performance of QKD systems. Single-mode fibers support only one light mode, minimizing dispersion and maintaining coherence over long distances. This property is especially beneficial for ensuring that the quantum states remain intact, facilitating accurate measurements by the single photon detectors. Conversely, multi-mode fibers, while capable of carrying more data, can introduce complications due to modal dispersion, which may compromise the quality of the transmitted quantum states. However, multi-mode fibers are valuable in classical applications where the ultimate goal is high data rates rather than the preservation of quantum states.

Single photon detectors must efficiently detect the incoming photons and distinguish them from background noise. The performance of detectors directly affects the overall efficiency of the QKD system, influencing key generation rates and ensuring the security of the transmitted information.

3.2 Single-Photon Detectors

Single-photon detectors play a crucial role in various scientific and technological fields, including medicine, biology, astrophysics, and quantum technologies. They are particularly valuable for measuring weak photon fluxes that traditional detectors cannot effectively capture. The advancements in SPDs have enabled significant progress in applications such as quantum cryptography, quantum computing, and experimental quantum optics, where high sensitivity and accuracy are essential (Kück 2020).

In QKD, SPDs are essential for ensuring the security of the communication channel by enabling the detection of single photons that carry quantum information. Having SPDs with ability to operate at high efficiency and low noise is vital for the implementation of secure communication protocols, where the presence of eavesdroppers can be detected through the behavior of the photons. Understanding the characteristics of SPDs, such as their timing resolution and efficiency, is key to enhancing their performance in these critical applications. In the following, some of the main **characteristics of SPDs** are introduced that correspond to major SPD variations in particular SPADs and superconducting SNSPDs (Kück 2020; Marquardt et al. 2023).

3.2.1 Characteristics of Single-Photon Detectors

In the following, definitions of key characteristics of SPDs that significantly influence their performance in QKD applications are provided. These characteristics, including dead time, photon detection efficiency, dark count probability, and others, play a crucial role in determining the effectiveness and reliability of SPDs.

Dead Time: After detecting a photon, a detector may experience a period of unresponsiveness, known as dead time (t_{dead}), during which it cannot reliably register additional photons. This limitation may arise from the fundamental properties of the detector itself or from constraints within the circuitry that records detection events. Consequently, the dead time imposes a maximum count rate of $1/t_{dead}$ for the detector.

Recovery Time: Recovery time (t_{rec}) is the shortest duration after which the detection efficiency is independent of the prior photon detection history. This characteristic is crucial for ensuring consistent performance, particularly in high-rate photon detection scenarios.

In SNSPD context, the post-detection interval is commonly termed ‘recovery time’. Where a distinction is made, ‘dead time’ denotes the period of effective insensitivity, while ‘recovery time’ denotes the duration until the detection efficiency returns to its nominal value (Bienfang et al. 2025).

Photon Detection Efficiency / System Detection Efficiency: Photon detection efficiency (η or PDE) refers to the likelihood of a photon being registered upon its arrival at the detector and, in the context of single-photon detectors used in QKD systems, this quantity is usually called the system detection efficiency (SDE) when all optical and coupling losses in the receiver are included (Bienfang et al. 2025). It can be quantified as the ratio of the count rate detected to the actual rate of incoming photons.

Dark Count Probability: The dark count probability (p_{dark}) denotes the chance of the detector registering counts without any incoming optical signal, which are known as false counts. For a gated detector[1], this is the probability that a detection event is registered in a specified time interval when no optical illumination is present. For a free-running detector, it indicates the probability of registering a detection event in one second or another specified time interval without any optical exposure.

Dark counts represent noise signals which arise from internal and external influences such as thermal noise. Distinguishing dark counts from signals indicative of eavesdropping is challenging, which can impact the security of the key exchange. Hence, robust error correction and privacy amplification are essential to mitigate this effect (Kück 2020).

Dark Count Rate: Dark count rate (R_{dc} or DCR) is defined as the average number of detection events registered by a photon detector in a given time period when no incident optical signal is present.

---

[1] This means that the detector is activated (gated) during specific time intervals when it is expected to receive photons. On the other hand, a free-running detector operates continuously, without any gating. For more details see Section 3.2.3.

Spectral Range: The detection efficiency of single-photon detectors varies with wavelength. Their spectral sensitivity depends on material properties such as the band gap that influence how efficiently they interact with photons at different wavelengths. The spectral range to which an SPD is sensitive determines the applications for which it is suitable.

Timing Jitter: Timing jitter (t_{jitter}) refers to the variability in the time interval between when a photon arrives at the detector input plane and when the corresponding electrical output signal (e.g., a voltage pulse) is generated. This variation affects photon counting module performance, potentially leading to slower detection and reduced efficiency, making it a critical consideration in QKD system design.

Afterpulsing Probability: The afterpulsing probability ($p_{afterpulse}$) is the probability that a detector registers a false detection event in the absence of radiation shortly after a correct photon detection event. This characteristic can impact the accuracy and reliability of detection.

Photon Number Resolution (PNR): Detectors capable of distinguishing between the presence of one or more photons are known as photon number resolving detectors. PNR detectors can determine whether a pulse contained how many photons were contained in a pulse, up to a detector-dependent maximum.

PNR allows for detecting multiple photons, which can enhance their functionality. However, this feature in case of QKD is only advantageous at the photon source part to allow to drop clock cycles with more than a single photon emitted. On the receiver (detector) side, PNR is not required in current protocols.

Active Area Size: The active area of a photon detector refers to the specific region that is sensitive to incoming photons, where photon detection occurs and the generation of a measurable signal takes place (Gulinatti 2020).

Maximum Counting Rate: Counting rate (MCR) refers to the highest speed at which the detector can respond to incoming photons. It is fundamentally the inverse of the dead time or pulse width of the detector (You 2020).

3.2.2 Requirements for Quantum Communication

The characteristics of single-photon sources and detectors play a crucial role in the performance of QKD and other quantum communication protocols. For example, consider the BB84 protocol with polarization encoding as a classic prepare-and-measure QKD scheme. Alice sends randomly polarized bits in two bases, and Bob measures in randomly chosen bases. They keep only the events where their bases matched to form a raw key, then apply error correction and privacy amplification to make it secure. In this setting, the security and efficiency of key distribution are directly influenced by non-ideality of the utilized photon sources and detectors. While advancements such as decoy-state methods, where additional weak pulses are sent to identify potential eavesdropping, have alleviated some challenges associated with characteristics of single-photon sources and detectors, effects of issues such as dark counts, efficiency, and timing jitter remain significant. These factors can introduce errors in the key agreement process, ultimately affecting the length and security of the shared key between communicating parties.

In QKD, the use of photon sources such as weak coherent laser pulses is accompanied with the probability of generating more than one photon. In this case, an eavesdropper might obtain information without being detected, by eavesdropping the additional photons generated from multi-photon pulses, that is referred to as photon number splitting attack. This highlights the importance of non-idealities, such as a non-zero probability of multi-photon emission, in estimating the security of the transmitted key. To address the multi-photon emission problem, sources often operate at lower photon rates, which reduces the likelihood of emitting multiple photons. However, this approach introduces its own challenges. Operating at a lower mean photon number means Bob (the receiver) records zero-photon time intervals more frequently which decreases the bit rate. Additionally, to obtain the same number of bits, Bob must analyze more time intervals, leading to an increased contribution of noise, including dark counts and stray (unwanted) photons. This results in a greater bit-error-rate and hence impacts the overall system performance. High detection efficiency and low dark count rates are essential to minimize false counts and ensure reliable detection (Eisaman et al. 2011; You 2020). However, use of single-emitter systems as photon source, offers the potential for higher security compared to weak coherent pulses, due to their ability to mitigate this multi-photon emission issue. In addition, decoy-state protocols can also mitigate multi-photon attacks, and experts generally consider their security comparable to that of real single-photon emitters.

Moreover, the efficiency of photon detection is another vital factor in QKD performance. Non-ideal detectors may detect fewer photons than expected, leading to an increased signal-to-noise ratio and a higher bit-error-rate. This directly translates to a shorter secret key for the same length of sifted key[2], thereby limiting the secure key exchange rate. Additionally, properties such as detector dead time can further worsen these issues. If the dead time exceeds the minimum time-bin spacing[3], communication rates decrease, and there is a risk of information leakage if a third party manipulates this timing. Hence, the time-bin spacing should be matched to the detector's dead time and timing jitter to avoid saturation and side channels (Eisaman et al. 2011; Marquardt et al. 2023).

The effectiveness of QKD systems, including factors like maximum transmission distance, Secret Key Rate (R_{SK}), and Quantum Bit Error Rate (R_{BE} or QBER), relies on the capabilities of the SPDs among other components. The fundamental equations for the decoy-state BB84 QKD are outlined below (You 2020):

$$\begin{cases} R_{SK} \propto \eta \cdot f \cdot u \cdot L \\ R_{BE} \propto R_{dc}/R_{SK} \end{cases},$$

where η represents the detection efficiency of the SPD, f denotes the clock frequency, u indicates the average photon number per pulse, L refers to the total channel loss, and R_{dc} is the dark count rate of the SPD. The equations above show that the performance of the QKD system relies on key SPD parameters, such as η and R_{dc}. Additionally, the dead time/recovery time and timing jitter (t_{jitter}) of SPDs will impact the performance of high-speed QKD systems, so the system clock rate must be adjusted to these detector parameters (You 2020).

---

[2] The sifted key is the initial raw key generated in QKD after the transmission of quantum states, where certain bits are retained based on the measurement results, and others are discarded to ensure compatibility between the communicating parties.

[3] The specific time interval during which a photon is expected to be detected or measured.

Table 1: Impact of SPD KPIs on QKD performance

SPD KPI	Affected QKD metrics	Impact on performance
Detection efficiency (η/PDE)	Secret key rate, QBER, max distance	Higher PDE yields more true detections per launched photon, improving signal-to-noise vs dark counts. Fiber loss grows with distance and therefore, a higher PDE boosts detected signal without increasing noise, keeping QBER (~noise/total counts) below the secure threshold at longer distances.
Dark count rate (DCR/p_{dark})	QBER, secret key rate, max distance	Higher false detections raise errors, especially when the real signal is weak. This means more errors to fix and more bits to discard for maintaining security, which decreases the secret key rate.
Dead time / Max count rate (MCR)	Key rate, effective PDE, QBER	After each click the detector is briefly blind. At high rates, more photons arrive during this blind period and are missed, reducing the key rate and effective efficiency. As a consequence, either the clock rate of the QKD system has to be limited, or multiple detectors have to be used.
Timing jitter	QBER, key rate	Jitter causes time-slot overlap. Longer gate durations are usually considered to address this issue, but they increase dark counts.
Afterpulsing probability ($p_{afterpulse}$)	QBER, key rate, security assumptions	Afterpulsing produces correlated false clicks that raise QBER; using hold-off time to suppress them increases dead time and reduces the key rate.
Spectral sensitivity (λ, bandwidth)	Channel loss, key rate, max distance	Aligning to 1310/1550 nm minimizes fiber loss, improving key rate and distance.

Table 1 summarizes how the aforementioned KPIs of detectors influence QKD performance metrics. QKD performance is mainly about detecting as many photons as possible while keeping false detections (dark counts) low. As distance grows, the signal gets weaker, so higher PDE helps by catching more of the scarce photons that still arrive. This keeps error rates acceptable and extends the key distribution distance securely. Similarly, a lower DCR allows to maintain a higher signal to noise ratio and therefore lowers QBER and extends key distribution distances.

The uncertainty when a detector records a photon (timing jitter) becomes very important for time bin encoded QKD. In this encoding method, information is carried by placing very short pulses into distinct time slots, and the receiver opens narrow detection gates around those slots. If jitter approaches the spacing or width of the slots, detections can land in the wrong slot (errors) or outside any slot (losses). To avoid misses, the gates are widened, which leads to a higher number of dark counts, raising the error rate and lowering the key rate.

Beyond QKD, the development of quantum repeaters is essential for enabling long-distance quantum communication. The performance of quantum repeaters relies heavily on the characteristics of single-photon sources and detectors. Imperfections in either component can lead to states that deviate from the desired entangled state, thereby decreasing the overall fidelity of the communication link. For instance, the requirements for dark counts and multi-photon emission probabilities are critical in maintaining the fidelity needed for effective quantum repeaters (Eisaman et al. 2011; Yoshida und Horikiri 2024).

3.2.3 Operational Modes and Architectural Setups of SPDs in QKD

Two primary operational modes for SPDs are **gated** and **free-running** detection. Gated operation means the detector is biased above its detection threshold only during short, synchronized detection windows and biased below that threshold outside these windows. Gated SPDs are designed to operate within specific time windows, allowing them to be synchronized with the arrival of photon pulses. This synchronization enhances the signal-to-noise ratio, making gated detectors particularly suitable for QKD applications that utilize pulsed laser sources. By reducing the detection of background noise, gated SPDs improve the overall fidelity of the key exchange process.

In contrast, free-running SPDs are continuously active and can detect photons at any time without the need for synchronization. This mode is beneficial when dealing with continuous wave (CW) light sources, where the photons are emitted without distinct time intervals. However, free-running SPDs may encounter higher background noise levels, which can compromise the performance of the QKD system. Despite this, they find applications in scenarios where rapid key generation is essential, and the continuous detection capability offers advantages in time-sensitive communications.

Architecturally, SPDs can be arranged in **arrays** to enhance their photon detection capabilities. An array of SPADs or SNSPDs allows for simultaneous detection which may originate from a single fiber (via splitting) or from multiple fibers. Each detector in the array can independently sense incoming photons, enabling the system to collect more data and generate keys at a faster rate. This parallel processing is helpful for QKD, where the rate of key generation directly impacts the system's performance.

Placing multiple detector channels in an array and using readout or position-to-time **multiplexing** and can help optimize the use of SPDs in QKD applications. Multiplexing involves combining multiple signals or data streams into a single transmission channel, which can be done in time (time multiplexing) or space (space multiplexing). In time multiplexing, individual detectors can be activated sequentially, minimizing crosstalk and enhancing the detection of weak signals. Spatial multiplexing means sending photons through multiple parallel spatial paths (e.g., using separate fibers) to a detector or array. This gives flexibility to match the source and channel setup to the QKD protocol (Zhao et al. 2013; Warburton et al. 2011; Ma et al. 2011).

By carefully selecting operational modes and architectural setups, researchers and engineers can optimize key generation rates and enhance the security of quantum communication systems towards more robust and efficient QKD implementations.

3.2.4 Single-Photon Avalanche Diodes (SPADs)

Single-Photon Avalanche Diodes (SPADs) are highly sensitive semiconductor devices designed to detect single photons used in various applications, including quantum key distribution (QKD), fluorescence lifetime imaging, Light Detection and Ranging (LiDAR) systems and quantum sensing technologies.

SPADs are semiconductor diodes that are operated in a way that individual photons can create an avalanche multiplication and thus a large electrical signal. SPADs can operate in various modes, including linear mode and Geiger mode. However, they primarily function in Geiger mode, where a high reverse bias voltage generates a strong electric field that triggers a multiplication process, allowing for the detection of single photons when they are absorbed. This process allows for the detection of single photons by exponentially increasing the output current, which is a significant advantage over traditional photodiodes (Kück 2020; Gulinatti 2024). The Geiger mode is particularly advantageous for applications like QKD, as it allows for the detection of extremely faint light signals, provided that the dark count rate and afterpulsing probabilities are sufficiently low, which is essential for ensuring secure communication (CEN-CENELEC 2023).

While commercial SPADs primarily use Geiger mode, there are ongoing efforts to enable linear-mode operations for photon counting. Linear mode offers a proportional output to the number of incoming photons, allowing for photon-number resolution and reduced after-pulsing, thanks to lower current flow. (Eisaman et al. 2011)

Photon detection mechanism

The operational principle of SPADs relies on the photoelectric effect. As a photon is absorbed in the semiconductor material, it generates an electron-hole pair. In conventional photodiodes, this would lead to a proportional increase in current based on the number of incident photons. However, in SPADs, if the applied electric field is sufficiently high, more than one electron-hole pair can be generated per absorbed photon, resulting in a self-sustaining avalanche effect. Once initiated, this avalanche continues until the detector is turned off, making it temporarily insensitive to additional photon events until the system resets. To detect additional photons, a SPAD must undergo this necessary reset interval (dead time) that deactivates the avalanche effect and restores its initial operating conditions, functioning like a mechanism that prepares the detector for subsequent detection events. (Kück 2020; Gulinatti 2024).

Key characteristics affecting performance

The performance of SPADs is influenced by several characteristics, including mainly photon detection efficiency, timing jitter, dark count rate, afterpulsing probability, and dead time, which were defined previously. Detection efficiency is critical in applications where photon availability is limited. Other parameters also influence performance of SPADs. For instance, a high DCR might prevent detecting weak signals, particularly in applications such as QKD, where the integrity of the signal is critical. Similarly, afterpulsing, which occurs when trapped carriers trigger further avalanches, can introduce noise and complicate the measurement of photon correlations (Gulinatti 2024). An optimal balance needs to exist among these parameters, as improving one may adversely affect another. For example, achieving a low dark count rate often requires cooling the SPAD, which can increase afterpulsing probability and dead time (Kück 2020; Gulinatti 2024).

Impact of semiconductor materials

The choice of semiconductor material significantly influences the performance of SPADs. **Silicon** is the most commonly used material, offering a good balance of low dark count rate and reasonable detection efficiency at room temperature for wavelengths between about 400 nm and 1000 nm. However, to extend sensitivity to longer wavelengths in telecom bandwidth, materials like **InP** are used as substrate and **InGaAs** as absorption layer (Gulinatti 2024). These materials excel in detecting infrared photons, which is particularly important for applications like fiber-based QKD, where the transmission of information occurs over longer wavelengths, typically around 1310 nm or 1550 nm.

However, InGaAs/InP devices often require operation at lower temperatures to mitigate higher dark count rates, which is addressed by the use of thermoelectric coolers. This can complicate integration of InGaAs/InP-SPADs into systems designed for high-speed applications (Gulinatti 2024). InGaAs/InP-SPADs operate effectively within a temperature range of 223 K to 293 K, where lower temperatures enhance photon detection efficiency by increasing avalanche triggering probability while reducing dark count rate. However, an optimal operating temperature must be maintained to balance PDE, DCR, and afterpulsing probability – as the latter increases at lower temperatures - for maximum performance in quantum communication (Wang et al. 2021a).

When comparing the key performance indicators of InGaAs/InP- and Si-SPADs, several critical differences emerge. Si-SPADs typically exhibit higher detection efficiencies at the respective optimal wavelength, reaching up to 80%, which is advantageous for applications requiring robust photon detection in the visible spectrum. In contrast, InGaAs/InP-SPADs, while well-suited for infrared detection, may have detection efficiencies as low as 20%. This disparity can significantly impact overall performance in photon-limited scenarios. (Kück 2020).

Moreover, the maximum counting rate is another critical KPI that is usually lower in InGaAs/InP-SPADs in comparison with Si-SPADs. According to experts, expected improvements in KPIs in InGaAs/InP-SPADs, particularly MCR and PDE, indicate strong potential for use in QKD systems. Research has shown that InGaAs/InP-SPADs can achieve MCRs in the GHz range. In (Namekata et al. 2011), a method for achieving QKD over 100 km using sinusoidally gated InGaAs/InP avalanche photodiodes is presented, which demonstrated a MCR of about 2 GHz. However, such advancements are still not practically shown in commercial products.

In addition, the integration of germanium with silicon is being explored to enhance performance while reducing afterpulsing and improving overall efficiency. Each material comes with trade-offs, such as thermal stability, spectral sensitivity, and the ability to operate in various environmental conditions, which must be considered in the design of SPAD systems (Gulinatti 2024).

Commercial SPADs

SPADs are a mature, commercially available technology with standardized modules from multiple manufacturers. In the following, we list exemplary Si-SPAD and InGaAs/InP-SPAD products identified through a non-exhaustive screening of publicly available information.

The commercial SPDs listed in tables 2 to 4 are intended as examples of values taken from datasheets of commercial systems and were selected non-systematically to illustrate typical values reported for some current products. The selection is not exhaustive. All specifications are taken from publicly available datasheets or equivalent manufacturer documentation and reflect nominal values under stated test conditions. Practical performance can vary with setup and operating conditions. Moreover, the definitions and measurement conditions of the listed parameters may differ between vendors, so the values are not necessarily directly comparable. The tables of commercial SPDs are not intended to serve as buyer’s guides and do not endorse any vendor. They are provided solely as reference overviews of some commercial products and their typical performance. The listed devices were selected as illustrative examples from products for which relevant parameters were readily accessible in publicly available documentation at the time of writing; the list is not exhaustive and no conclusions should be drawn about unlisted products. Verified specifications should be taken from the latest datasheets and official documentation.

Table 2: KPIs of a selection of Si-SPAD products

Manufacturer	Max. Photon Detection Efficiency (PDE)	Timing jitter	After-pulsing rate	Dark Count Rate (DCR)	Dead time	(Max) Counting Rate	Spectral Range	Active area
ID Quantique[4]	35% at 500 nm	≤60 ps (typ. <40 ps)	< 0.5%	7-1000 Hz	< 45 ns	20 MHz	350-900 nm	20 µm / 50 µm / 100 µm
	80% at 800 nm	200-1000 ps (typ. <400 ps)	N/A	300-4000 Hz	1 µs	N/A	350-1000 nm	500 µm
Laser Components[5]	75% at 670 nm	1000 ps	0.2-1%	10-250 Hz	42-48 ns	20 MHz	350-1000nm	100 µm
	70% at 520 nm	1000 ps	0.2%	10-250 Hz	42-48 ns	20 MHz	350-1000nm	100 µm
	70% at 670 nm	1000 ps	0.2-1%	50-500 Hz	42-48 ns	20 MHz	400-1000 nm	100 µm
	75% at 670 nm	350 ps	1%	100-250 Hz	42-45 ns	20 MHz	400-1000 nm	100 µm
Micro Photon Devices[6] **(IT)**	49% at 550 nm	35-50 ps	0.1 - 3%	5-500 Hz	77 ns	12-13 MHz	400-650 nm	20 µm / 50 µm / 100 µm
Excelitas Technologies (US)[7,8]	70% at 650 nm[7]	350 ps	0.5-1%	25-1500 Hz	22-42 ns	37 Mc/s	400-1060 nm	180 µm
	75% at 650 nm[8]	225 ps	1-3%	100-1500 Hz	22-35 ns	N/A	650-800 nm	180 µm
	70% at 780 nm[8]	350 ps	1-3%	100-1500 Hz	22-35 ns	N/A	780-900 nm	180 µm
Thorlabs[9] **(US)**	66% at 650 nm	N/A	1%	300 - 1500 Hz	< 35 ns	20 MHz	350-1100 nm	500 µm
	35% at 500 nm	N/A	3%	60 Hz	35 ns	28 MHz	350-900 nm	20 µm
	35% at 500 nm	N/A	3%	200 Hz	45 ns	22 MHz	350-900 nm	50 µm
	70% at 670 nm	1000 ps	0.2%	100-250 Hz	45 ns	20 MHz	400-1000 nm	100 µm
Hamamatsu (JP)[10,11]	65% at 630 nm[10]	N/A	0.1%	20–60 Hz	N/A	20 MHz	400–1000 nm	50 µm
	65% at 630 nm[10]	N/A	0.1%	150–450 Hz	N/A	7 MHz	400–1000 nm	100 µm
	70% at 450 [11]nm	N/A	0.1%	7–25 Hz	N/A	30 MHz	320–900 nm	50 µm
	70% at 450 nm[11]	N/A	0.1%	30–100 Hz	N/A	20 MHz	320–900 nm	100 µm

Table 2 includes detection efficiency, timing jitter, afterpulsing, dark count rate, dead time, maximum counting rate, spectral range, and active area, for selected commercially available Si-SPA

---

[4] https://cdn-adepci1.actonsoftware.com/acton/cdna/11868/f-0236/1/

[5] https://www.lasercomponents.com/fileadmin/user_upload/home/Datasheets/manuals/lc-photon-counter/count-series-user-manual.pdf

[6] https://www.micro-photon-devices.com/datasheet/MPD_PDM_Datasheet.pdf

[7] https://www.excelitas.com/file-download/download/public/60241?filename=Excelitas_SPCM-AQRH_Family_datasheet.pdf

[8] https://www.excelitas.com/file-download/download/public/60241?filename=Excelitas_SPCM-AQRH_Family_datasheet.pdf

[9] https://www.thorlabs.com/single-photon-detectors?partnumber=SPDMA&tabName=Overview

[10] https://www.hamamatsu.com/content/dam/hamamatsu-photonics/sites/documents/99_SALES_LIBRARY/ssd/c16531_series_kacc1312e.pdf

[11] https://www.hamamatsu.com/content/dam/hamamatsu-photonics/sites/documents/99_SALES_LIBRARY/ssd/c11202series_kacc1207e.pdf

modules from multiple manufacturers from Europe, the US and Japan. The listed products are illustrative examples and do not represent a complete survey of all available Si-SPAD modules. Entries, where manufacturers do not disclose a specification are marked as not available (N/A).

Across the products listed, peak PDEs span roughly 35–80% depending on wavelength and device design, with higher efficiencies near the red/near-IR, where silicon performs best. Dark noise and afterpulsing are present and depend on temperature, bias, and dead time settings. Consistent with the table, modules with shorter dead times (≈35–50 ns) advertise higher maximum counting rates (≈20–37 MHz), while devices with longer dead times (e.g., ≈77 ns or ≈1 µs) show lower MCRs (≈12–13 MHz). Increasing hold-off to suppress afterpulsing effectively lengthens dead time and reduces the usable count rate. From a QKD perspective, Si-SPADs are attractive for free-space or short-range implementations due to mature, compact modules that operate at or near room temperature. Their usable spectral range is visible to near infrared (≈350–1000 nm), so they are typically not the detectors of choice for the most common fiber-based QKD at 1310/1550 nm. Regarding timing resolution, the jitter in Si-SPADs is generally low enough for time-correlated protocols such as time-bin and decoy-state QKD.

Table 3: KPIs of a selection of InGaAs/InP-SPAD products

Manufacturer	Photon Detection Efficiency (PDE)	Timing jitter	After pulsing rate	Dark Count Rate (DCR)	Dead time	(Max) Counting Rate	Spectral Range	Active area
Micro Photon Device (IT)[12,13]	32% at 1550 nm[12]	100-130 ps (all modes); 60 ps (Gated mode)	N/A	5-10 kHz	1 µs–3 ms	free-running: ≤1 MHz; gate repetition up to 100 MHz	900 -1700 nm	25 µm
	25% at 1550 nm[13]	130-200 ps all modes); 70-100 ps (Gated mode)	N/A	0.5-1.2 kHz	1 µs–3 ms	free-running: ≤1 MHz; gate repetition up to 100 MHz	900 -1700 nm	10 µm
	25% at 1550 nm[13]	90-130 ps (all modes); 50-70 ps (Gated mode)	N/A	2.6-5 kHz	1 µs – 3 ms	free-running: ≤1 MHz; gate repetition up to 100 MHz	900 -1700 nm	25 µm
ID Quantique (CH)[14,15]	10-25% at 1550 nm; extended 30-35% (no guaranteed noise)[14]	200 ps max (150 ps typ.)	N/A	6 kHz / 10 kHz at 25% PDE	100 ns – 80 µs	100 MHz (Gated model) / 1 MHz (Free-running model)	900 -1700 nm	N/A
	10%, 15%, 20%, 25% at 1550 nm[15]	200 ps max (150 ps typ.)	N/A	At 10% PDE: <80 Hz; at 20% PDE: <200 Hz	2 - 100 µs	N/A	900 -1700 nm	N/A
	10%-30% at 1550 nm[16]	150 ps	< 0.1%	<1000 Hz (at 10% PDE)	100 ns – 1 ms	N/A	900 -1700 nm	N/A

---

[12] https://www.micro-photon-devices.com/datasheet/MPD_PDM-IR_Datasheet_Freespace.pdf

[13] https://www.micro-photon-devices.com/datasheet/MPD_PDM-IR_Datasheet_Fiber.pdf

[14] https://cdn-adepci1.actonsoftware.com/acton/cdna/11868/f-80a02dd4-31f4-45d6-b096-bcd296ccc908/1/10

[15] https://cdn-adepci1.actonsoftware.com/acton/cdna/11868/f-0234/1/9

[16] https://www.aureatechnology.com/wp-content/uploads/2022/04/AUREA_SPD_NIR_OEM_data_sheet_2017web.pdf

Manufacturer	Photon Detection Efficiency (PDE)	Timing jitter	After pulsing rate	Dark Count Rate (DCR)	Dead time	(Max) Counting Rate	Spectral Range	Active area
Aurea Technology (FR)[16,17,18,19]	Up to 40% at 1550 nm[17]	<100 ps	0.0005% per gate	≈1×10^6 Hz (per gate, at 30% PDE)	5 ns	200 MHz	900 – 1700 nm	N/A
	10%-30% at 1550 nm[18]	150 ps	< 0.1%	<800 Hz (at 10% PDE)	100 ns - 1 ms	N/A	900 – 1700 nm	N/A
	10%-30% at 1550 nm[19]	150 ps	< 0.1%	<800 Hz (at 10% PDE)	100 ns – 1 ms	N/A	900 – 1700 nm	N/A

Table 3 summarizes KPIs of a selection of commercial InGaAs/InP-SPAD modules across gated and free running operation in the 900–1700 nm band. Timing jitters are generally lower in gated operation. Dead time limits the maximum counting rate. Dark noise is reported either as counts per second for free running modules or as a probability per gate for fast gated instruments. These metrics reflect vendor operating points where efficiency settings trade sensitivity against noise and afterpulsing.

From a QKD perspective, detection efficiencies of 10 – 40 percent are relatively low compared with Si-SPADs. Noise levels are higher, and maximum counting rates are constrained by longer dead times, so very fast key exchange is hard to achieve. The strength of these devices is their operation in the telecom band, which matches low loss fiber and existing infrastructure. Gated operation helps timing alignment and noise rejection for pulsed QKD. Free running modules support continuous operation but need precise settings to manage background noise such as optical and detector-internal noise (dark counts, afterpulsing). Overall, they are practical for fiber-based QKD where wavelength compatibility is the priority, with the trade-off of lower speed and higher noise than Si-based detectors.

Players in R&D and industry

As identified by the non-exhaustive search in this study, among the leading Si-SPAD industry players are Hamamatsu Photonics (JP), Micro Photon Devices/MPD (IT), AUREA Technology (FR), Laser Components (DE), Excelitas Technologies (US), RedWave Labs (UK), DuoTec (DE), Xfab (DE), PicoQuant (DE), and ID Quantique (CH).

Some manufacturers of InGaAs/InP-SPADs include Fraunhofer HHI (DE), Phlux Technologies Ltd. (UK), Wooriro (KR), Lonten (CN), OEC Optoelectronics Components GmbH (DE), and ID Quantique (CH).

3.2.5 UP-Conversion SPDs

Single-photon detection in the O- and C-band is challenging as most available detectors come with some drawback compared to the less expensive Si-SPADs for the VIS (up to 1 µm wavelength). While SNSPDs offer outstanding performance they come with a high price and require cryogenic cooling that often is bulky and has high energy consumption. For size reduction, SPADs based on InGaAs can be used, however, performance is limited in particular by the deadtime and high dark

---

[17] https://aureatechnology.com/wp-content/uploads/2024/03/AUREA_Technology_GHz-NIR-single-photon-detector_GIGAXEA_Jan_2024.pdf

[18] https://www.aureatechnology.com/wp-content/uploads/2025/03/AUREA_Datasheet_SPD_A_NIR_V2.0_2019-1.pdf

[19] https://aureatechnology.com/wp-content/uploads/2024/03/LYNXEA_NIR_22.pdf

count rate (see discussion above). Another solution for single-photon detection with improved performance is to convert the single photons by sum frequency conversion into the absorption range of Si-SPADs, often referred to as quantum frequency converter. Thus, the improved performance of Si-SPADs in comparison to InGaAs/InP-SPADs are utilized while still having a reasonable price.

The system for a quantum frequency converter consists of a pump laser, converting the telecom wavelengths to below 900nm. The sum frequency conversion happens in a periodically poled nonlinear crystal, such ar lithium niobate or potassium titanyl phosphate (KTP). The converted single photons are then detected with Si-SPADs. The overall detection efficiency is similar to InGaAs/InP-SPADs but now with improved performance on dark count rate, deadtime, etc. This type of single-photon detector has already been demonstrated in QKD experiments verifying its capabilities (Yao et al. 2020; Wang et al. 2023a).

However, up-conversion SPDs for QKD also face challenges. Coupling light from fiber to the waveguide can be challenging, so small mismatches add loss and, thus, reduce detection efficiency. The strong pump laser needed for conversion can also create unwanted background light (for example, from Raman scattering), which grows with pump power. To keep noise low, longer-wavelength pumps near 1.95 µm and a stack of optical filters are used, but these steps introduce additional loss. In practice, performance depends on carefully balancing coupling, pump power, and filtering (Yao et al. 2020).

To the best of our knowledge, there are only few vendors offering quantum frequency converters or up-conversion SPDs, as of now.

3.2.6 Superconducting Nanowire Single-Photon Detectors (SNSPDs)

Superconducting nanowire single-photon detectors have emerged as a highly promising technology in quantum communication. SNSPDs have demonstrated exceptional performance, achieving secure key rates over considerable distances and significantly surpassing the performance limitations of single-photon avalanche diodes. The first successful QKD experiment using SNSPDs was conducted in 2005 (Hadfield et al. 2006), and ongoing advancements have continued to extend the transmission distance records in fiber optic communication, making SNSPDs the preferred choice for high-performance quantum communication applications. Despite these advantages, SNSPDs require cryogenic operation, resulting in higher operational costs and higher complexity of the systems. Therefore, we discuss their practical trade-offs in the following.

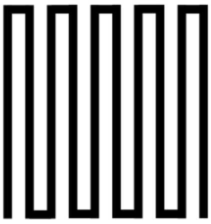
In addition to quantum communication, SNSPDs have been utilized in various advanced quantum information applications, including quantum teleportation, quantum random number generation, photonic quantum computing and the validation of Bell's inequalities. These applications showcase the versatility and robustness of SNSPDs in experimental quantum optics and quantum computing (You 2020).

Photon detection mechanism

SNSPDs represent a sophisticated technology for photon detection, characterized by their unique microscopic detection mechanism. Main element of the SNSPD is a very thin (approximately 5 nm thick) superconducting film, patterned into a narrow (width around 100 nm) nanowire meander structure that spans the detector area, typically made from materials like niobium nitride (NbN) or tungsten silicide (WSi). When operated below their critical temperature and current-biased close to their switching current, these detectors are capable of achieving high detection efficiencies and fast response times (Kück 2020).

The nanowire is usually patterned into a meander (serpentine) geometry, creating a large active area with high fill factor so that incoming photons are efficiently intercepted (see Figure 1). In meandered SNSPDs, a key limitation is current crowding in sharp 180° bends, which can degrade efficiency, dark counts, and timing. However, rounded or locally thickened bends mitigate this and improve performance (Xiong et al. 2022).

Figure 1: Meandered nanowire in SNSPDs



Source: own graphic

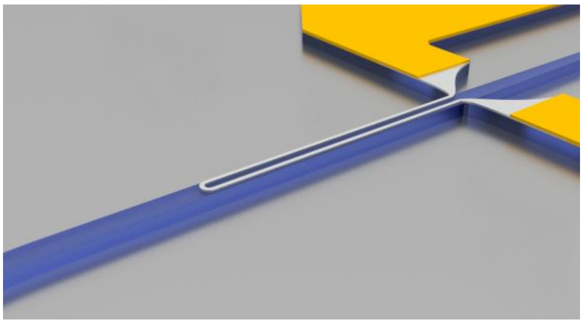
The detection process begins with a photon being absorbed by the nanowire, which may break hundreds of Cooper pairs (two electrons weakly paired and moving together as the superconducting charge carrier) due to the high energy of a single photon (approximately 1 eV) compared to the binding energy of a Cooper pair (around 3.2 meV for NbN). This breaking of Cooper pairs creates a hotspot in the nanowire, which causes the supercurrent to be diverted into the surrounding superconducting path. In addition to this hotspot picture, energy dissipation associated with the motion of tiny magnetic vortices in the superconductor can also assist the formation of the resistive region. As a result, the current near the hotspot may exceed the switching current, causing the hotspot to expand and form a resistive slot across the nanowire. This resistive slot, typically several hundred ohms, will grow along the direction of the nanowire due to Joule heating. Consequently, the supercurrent produces a transient voltage pulse across the nanowire that is directed into the readout circuit, resulting in a measurable signal. After the event, the resistive slot cools down and the superconducting state is restored (short dead time), allowing the SNSPD to reset and be ready for the next incoming photon (You 2020).

Key characteristics affecting performance

SNSPDs exhibit several key characteristics that greatly influence their performance metrics, particularly in QKD applications. As introduced in the section 3.2.1, one crucial metric is the system detection efficiency (SDE). SDE combines the coupling efficiency, absorption efficiency, and intrinsic triggering efficiency. In this context, coupling efficiency is the fraction of input photons delivered to the detector's active area, absorption efficiency is the fraction of those photons absorbed in the nanowire, and intrinsic (triggering) efficiency is the probability that an absorbed photon actually generates a detection pulse at the chosen bias and temperature (You 2020).

Among the optical structures developed for SNSPDs, the vertical coupling method stands out for achieving the highest SDE in standalone modules (You 2020). In vertical coupling, fiber/free-space light is focused normal to the chip onto the meandered nanowire. The ability to effectively couple incoming photons into the active area of the detector is essential here. Advancements such as cryogenic nanopositioning techniques have significantly reduced coupling loss to ≈1%, and optimized cavities can make the nanowire absorb nearly all the incoming light (You 2020). By contrast, in waveguide coupling the nanowire is integrated on top of an on-chip waveguide and absorbs the guided light over a short section of the waveguide, enabling near-unity on-chip detection efficiency (OCDE), compact arrays, low jitter, and straightforward multiplexing for photonic-integrated receivers (see Figure 2) (Raj et al. 2025).

Figure 2: Waveguide-coupled SNSPD



Source: Pixel Photonics

The DCR in SNSPDs is composed of background DCR and intrinsic DCR, with the former being influenced by thermal electromagnetic radiation and stray light. For efficient operation, techniques such as cooled fiber optics and dielectric filters are employed to minimize background noise. Intrinsic DCR is mainly influenced by the natural movement of magnetic flux spots within the nanowires and can typically be controlled at lower bias currents (You 2020). Keeping the DCR low is essential for QKD, as it directly affects the signal-to-noise ratio and the overall performance of the key distribution process.

For high-speed QKD, timing jitter is critical. Various sources contribute to system timing jitter in SNSPDs, including the detector itself, signal-to-noise ratio, and laser synchronization. Minimizing jitter is critical to accurately timestamp photon arrivals, which is vital for secure key generation. Recent advancements in SNSPD design have led to reductions in jitter, further enhancing their suitability for QKD applications.

The counting rate of SNSPDs is limited by thermal relaxation times and the kinetic inductance of the nanowires, as well as by time constants associated with the external bias and readout circuit. While the maximum counting rate can reach tens of GHz, practical implementations often yield lower rates due to the gradual recovery of the detector's state after photon absorption. Techniques to improve MCR, such as using multiple nanowires in parallel or interleaved configurations, have been explored to enhance overall performance (You 2020).

In addition to the key metrics mentioned above, there are other parameters worth noting. For example, SNSPDs can be sensitive to different wavelengths of light, and researchers are exploring ways to improve their performance across a broader range such as below 500 nm up to 2000 nm. Lastly, polarization sensitivity can impact detection and has led to the development of designs that either reduce or enhance this sensitivity based on the application needs. These additional features make SNSPDs versatile tools in quantum communication and related fields (You 2020).

Unlike SPADs, afterpulsing in SNSPDs is negligible because their detection mechanism does not involve carrier avalanches, although afterpulsing has been observed in some commercial devices (Raupach et al. 2023). There are no trapped charges that later release and cause false detections. An SNSPD detection is a brief hotspot in the superconductor that cools, and the current simply recovers. Therefore, SNSPDs typically do not need hold-off time to suppress afterpulses. Their recovery time is set by the device’s natural cooldown back to the superconducting state and by the reset dynamics of the readout circuit. Any remaining false counts mostly come from background photons or electronic noise, which are reduced with spectral filtering and shielding.

One operational issue is latching, where the nanowire remains in a resistive state after strong or sustained illumination, leading to extended recovery time and loss of photon sensitivity. Modern "latch-free" device designs largely mitigate this, so latching is generally not a critical limitation for current QKD systems, though it can still occur under extreme conditions.

Impact of materials used

A key factor in selecting materials for SNSPDs is their critical temperature (T_c), the point at which they become superconductive. Generally, materials with lower T_c, such as WSi and MoSi, can detect single photons more effectively, although they may also have limitations, such as reduced signal strength and higher cooling costs. High-temperature superconductors like $YBa_2Cu_3O_{7-x}$ are not suitable for SNSPDs due to their poor sensitivity to photons and manufacturing challenges (You 2020).

Most SNSPDs are made from niobium nitride (NbN), which has a relatively high critical temperature of about 10 K and a very fast hotspot cooling time of less than 100 ps. NbN detectors are known for their high detection efficiencies and can achieve count rates in the hundreds of MHz range, with low jitter and dark count rates, making them effective for various applications (Kück 2020). The recovery time of NbN detectors is only a few nanoseconds, allowing for advanced measurements with a single detector. However, the detection efficiency drops significantly for longer wavelength photons, prompting research into narrower NbN nanowires and alternative materials to enhance performance in the near- and mid-infrared ranges (You 2020; Kück 2020).

Cryogenic temperatures are essential for operating SNSPDs, which need to be cooled to temperatures below half of their critical temperature. For Nb(Ti)N SNSPDs, two-stage Gifford–McMahon (G–M) cryocoolers are commonly used, providing cooling temperature of around 4.2 K and capable of operating continuously at 2 K. To achieve even lower temperatures for materials like WSi and MoSi, more advanced cryocoolers, such as dilution refrigerators, may be necessary, but these systems are costly and less portable (You 2020; Kück 2020).

The size, weight, and power (SWaP) of cryogenic systems are important for practical applications, especially in communication base stations. Traditional two-stage G–M cryocoolers can be bulky, urging research into more compact and efficient alternatives. A recent prototype combining a pulse-tube cryocooler with a 4He Joule–Thomson cooler achieved a minimum temperature of 2.6 K with a lower power requirement and weight. This setup showed a system detection efficiency of 50% and a jitter of 48 ps (You et al. 2018). While these advances are promising, further improvements are needed to make cryogenic systems more practical and cost-effective for SNSPDs (You 2020).

SNSPD systems can offer **photon number resolution** (already defined in section 3.2.1) for a small number of photons. While this feature is not required for QKD itself, it is very crucial for the characterization of quantum light sources, for instance to validate the mean photon number of faint pulse sources. The characterization step is a major part on the way towards certification of practical QKD systems. Photon number resolution is achieved by different schemes: One variant is the precise measurement of the current during the absorption as the current over time has a very individual characteristic for different photon numbers (Sauer et al. 2023). This technique is not applicable to all types of SNSPDs and has some uncertainty in the exact resolution, in particular for higher photon numbers it is getting harder to differentiate the exact number. Another approach utilizes pixelized SNSPDs wherein each pixel allows for a single photon absorption. The combined current of all pixels directly correlates to the absorbed photon number. While the identification of photon number is certain, the multi-photon absorption probability on a single pixel increases with larger photon numbers and thus limits the resolution for larger photon numbers. The idea of counting individual photon absorption processes can also be achieved by inserting multiple delay lines in front of the detector to achieve photon number resolution by counting consecutive absorbed photons. This approach has similar limitation like the multi-pixel approach as the number of delay lines limits the maximum photon number resolved and at the same time loss in the interferometers reduces the precision of photon counting.

Commercial SNSPDs

Table 4 compiles KPIs for several commercially available SNSPD systems from different manufacturers from Europe and the USA. Values vary with wavelength band, detector design, bias conditions, and the amount of optical filtering, so manufacturers often provide ranges or configuration-dependent specifications; where not disclosed, entries are marked as not available. In case of SNSPDs, the post-detection insensitivity interval is mostly referred to as "recovery time" (see section 3.2.1), as used in the table. Practically, the maximum counting rate is limited by recovery interval and is often approximated as the inverse of the recovery time.

Table 4: KPIs of a selection of SNSPD products

Manufacturer	Photon Detection Efficiency (PDE)	Timing jitter	Dark Count Rate (DCR)	Recovery time	(Max) Counting Rate	Spectral Range / Wavelength	Operating temperature
ID Quantique[20] (CH)	80-90% Peak system detection efficiency (SDE): at 1550 nm	<20-40 ps (typ. <30 ps; as low as <20 ps)	<5 Hz (<500-950 nm), <20 Hz (950-1300 nm), <100 Hz (1300– >1600 nm)	Standard: typ. < 30 ns; Parallel: < 10 ns	Standard: >30 MHz; Parallel: > 250 MHz; multi-pixel: > 1 GHz across all pixels	<500 nm to >2000 nm	>2 K
Single Quantum[21] (NL)	≥90% (800/900/1550 nm); ≥ 85% (1064/1310 nm)	≤ 15 ps	≤1 Hz (800/900/1550 nm); ≤10 Hz (1064/1310 nm)	N/A	≥80 MHz (800/900 nm); ≥50 MHz (1064/1310/1550 nm); optional ultra-high count rate detectors ≥600–800 MHz	800, 900, 1064, 1310, 1550 nm	2.5 K
Photon Spot[22] (US)	70-75% at 1550 nm	<100 ps	<100 Hz	<100 ns	N/A	637, 780, 825, 940, 1310. 1550 nm	N/A
Quantum Opus, LLC[23] (US)	≥90% at 850 nm/950 nm; ≥80% at 1310 nm/1550 nm	<80 ps (850/950 nm); <100 ps (1310/1550 nm)	<1 Hz (850/950 nm); 10 Hz (1310 nm); 100 Hz (1550 nm)	50 ns	N/A	850, 950, 1310, 1550 nm	< 2.5 K

The table also distinguishes system architectures. "Standard" SNSPD channels typically use a single detector element with moderate recovery times. "Parallel" configurations use multiple detector elements that share the same optical mode (same fiber, same spatial position), distribute detection

---

[20] https://cdn-adepci1.actonsoftware.com/acton/cdna/11868/f-023b/1/31

[21] https://www.singlequantum.com/wp-content/uploads/2024/12/SQ-General-Brochure-2.pdf

[22] https://www.photonspot.com/detectors

[23] https://www.quantumopus.com

events across the elements or channels to reduce effective recovery time and increase counting rate. "Multi-pixel" arrays are 1D/2D arrays of pixels, where each pixel is a detector element viewing a different spatial position/mode. This enables spatial multiplexing and increases total throughput across distinct modes.

Spectrally, products are optimized for visible and near-infrared bands, including telecom wavelengths, with options for broadband operation. All systems operate at cryogenic temperatures. The cryostat type sets the base temperature, which influences efficiency, timing jitter, and dark counts. In the commercial products surveyed, afterpulsing is not reported. For SNSPDs, afterpulsing is generally negligible in properly designed devices, although it has been observed in some commercial systems (Raupach et al. 2023). In contrast, in SPADs afterpulsing is typically present and must be considered.

SNSPDs are well suited for QKD because of their high detection efficiency, ultra-low dark counts, and low timing jitter that reduce the quantum bit error rate (QBER) and increase key rates over long distances. However, cryostats add cost, bulk, and operational complexity compared to SPADs.

Players in R&D and industry

Some examples for SNSPD industry players are Single Quantum BV (NL), Pixel Photonics GmbH (DE), Scontel (RU), Photon Spot (US), Quantum Opus (US), Photon Technology (CN), and ID Quantique (CH).

3.2.7 Comparison of SPAD and SNSPD Variations

Table 5 compares the benefits and drawbacks of the discussed SPDs in the context of QKD. For QKD, Si-SPADs offer good efficiency and timing performance at low cost, but their spectral limitation, that is poor sensitivity at 1550 nm, makes them unsuitable for standard fiber-based links. They can be a solid choice for free-space or short-reach systems at visible/near-IR wavelengths, but they are not competitive for C- and O-band operation typically used in fiber QKD.

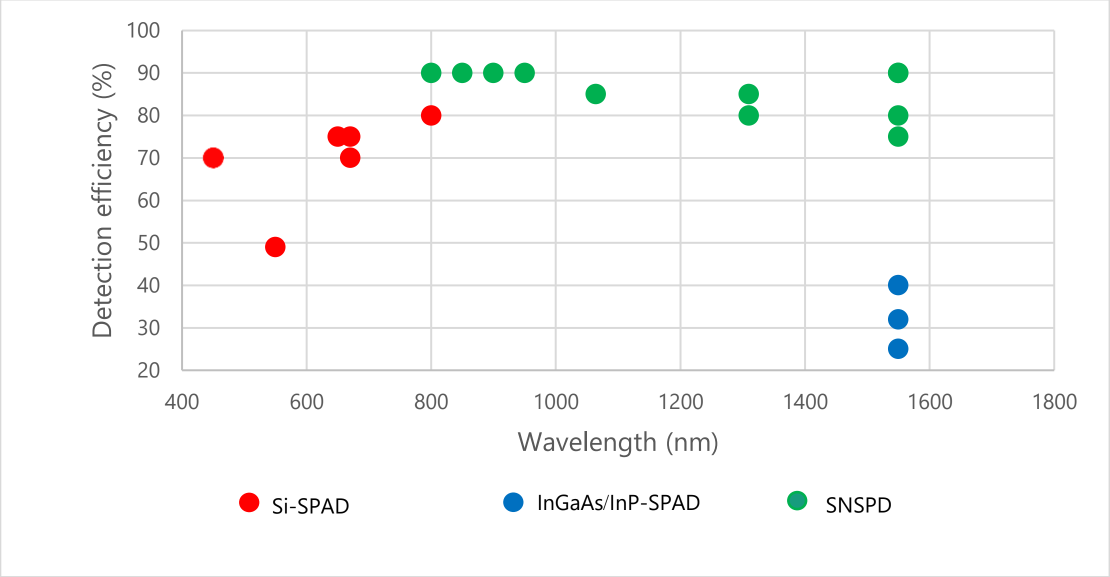
InGaAs/InP-SPADs operate at 1550 nm and are compact and cheaper than SNSPDs, but their overall performance is limited: lower detection efficiency, higher dark counts (noise), longer dead times, and generally lower speed, which constrain secure key rates and distances. SNSPDs deliver the best QKD performance, due to very high detection efficiency, ultralow jitter, short recovery times, and extremely high-count rates which enable the highest key rates and longest reaches. However, they carry the considerable overhead of cryogenic cooling, including high cost, larger footprint, significant power consumption, and maintenance overhead.

Table 5: **Comparative overview of Si-SPAD, InGaAs/InP-SPAD and SNSPD technologies for QKD**

SPD Type	Strengths	Weaknesses
Si-SPADs	• Sufficient detection efficiency • (Comparatively) Low size and cost • Relatively short Deadtimes • Miniaturization possible • Timing is relatively good, in the scale of hundreds of ps • Suitable for mass production • Low cost	No efficient detection above 1000nm and hence not suitable for typically used wavelength in fiber (around 1310 nm and 1550nm)
InGaAs/InP-SPADs	• Detection in typically used wavelength regions (around 1310 nm and 1550nm) • Miniaturization possible • Lower cost than SNSPDs	• Low detection efficiency • Long Dead Time • Higher Cost compared to Si-SPADs (high defect rate in production) • High dark count rate (noise) • Thermoelectric (TEC) cooling required
SNSPDs	• Very high PDE/SDE (photon/ system detection efficiency) • Photon number resolution -> not important on the receiver side; on the source side helps to reject clock cycles with more than a single photon • Short deadtimes / recovery Time • Timing jitter very low • Extremely high-count rates • Free running and no afterpusling	• Cryogenic cooling required • Cryogenics life cycle / maintenance needs • High energy demand: Power in range of kW (detector nW) • Large space demand • High costs

Figure 3 illustrates maximum detection efficiencies reported for various wavelengths for the commercial SPDs reported in Tables 2-4. As the Figure shows, SNSPDs offer the highest efficiencies and can detect a broader spectrum of signals from visible to NIR including very high SDEs at 1550 nm. Si-SPADs deliver moderate to high peak detection efficiencies across the visible to near-IR up to 800 nm. In contrast, InGaAs/InP-SPADs cover the telecom band (including 1310 and 1550 nm) but typically exhibit much lower detection efficiencies.

Figure 3: **Comparison of detection efficiencies and spectral ranges of commercial Si-SPADs, InGaAs/InP-SPADs, and SNSPDs (data and references are listed in tables 2-4).**



3.2.8 Other Single-Photon Detectors

Single-Photon Detectors Based on Quantum Dots

Quantum dots (QDs) have been mostly explored for application in QKD as single-photon sources; however, their integration in photonic devices can also improve detection of single photons and add features such as photon number resolution. QDs have been used for photodetection in various structures namely photoconductors, phototransistors and photodiodes for relatively large spectral range including visible to infrared light (Wang et al. 2023b).

QDs are indeed nanoscopic ensembles of semiconductor materials exhibiting discrete electronic energy levels and bandgaps due to their spatial limitation, which can be used for individual optical transitions of single electrons (Arakawa und Holmes 2020). The energy bandgap of the QD can be engineered by the material and the QD size. As the size of the quantum dot decreases, the energy bandgap increases, leading to a blue shift in the absorption and emission peaks. This allows for tunable absorption characteristics across various wavelengths which enables detecting a wide range of photon energies (Wang et al. 2023b).

When a photon with energy greater than the energy bandgap of the QD is absorbed, it generates an electron-hole pair. The resulting electron-hole pairs can be separated by an internal electric field, present in the device structure such as diodes. The electrons are then collected at the electrodes, generating a measurable photocurrent which allows to detect photon absorption (Wang et al. 2023b).

One prominent type of QD-based SPD is the QD Coupled Resonant Tunneling Diode (QD-cRTD) (Wang et al. 2022; Weng et al. 2015). RTDs are semiconductor devices that utilize the quantum mechanical phenomenon of tunneling. In an RTD, electrons tunnel resonantly through a double-barrier quantum well structure consisting of two thin barriers surrounding a single quantum well, where the electron energy levels are quantized. This resonant tunneling produces negative differential resistance and an N-shaped current–voltage characteristic, enabling ultrafast on–off switching (Zhang et al. 2021).

In the case of QD-cRTDs, individual quantum dots are closely coupled with adjacent quantum wells within the diode. When a photon is detected, it generates an electron-hole pair, and the hole gets trapped in the quantum dot. This trapping reduces the flow of tunneling current, allowing the device to change its output in response to light (Weng et al. 2015).

Research has shown that QD-cRTDs can effectively distinguish between one-photon and two-photon states, achieving high accuracy rates of 90% and 98%, respectively (Weng et al. 2015). This photon number resolution ability makes them promising for applications that require precise detection of photon-number states.

Another type of QD-based SPD is the Quantum Dot Field-Effect Transistor (QDFET). This device incorporates a thin layer of quantum dots as the active material, positioned between the gate electrode and the conduction channel. When the QDFET is illuminated, it generates electron-hole pairs in the active region. An internal electric field then separates these pairs, allowing holes to be trapped in the quantum dots (Wang et al. 2022; Wang et al. 2023b; Gansen et al. 2006).

As holes accumulate in the quantum dots, they alter the carrier concentration in the two-dimensional electron gas (2DEG) region of the transistor, which is a highly conductive layer of electrons formed in the semiconductor material. This change in carrier concentration can be measured as a variation in current, enabling the QDFET to detect single photons.. The device has been reported to achieve high counting rates of up to 400 kHz and an internal efficiency of 68% (Wang et al. 2022),

Single-photon detectors based on quantum dots have demonstrated ultra-low dark count rates ($\approx 2 \times 10^{-3}$ Hz) and detection efficiencies of up to 68%. However, these technologies remain largely in the early stages of development and primarily in the research phase, as the material growth processes are still immature and cryogenic operation (≈ 4 K) is required to suppress background noise, hindering their practical applications (Wang et al. 2022).

Photomultiplier Tubes (PMTs)

Photomultiplier tubes are devices used for detecting visible photons. They work by converting incoming photons into electrons through a photocathode. When a photon strikes the photocathode, it generates an electron. This electron then undergoes a multiplication process across a series of components known as dynodes. Each dynode is designed to accelerate the electron, causing it to knock out additional electrons upon impact, leading to a significant amplification of the signal. This process can result in the generation of about 10^6 electrons from a single photon. PMTs typically operate in a vacuum and have efficiencies ranging from 10% to 40%, which is influenced by the initial photoelectron emission. While some PMT models can partially resolve the number of incoming photons, their overall efficiency may not meet the demands of modern applications (Eisaman et al. 2011; Wang et al. 2021b).

PMTs offer several advantages, including large sensitive areas, fast response times, and low dark count rates, which can be reduced further by cooling. They can operate at room temperature; however, they tend to be bulky. Despite these benefits, their reliance on vacuum technology poses challenges in terms of lifetime, reliability, and scalability, making them less favorable for certain contemporary uses (Eisaman et al. 2011; Wang et al. 2021b). PMTs are commonly used in applications such as medical imaging and radiation detection, but they are not suitable for QKD due to their limitations in precision and efficiency.

Transition Edge Sensors (TES)

Transition Edge Sensors are cryogenic energy sensors that utilize the highly temperature-dependent resistance of superconducting phase transitions. Typically composed of ultralow-temperature superconducting films, such as tungsten or titanium–gold bilayers, TES devices exhibit high detection efficiency and unique photon number resolvability. When photons are absorbed, they produce measurable resistive changes during the transition from a normal to superconducting state. However, TES detectors usually require sub-Kelvin operating temperatures and can exhibit low speed, meaning a longer response time to incoming photons, as well as high timing jitter (You 2020).

TES detectors are particularly attractive for scientific applications such as cosmic microwave background and sub-millimeter astronomy, high-resolution X-ray/gamma-ray spectroscopy, and quantum-optics metrology (Lucia et al. 2024), due to their high detection efficiency across a range of wavelengths, from millimeter waves to gamma-rays, as well as their low dark count rates. The signal output from TES detectors is proportional to the incoming energy, allowing for photon number resolution, which can be crucial for applications in quantum cryptography and characterizing single-photon sources. Despite these advantages, TES detectors require cryogenic environments for operation and have associated timing jitter and longer pulse durations compared to other detector technologies, such as avalanche photodiodes, which make them unsuitable for QKD applications (Kück 2020).

Microwave Kinetic Inductance Detector (MKID)

Microwave Kinetic Inductance Detectors are thin-film high-Q[24] superconducting micro-resonators that detect incoming photons by measuring changes in their resonance frequency and internal quality factor. When photons interact with the superconductor, they break Cooper pairs, leading to detectable shifts in frequency and internal dissipation. These measurements are referred to as frequency readout and dissipation readout, respectively, making MKIDs a promising technology for sensitive photon detection (You 2020).

MKIDs promise unique advantages, including the potential for multiplexing and simplified detection schemes, which could enhance their application in various fields, such as astrophysics and quantum communication. However, practical implementations of these technologies are still in development, and further research is needed to fully realize their capabilities (You 2020; Zmuidzinas 2012).

3.3 Coherent Detectors

In contrast to DV-QKD, coherent detection is fundamental in continuous-variable quantum key distribution (CV-QKD) systems, utilizing optical devices such as beam splitters to achieve interference between a quantum signal and a strong local oscillator (LO). The beam splitter divides the incoming light, allowing for simultaneous measurement of different light paths, which is essential for extracting information from the quantum states.

In CV-QKD, the information is typically encoded in the quadratures of the electromagnetic field, specifically the position and momentum quadratures. These quadratures can be represented as two-dimensional vectors in phase and space, and measuring them accurately is crucial for secure key distribution. While a homodyne detector measures one quadrature at a time, the security analysis requires information from both quadratures, necessitating advanced techniques to switch

---

[24] High-Q" refers to a quality factor (Q factor) that indicates a resonator's ability to maintain resonance with low energy loss, resulting in a narrow resonance peak. This characteristic enhances sensitivity to small changes, making high-Q resonators ideal for precise measurements in applications like photon detection.

measurement bases. Heterodyne detection, on the other hand, allows simultaneous measurement of both quadratures by employing two phase-shifted LOs. This is indeed a dual-homodyne setup which enhances the detection's robustness against phase fluctuations, providing richer information for key generation. The heterodyne detector structure facilitates high-speed detection with reduced noise, though it requires more complex setups compared to homodyne detectors. Despite the added complexity, the ability to retrieve both quadratures concurrently significantly improves the system's performance, making it more suitable for practical QKD applications (Zhang et al. 2024).

Both detection methods have distinct advantages and disadvantages. Homodyne detectors are simpler and provide high sensitivity, but their single quadrature measurement makes them more susceptible to noise interference. In contrast, heterodyne detectors can measure both quadratures simultaneously, offering better noise resistance and higher key rates. However, their increased complexity and reliance on advanced electronics can pose practical challenges during implementation (Zhang et al. 2024).

Recent advancements in coherent detection technology have led to enhanced performance metrics for both homodyne and heterodyne detectors. The integration of photonic circuits has enabled the development of chip-based detectors with high bandwidth and low electronic noise (Zhang et al. 2024).

4 Technology Outlook and Roadmap

In this chapter, we aim to provide a clear understanding of the development paths, key performance metrics, and commercialization dynamics focusing on Si-SPADs, InGaAs/InP-SPADs, and SNSPDs with respect to their application in QKD. We focus on major KPIs which are critical to QKD reliability and performance. The chapter highlights the main technological and commercialization challenges of these SPD devices, assesses their suitability for different QKD scenarios and provides a roadmap with indicative timelines for performance gains, integration and manufacturability improvements. The results presented in this chapter are based primarily on expert interviews and a roadmapping workshop with experts from research and industry.

4.1 Key Performance Indicators

Table 6 provides typical performance values of SPDs available on the market according to experts. We compare Si-SPADs, InGaAs/InP-SPADs, and SNSPDs across KPIs relevant to QKD. Broadly, SNSPDs lead on core performance metrics (high detection efficiency, ultralow DCR, fast recovery, low jitter), Si-SPADs are strong for visible applications at room temperature, and InGaAs/InP-SPADs are telecom compatible but need critical improvement in PDE, DCR, and dead time. In contrast to the nominal specifications of commercial devices summarized in Section 3.2, the values reported in Table 6 reflect expert estimates of practically achievable performance under typical operating conditions and are therefore mostly lower than the vendor-quoted KPIs.

Regarding scalability and multi-channel setups, Si-SPADs are the most straightforward to scale at room temperature, with compact modules and arrays and low per-channel overhead. InGaAs/InP-SPADs also support multi-channel systems. Several detectors and channels can be integrated into a single package, and the optimal density depends on the application, TEC cooling, and afterpulsing management. SNSPDs mostly offer multiple channels per chip and 40+ channels per system. Per chip, hundreds of channels are in principle possible, but typically 28 channels are made today.

Table 6: Typical KPI ranges for Si-SPADs, InGaAs/InP-SPADs and SNSPDs

KPI	**Si-SPAD**	**InGaAs/InP-SPAD**	**SNSPD**
Photon detection efficiency (PDE)	🟡 50–65%	🔴 10–40%	🟢 70–90%
Dark count rate (DCR)	🟢 20–200 Hz	🔴 200 Hz–10 kHz	🟢 <1–100 Hz
Dead time (SPAD)/ Recovery time (SNSPD)	🟡 20–100 ns	🔴 100 ns–100 µs	🟢 <10 ns
Max. counting rate (MCR)	🟡 20–80 MHz	🔴 10 kHz–10 MHz	🟢 10–100 MHz
Afterpulsing	🔴 0.5–1%	🔴 ≈1%	🟢 Negligible
Timing jitter	🟡 300–1000 ps	🟡 60–300 ps	🟢 <30–100 ps
Spectral range	🟡 350–1000 nm	🟡 900–1700 nm	🟢 400–2000 nm
Operating temperature	🟢 Room temp.	🟡 ≈220 K, TEC	🔴 2.5–3 K
Size of active area	🟢 20–500 µm	🟡 ≈10 - 80 µm	🟡 50 µm

KPI	Si-SPAD	InGaAs/InP-SPAD	SNSPD
Multi-channel integration	🟢 possible	🟡 possible	🟡 possible
Price	🟡 €2–8k	🔴 €15–20k	🔴 €100–200k

🟢 No immediate improvement needed

🟡 Desirable to improve

🔴 Critical improvement required

Cost is a determining factor in QKD deployments, thus, a performance/cost trade-off is required when selecting SPDs. Typical single-channel module prices are ≈€2–8k for Si-SPADs and ≈€15–20k for InGaAs/InP-SPADs. In QKD systems, at least three SPAD channels are typically required, so the total detector cost per receiver is correspondingly higher. For SNSPDs, price is around ≈€100k for the base cryogenic system (without channels) plus ≈€8–20k for each channel, with total cost scaling with channel count and readout complexity. Cost drivers include material/process yield, cooling and cryogenics, packaging, and high-bandwidth readout.

There is motivation for up-conversion receivers as they allow to shift 1310/1550 nm photons to the visible band detectable by Si-SPADs at room temperature, which offers telecom compatible operation with the efficiency, speed, and low noise of silicon-based devices. However, this is not yet a broadly marketed segment. To the best of our knowledge only a few companies currently sell or are close to selling such products. Given their higher price (≈€30k/channel), up-conversion KPIs must offer at least the performance of InGaAs/InP-SPADs. In practice they currently offer PDE >25%, DCR ≈1 Hz, and dead times <100 ns. They have, in principle, the potential to deliver higher efficiency, faster operation, and lower noise at telecom wavelengths than today's InGaAs modules. Nevertheless, complexities with system-level overhead (pump lasers, alignment/stability) and multi-channel scaling (pump distribution, added optics per channel) need to be managed.

4.2 Technology and Market Challenges

The improvement of performance and cost in current state-of-the-art technologies faces a variety of challenges, which will be discussed in this section. The most important challenges are illustrated in Figure 4.

Security is a key aspect of QKD systems. The promise of ultra-secure communication is central, but current discussions focus on **side-channel attack risks** that arise from implementation limitations. These risks should be mitigated and better understood. In cases in which attack risks cannot be entirely excluded, they should be made quantifiable and minimized as much as possible.

Ease of setup and operation is critical for QKD systems. Optical setups often experience drifts that require correction or recalibration over time. Automation is highly desired in this area, as network systems should not demand extensive attention during operation. This includes the complexity in control systems and their automation. The overall aim is to improve **user-friendliness** in terms of complexity of operation and **maintenance**, reducing the training required for operators and implementers. Such challenges are typical of technologies transitioning from the prototyping phase to commercialization. Regarding the current detection units for QKD systems, significant progress has been already made, but they still offer room for further improvement. Long **lifetimes** are important to achieve reasonable total cost of ownership and minimize maintenance requirements.

Environmental influences such as temperature, light, and magnetic fields can affect performance, potentially increasing the quantum bit error rate (QBER) and reducing the effective key rate by increasing the detector's dark counts or reducing its photon detection efficiency. These **sensitivity** issues can be mitigated through careful system engineering, though inherent robustness of the photon detectors remains an advantageous attribute.

The **integration** of QKD systems poses engineering challenges, with the goal being to achieve systems with low size, weight, and power consumption (SWaP). A low number of optical interfaces is one approach to reduce coupling losses. **Miniaturization** is a crucial requirement to tap into broader markets with more stringent limitations, with mobile devices being the ultimate goal for enabling further use cases. While SPADs are already small and offer good overall miniaturization potential, SNSPDs will remain limited in the next years.

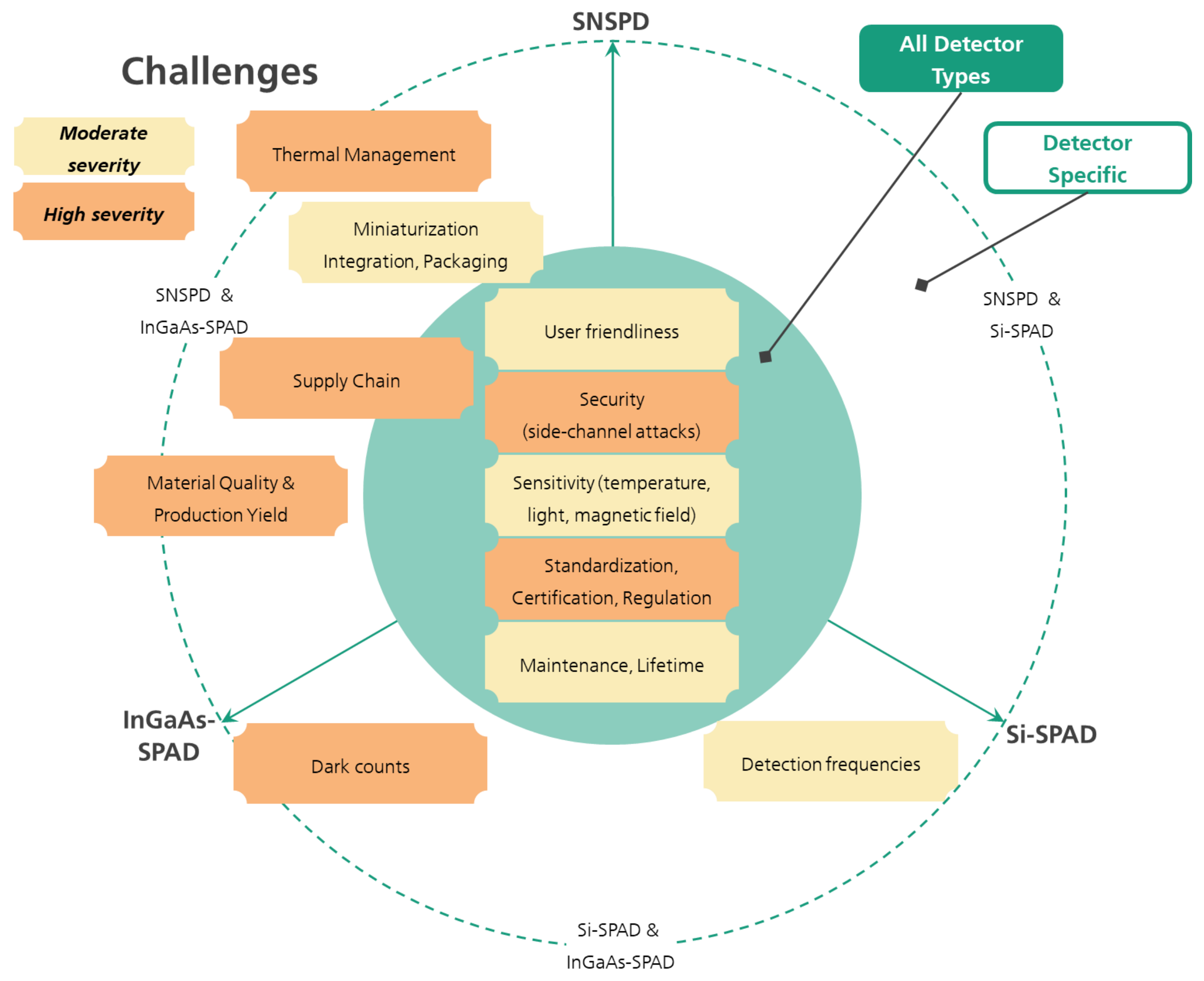
Imperfect **material qualities** can have a significant impact on detection efficiency. Si-SPADs are produced using well-established methods under highly controlled clean room conditions, resulting in consistently high material quality. However, the production of InGaAs/InP-SPADs is more challenging and has not yet been translated into large-scale, ultra-high-quality manufacturing processes. Therefore, further developments in this area are anticipated. Improving substrate materials is also relevant, as larger substrate sizes would be beneficial for mass production, while their quality influences the overall performance of the diode. While testing can help control quality, this reduces yield: for SNSPDs, achieving good material quality often relies on careful post-production selection, which can result in **production yields** as low as a few percent. Despite these challenges, the quality of final products is very well controlled, though this may lead to a loss in production yield, particularly for waveguide-coupled SNSPDs. Complexity in production processes and associated costs remain significant constraints.

Cooling requirements differ between detector types and introduce additional challenges for **thermal management**. For InGaAs/InP-SPADs, thermoelectric coolers are required to operate at reduced temperatures that minimize dark counts. SNSPDs, on the other hand, operate at cryogenic temperatures, which are significantly more expensive both in terms of initial investment and ongoing operational costs. Cryogenic cooling is, however, a well-established technology. If the temperature range for SNSPDs could be elevated, it would offer substantial advantages for broader commercialization. Significant advancements, while highly desirable, are unlikely in the near term future.

The limited wavelength detection window of Si-SPADs is the primary reason why their otherwise excellent specifications are insufficient for the large volume of QKD applications that rely on telecom wavelengths. The limited **detection frequencies** are an intrinsic property of the material (bandgap), leaving little room for improvement. Thus, it is more of a fundamental limitation than a technical challenge. In contrast, InGaAs/InP-SPADs offer a wavelength window that is better suited for these applications, and ongoing research efforts are targeting specific improvements. For SNSPDs, wavelength-related challenges are not critical.

Dark counts significantly limit the performance of QKD links. Further improvement is strongly anticipated for InGaAs/InP-SPADs, while other detector types already achieve values that are suitable for most commercial QKD applications.

Figure 4: Challenges for future developments of single-photon detectors for QKD. General challenges are placed in the center, detector-specific challenges more towards the outside of the circle.



Source: Results based on workshop

High-security communication systems must comply with **regulatory requirements, standardization, and certification**. Entering fields as highly regulated as secure communication poses challenges for new technologies, not only in terms of technical aspects but also organizational and bureaucratic hurdles. Standardization offers a path to leverage scaling effects and improve performance comparability, yet it imposes restrictions that may limit opportunities for innovation or individual technical developments.

Supply chain risks are highly relevant, as the accessibility of materials can influence cost and availability. Factors such as trade policies and embargoes play a crucial role. This is especially pertinent for raw materials needed in the production of technologies. For example, SPAD diodes are critical components, and initial production has been concentrated in regions such as China and the US. Electronic components, in general, are largely manufactured outside Europe, though the region is expected to have relevant competencies to mitigate potential supply chain bottlenecks in this field.

4.3 Application Mapping and Prioritization

The choice of single-photon detector determines which protocols can be used (or vice versa) and what overall system performance can be achieved on the QKD link. Therefore, it directly impacts the use cases and application scenarios that the system is suitable for. The prioritized detector types for different configurations of distance, desired key rate and the link medium (fiber, ground-to-ground free-space, satellite-to-ground) are shown in Table 7.

Table 7: Typical choice of single-photon detectors for different DV-QKD scenarios. Predominant technologies are written in bold, alternatives in regular font.

Distance	**Fiber-based QKD**			**Free-space QKD**		**Satellite QKD (ground)**
	< 50 km	**50 – 120 km**	**120 – 200 km**	**< 50 km**	**50 – 150 km**	
< 1 kb/s	**InGaAs/InP-SPAD**	**InGaAs/InP-SPAD** (sender: Si-SPAD)	**SNSPD** InGaAs/InP-SPAD (sender: Si-SPAD)	**Si-SPAD** SNSPD InGaAs/InP-SPAD	**Si-SPAD** SNSPD	**SNSPD**
1 kb/s – 100 kb/s	**InGaAs/InP-SPAD**	**SNSPD** InGaAs/InP-SPAD	**SNSPD** InGaAs/InP-SPAD	**SNSPD** Si-SPAD InGaAs/InP-SPAD	**SNSPD**	**SNSPD**
100 kb/s – 10 Mb/s	**SNSPD**	**SNSPD**	**SNSPD**	**SNSPD**	**SNSPD**	**SNSPD**

Source: Results based on Workshop

A rule of thumb for the optimal choice of single-photon detector could be boiled down to (i) if high performance (i.e. distance and/or key-rate) is desired, the comparatively expensive SNSPDs are the best choice, while SPADs offer cost-effective alternatives for scenarios with low key-rates and short distances. And (ii) in scenarios in which telecom wavelength are used, InGaAs/InP-SPADs will be employed instead of Si-SPADs, latter of which are the preferred SPAD technology, if shorter wavelengths (e.g., 810nm) can be used.

However, the complete picture is more nuanced. In fiber-based QKD applications, Si-SPADs can have a significant relevance as well, even though the quantum channel itself usually operates at telecom wavelengths. Some protocols rely on the initial creation of entangled photon pairs and the subsequent detection of the sender of one of the two photons (heralding). Information about the polarization and the timing of the emitted photon can be obtained by this measurement. The heralded photon can be tuned to wavelengths, which can exploit the optimal photon detection efficiency of Si-SPADs, as it does not have to pass through a long fiber.

The optimal wavelength for free-space links depends on the detection efficiency of the receiver unit, as well as the absorption and perturbation on the optical path through the atmosphere. Both, 1550nm with InGaAs/InP- or 810nm and Si-SPADs (or other wavelengths in the detection windows) can be used in theory, even though the latter is more common. At 1550 nm, free-space receiver architectures based on InGaAs/InP-SPADs can also leverage coupling into multimode fibers to realize large fields of view and relaxed pointing requirements, whereas current SNSPD systems are predominantly optimized for single-mode fiber coupling.

As we focus on single-photon detectors for DV-QKD in this report, we did only discuss these technologies in this section. However, it should be noted that CV-QKD offers an attractive alternative for short-distance links, preferably via fiber.

Even though the different detector types have different strengths and weaknesses, they all anticipate increasing market sizes. As SPADs are low-cost alternatives, more devices are expected to be sold in comparison to SNSPDs on the short- to mid-term. The number of annual sales for quantum communication applications could lie in the next few years at the order of a few hundred, potentially reaching more than a thousand around 2030. However, this is merely speculative, as no good estimates on current and future sales have been published. The market for the discussed types of single-photon detectors will reach beyond QKD, and into different quantum sensing applications.

4.4 Technology Roadmap of QKD Single-Photon Detectors

Here we synthesize the workshop outcomes and the roadmap graphic into a concise technology outlook for SPDs with respect to their use in QKD. The roadmap balances two topics: (i) performance (efficiency, noise, timing, maximum count rate) needed for higher key rates and longer reach, and (ii) deployability (cost, cooling, standardization) needed for widespread commercial uptake across fiber, free-space, and satellite links (see Figure 5).

The QKD application mapping underscores Si-SPADs suitability for short-range/free-space at visible/NIR, InGaAs SPADs for telecom fiber links, and SNSPDs for the highest rates and longest distances when jitter and noise budgets are tight.

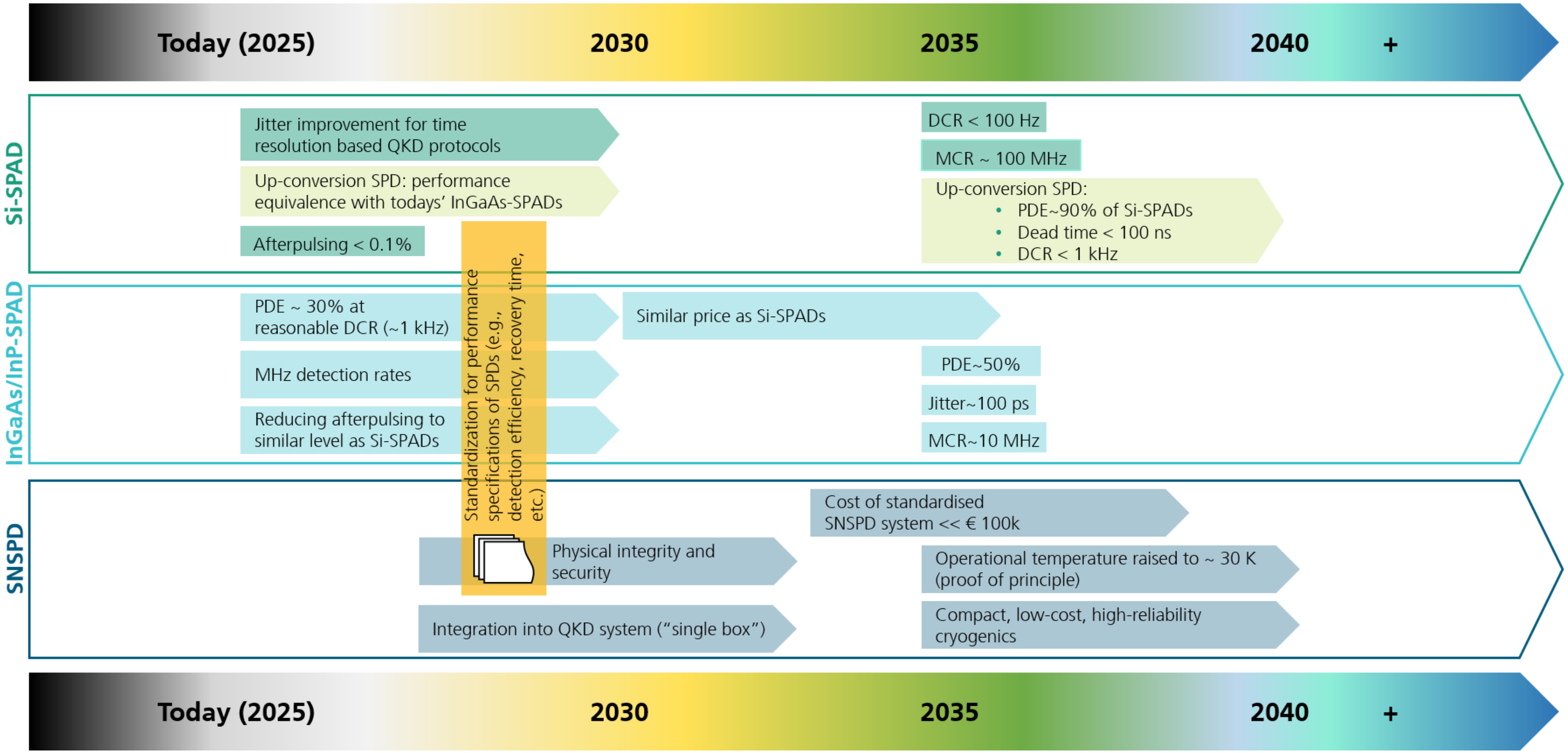
SNSPDs will set the performance ceiling but face high costs and the need for cryogenics as primary barriers. Some experts argued that costs will only considerably drop when operating temperatures near ≈25–30 K are achieved, unlocking the potential use of cheaper, longer-lived coolers. Superconducting materials operating up to ≈25 K are currently researched, so with steady progress this could become practical within ≈10 years or more according to some experts. In parallel, prices can fall through fabrication scale up and feature standardization by moving from customized modules to batches of identical devices. Performance improvements will focus on optical coupling and multipixel architectures to lift usable count rates while preserving today’s ultra low dark counts and low jitter, which are already well suited for time bin and high-rate protocols.

InGaAs/InP-SPADs remain the dominant lower-cost technology for telecom fiber. Near term goals prioritize higher efficiency without noise penalties. According to experts, a PDE of ≈30% at ≈1 kHz DCR is viewed as achievable in a few years, if market demand warrants. Current devices already reach ≈25% PDE at ≈1 kHz DCR. However, experts note that further optimization of InGaAs/InP-SPADs is technically challenging and will require strong market drive to justify the necessary R&D and manufacturing investments. High speed gating (e.g., 1 GHz) is progressing, but the usable counting rate is still capped by dead time and afterpulsing control. Standardization efforts by metrology institutes could yield initial norms for all SPD types before 2030, although vendors note that aligning commercial products to new rules takes time. Over a 10-year horizon, the roadmap targets roughly a jitter in the range of 100 ps, maximum counting rates of approximately10 MHz, and PDE approaching 50%.

Si-SPADs remain attractive for free-space and short-range applications due to room temperature operation, mature modules, and strong PDE in the spectral range (≈350–1000 nm) makes them less suited to 1310/1550 nm fiber unless paired with up conversion.

Up conversion SPDs bridge telecom wavelengths to the visible for detection with Si-SPADs. They offer room temperature operation at 1310/1550 nm but must overcome conversion loss and pump induced noise. Experts expect incremental gains over 3–5 years with better integrated, lower noise modules becoming competitive in performance with InGaAs/InP-SPADs. In 10 years, up-conversion SPDs are expected to achieve a PDE approaching 90% of that of Si-SPADs, dead time below 100 ns, and a DCR around 1 kHz. By comparison, Si-SPADs are expected to reach DCR < 100 Hz while supporting maximum count rates in the range of 100 MHz.

Figure 5 QKD Single-Photon Detectors: Technology Roadmap addressing milestones and KPI Targets (Si-SPAD, up-conversion SPD, InGaAs/InP-SPAD, SNSPD)



Jitter improvement for time resolution based QKD protocols

Up-conversion SPD: performance equivalence with todays' InGaAs-SPADs

Afterpulsing < 0.1%

DCR < 100 Hz

MCR ~ 100 MHz

Up-conversion SPD:
- PDE~90% of Si-SPADs
- Dead time < 100 ns
- DCR < 1 kHz

Standardization for performance specifications of SPDs (e.g., detection efficiency, recovery time, etc.)

PDE ~ 30% at reasonable DCR (~1 kHz)

MHz detection rates

Reducing afterpulsing to similar level as Si-SPADs

Similar price as Si-SPADs

PDE~50%

Jitter~100 ps

MCR~10 MHz

Cost of standardised SNSPD system << € 100k

Physical integrity and security

Integration into QKD system ("single box")

Operational temperature raised to ~ 30 K (proof of principle)

Compact, low-cost, high-reliability cryogenics

Source: Own graphic

5 Conclusions

This study explores technological and deployment aspects of several single-photon detectors practical for dependable and scalable DV-QKD. By linking detector KPIs to secure key rate, quantum bit error rate, usable clock speed, and distance, we clarify how device choices translate into QKD system outcomes. The report provides a comparative analysis across Si-SPADs, InGaAs/InP-SPADs, up-conversion detectors, and SNSPDs, which reveals optimal deployment choices across fiber, free-space, and satellite use cases.

The central conclusion is that there is no universally best detector for application in QKD. The right choice depends on the required reach, key rate, wavelength, budget and operational constraints. SNSPDs provide the best possible performance through very high efficiency, ultra low noise, and low jitter, which enables longer distances and higher rates in fiber and premium links. Their need for cryogenic operation remains the main barrier that affects cost, size, and maintainability, yet steady improvements in compact cryostats and multi-pixel architectures are widening the scope of viable deployments. InGaAs/InP-SPADs are the practical option for telecom fiber cooling is acceptable and where reach and rate targets are moderate. Their efficiency, dark counts, and dead time still constrain the system performance, but incremental gains continue and are likely with focused investment. Si-SPADs remain the dominant low-cost choice for visible/NIR free-space and satellite terminals due to their compact modules, relatively high efficiency, and manageable timing jitter and noise. Up-conversion devices are emerging as a bridge between telecom compatibility and Si-SPAD-class speed and noise. Their broader adoption will depend on reducing conversion loss and pump-induced noise while simplifying multi-channel integration.

The roadmap translates these insights into development priorities. Near-term actions include improving InGaAs/InP-SPAD efficiency without raising noise, increasing their counting rates, as well as reducing Si-SPAD jitter and afterpulsing while sustaining higher count rates. Other expected improvements include maturing up-conversion detectors to at least match the current performance of InGaAs/InP-SPADs. In addition, standardization is expected to emerge from joint efforts by metrology institutes and SPD manufacturers, with harmonized specifications across all device types and performance metrics.

Mid-term to long-term steps aim at SNSPDs with higher channel density, better optical coupling, robust arrays with aggregate gigahertz class throughput. Further goals include a stronger feature standardization to move beyond current customized single device production to a larger scale manufacturing and thus better pricing and broader adoption. Longer-term paths points to improved KPIs for all studied SPDs that reflect the potential of device technology, i.e., higher detection efficiency, increased counting rates, lower noise and jitter, and scalable multi pixel performance. For SNSPDs, in particular, advancements in cryogenics are expected, with the possibility of operation at considerably higher temperatures enabled by alternative cooling materials currently under research.

Finally, adoption will depend on practical constraints beyond physics. Cost, cooling, size and power, reliability and maintenance, supply chain resilience, user training, and regulatory compliance must be part of technology planning. Selection should follow QKD application scenarios in quantified requirements for distance and key rate, then validate performance through standardized testbeds and security evaluations. Manufacturers and metrology institutes can accelerate progress by converging on clear specifications and by offering reproducible measurements across products.

References

Arakawa, Yasuhiko; Holmes, Mark J. (2020): Progress in quantum-dot single photon sources for quantum information technologies: A broad spectrum overview. In: *Applied Physics Reviews* 7 (2), Artikel 021309. DOI: 10.1063/5.0010193.

Bienfang, Joshua; Gerrits, Thomas; Kuo, Paulina; Migdall, Alan; Polyakov, Sergey; Slattery, Oliver T. (2025): Single-photon Sources and Detectors Dictionary. National Institute of Standards and Technology. Gaithersburg, MD.

CEN-CENELEC (2023): Standardization Roadmap on Quantum Technologies. Release 1.

Eisaman, M. D.; Fan, J.; Migdall, A.; Polyakov, S. V. (2011): Invited review article: Single-photon sources and detectors. In: *The Review of scientific instruments* 82 (7), S. 71101. DOI: 10.1063/1.3610677.

Gansen, Eric J.; Rowe, Mary A.; Rosenberg, Danna; Greene, Marion; Harvey, Todd E.; Su, Mark Y. et al. (Hg.) (2006): Single-photon detection using a semiconductor quantum dot, optically gated, field-effect transistor. 2006 Conference on Lasers and Electro-Optics and 2006 Quantum Electronics and Laser Science Conference. Long Beach, CA, USA.

Gulinatti, Angelo (2024): Single photon avalanches diodes. In: *Photoniques*, Artikel 125. DOI: 10.1051/photon/202412563.

Hadfield, Robert H.; Habif, Jonathan L.; Schlafer, John; Schwall, Robert E.; Nam, Sae Woo (2006): Quantum key distribution at 1550nm with twin superconducting single-photon detectors. In: *Applied Physics Letters* 89 (24), Artikel 241129. DOI: 10.1063/1.2405870.

Heindel, Tobias; Kim, Je-Hyung; Gregersen, Niels; Rastelli, Armando; Reitzenstein, Stephan (2023): Quantum dots for photonic quantum information technology. In: *Adv. Opt. Photon.* 15 (3), S. 613. DOI: 10.1364/AOP.490091.

Kück, Stefan (2020): Einzelphotonenmetrologie. In: *PTB-Mitteilungen* (Heft 3: Quantentechnologie mit Atomen und Photonen Teil II). Online verfügbar unter https://www.ptb.de/cms/en/presseaktuelles/journals-magazines/ptb-mitteilungen/verzeichnis-der-ptb-mitteilungen/ptb-mitteilungen-2020/heft-3-quantentechnologie-mit-atomen-und-photonen-teil-ii.html.

Lucia, Mario de; Dal Bo, Paolo; Di Giorgi, Eugenia; Lari, Tommaso; Puglia, Claudio; Paolucci, Federico (2024): Transition Edge Sensors: Physics and Applications. In: *Instruments* 8 (4), S. 47. DOI: 10.3390/instruments8040047.

Ma, Xiao-song; Zotter, Stefan; Kofler, Johannes; Jennewein, Thomas; Zeilinger, Anton (2011): Experimental generation of single photons via active multiplexing. In: *Phys. Rev. A* 83 (4). DOI: 10.1103/PhysRevA.83.043814.

Marquardt, Christoph; Seyfarth, Ulrich; Bettendorf, Sven; et al. (2023): Implementation Attacks against QKD Systems. Hg. v. Federal Ofce for Information Security (BSI). Online verfügbar unter https://www.bsi.bund.de/EN/Service-Navi/Publikationen/Studien/QKD-Systems/Implementation_Attacks_QKD_Systems_node.html.

Namekata, N.; Takesue, H.; Honjo, T.; Tokura, Y.; Inoue, S. (2011): High-rate quantum key distribution over 100 km using ultra-low-noise, 2-GHz sinusoidally gated InGaAs/InP avalanche photodiodes. In: *Optics express* 19 (11), S. 10632–10639. DOI: 10.1364/OE.19.010632.

Orsucci, Davide; Kleinpaß, Philipp; Meister, Jaspar; Marco, Innocenzo de; Häusler, Stefanie; Strang, Thomas et al.: Assessment of practical satellite quantum key distribution architectures for current and near-future missions. DOI: 10.48550/arXiv.2404.05668.

Raj, Vidur; Azem, Adan; Patterson, Max; Namburi, Devendra Kumar; Young, Jeff F.; Hadfield, Robert H. (2025): Waveguide integrated superconducting nanowire single-photon detectors for integrated photonics. In: *J. Phys. D: Appl. Phys.* 58 (24), S. 243001. DOI: 10.1088/1361-6463/add946.

Raupach, Sebastian M. F.; Sidorova, Mariia; Semenov, Alexej D. (2023): Photon number dependent afterpulsing in superconducting nanostrip single-photon detectors. In: *Phys. Rev. B* 108 (5). DOI: 10.1103/PhysRevB.108.054507.

Sauer, Gregor; Kolarczik, Mirco; Gomez, Rodrigo; Conrad, Johanna; Steinlechner, Fabian (2023): Resolving Photon Numbers Using Ultra-High-Resolution Timing of a Single Low-Jitter Superconducting Nanowire Detector.

Schmaltz, Thomas; Endo, Chie; Becher, Christoph; Schmidt, Jessica; Krieg, Linus; Weymann, Lukas et al. (2024): Monitoring Report 1 - Quantum Communication.

Schmaltz, Thomas; Endo, Chie; Weymann, Lukas; Wicke, Tim; Shirinzadeh, Saeideh; Friedewald, Michael et al. (2025): Application Perspectives in Quantum Communication.

Wang, Hailu; Guo, Jiaxiang; Miao, Jinshui; Luo, Wenjin; Gu, Yue; Xie, Runzhang et al. (2022): Emerging Single-Photon Detectors Based on Low-Dimensional Materials. In: *Small (Weinheim an der Bergstrasse, Germany)* 18 (5), e2103963. DOI: 10.1002/smll.202103963.

Wang, Shuai; Han, Qin; Ye, Han; Geng, Liyan; Lu, Ziqing; Xiao, Feng; Xiao, Fan (2021a): Temperature dependency of InGaAs/InP single photon avalanche diode for 1 550 nm photons. In: *Infrared and Laser Engineering* 50 (11), S. 20210453. DOI: 10.3788/IRLA20210453.

Wang, Weilan; Jiang, Yuheng; Wang, Changzhu; Li, Xuan (Hg.) (2021b): Research Progress on Detection of Weak Light Signal by Photomultiplier Tube. International Conference on Advanced Electrical Equipment and Reliable Operation (AEERO).

Wang, Xina; Jiao, Xufeng; Wang, Bin; Liu, Yang; Xie, Xiu-Ping; Zheng, Ming-Yang et al. (2023a): Quantum frequency conversion and single-photon detection with lithium niobate nanophotonic chips. In: *npj Quantum Inf* 9 (1). DOI: 10.1038/s41534-023-00704-w.

Wang, Zan; Gu, Yunjiao; Li, Xiaoman; Liu, Yan; Liu, Fenghua; Wu, Weiping (2023b): Recent Progress of Quantum Dot Infrared Photodetectors. In: *Advanced Optical Materials* 11 (19), Artikel 2300970. DOI: 10.1002/adom.202300970.

Warburton, Ryan E.; Izdebski, Frauke; Reimer, Christian; Leach, Jonathan; Ireland, David G.; Padgett, Miles; Buller, Gerald S. (2011): Single-photon position to time multiplexing using a fiber array. In: *Optics express* 19 (3), S. 2670–2675. DOI: 10.1364/OE.19.002670.

Weng, Qianchun; An, Zhenghua; Zhang, Bo; Chen, Pingping; Chen, Xiaoshuang; Zhu, Ziqiang; Lu, Wei (2015): Quantum dot single-photon switches of resonant tunneling current for discriminating-photon-number detection. In: *Scientific reports* 5, S. 9389. DOI: 10.1038/srep09389.

Xiong, Jia-Min; Zhang, Wei-Jun; Xu, Guang-Zhao; You, Li-Xing; Zhang, Xing-Yu; Zhang, Lu et al. (2022): Reducing current crowding in meander superconducting strip single-photon detectors by thickening bends. In: *Supercond. Sci. Technol.* 35 (5), S. 55015. DOI: 10.1088/1361-6668/ac5fe4.

Yao, Ni; Yao, Quan; Xie, Xiu-Ping; Liu, Yang; Xu, Peizhen; Fang, Wei et al. (2020): Optimizing up-conversion single-photon detectors for quantum key distribution. In: *Optics express* 28 (17), S. 25123–25133. DOI: 10.1364/OE.397767.

Yoshida, Daisuke; Horikiri, Tomoyuki (2024): Multiplexed quantum repeaters based on single-photon interference with mild stabilization. In: *Commun Phys* 7 (1).
DOI: 10.1038/s42005-024-01849-6.

You, Lixing (2020): Superconducting nanowire single-photon detectors for quantum information. In: *Nanophotonics* 9 (9), S. 2673–2692. DOI: 10.1515/nanoph-2020-0186.

You, Lixing; Quan, Jia; Wang, Yong; Ma, Yuexue; Yang, Xiaoyan; Liu, Yanjie et al. (2018): Superconducting nanowire single photon detection system for space applications. In: *Optics express* 26 (3), S. 2965–2971. DOI: 10.1364/OE.26.002965.

Zhang, Weikang; Al-Khalidi, Abdullah; Figueiredo, José; Al-Taai, Qusay Raghib Ali; Wasige, Edward; Hadfield, Robert H. (2021): Analysis of Excitability in Resonant Tunneling Diode-Photodetectors. In: *Nanomaterials (Basel, Switzerland)* 11 (6). DOI: 10.3390/nano11061590.

Zhang, Yichen; Bian, Yiming; Li, Zhengyu; Yu, Song; Guo, Hong (2024): Continuous-variable quantum key distribution system: Past, present, and future. In: *Applied Physics Reviews* 11 (1), Artikel 011318. DOI: 10.1063/5.0179566.

Zhao, Q.; McCaughan, A.; Bellei, F.; Najafi, F.; Fazio, D. de; Dane, A. et al. (2013): Superconducting-nanowire single-photon-detector linear array. In: *Appl. Phys. Lett.* 103 (142602).
DOI: 10.1063/1.4823542.

Zmuidzinas, Jonas (2012): Superconducting Microresonators: Physics and Applications. In: *Annu. Rev. Condens. Matter Phys.* 3 (1), S. 169–214. DOI: 10.1146/annurev-conmatphys-020911-125022.