



# Application of Single Photon Detector in Medical Imaging Technology

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**Abstract.** In recent years, single photon detection technology has made a breakthrough in the field of medical imaging, and promoted the development of high sensitivity, low noise and high-resolution imaging systems. A new type of single photon detector (SPD) based on superconducting materials, wide band gap semiconductors and perovskites and its application in medical imaging are reviewed in this paper. Through the optimal design of the superconducting nanowire single photon detector (SNSPD), great sensitivity of photon detection has been achieved at 3.7 K operating temperature (system efficiency 14.1%). Additionally, a large detection area of  $400 \times 400 \mu\text{m}^2$  has been successfully realized through this design optimization. Gallium nitride (GaN) -based X-ray single photon detectors are designed with vertical p-i-n structure to reduce dark current to 7 pA (-200 V) and achieve linear response in the 10-20 keV energy spectrum. The perovskite single crystal X-ray detector maintains stability in the air for 1.5 years. The normalized signal-to-noise ratio is improved significantly through layer thickness optimization and zero bias operation. In addition, the innovative combination of quantum parametric mode sorting (QPMS) technology and photon-counting CT system achieves 94% classification accuracy at 500 times background noise and breaks traditional CT spatial resolution to 150  $\mu\text{m}$ . These technological innovations provide new solutions for non-invasive blood flow monitoring, low-dose X-ray imaging, and high-precision tumor diagnosis, marking a key step toward high sensitivity, robustness, and multimodal fusion in medical imaging.

**Keywords:** Single Photon Detectors; Superconducting Nanowire Detectors; X-Ray Imaging; Quantum Parametric Mode Sorting

## 1 Introduction

Medical imaging stands as a cornerstone of modern diagnostics, yet it faces two key limitations: the inability to resolve weak signals in low-photon-flux environments and the degradation of performance under real-world biological interference. Conventional single-photon detectors, such as silicon-based single-photon avalanche diodes (Si-SPADs) and photomultiplier tubes, have been pivotal in clinical applications [1]. However, their narrow wavelength sensitivity, limited dynamic range, and

susceptibility to electromagnetic interference or radiation hinder applications in deep-tissue imaging, multi-energy computed tomography (CT), and real-time functional monitoring. For instance, near-infrared imaging is essential for non-invasive hemodynamic assessment but suffers from poor detection efficiency beyond 1000 nm. Meanwhile, X-ray photon-counting systems find it challenging to balance spatial resolution with dose reduction [2]. These challenges underscore the urgent need for detector technologies that transcend classical performance trade-offs.

In response, recent advances in material science and quantum optics have unlocked unprecedented opportunities. Superconducting detectors, wide-bandgap semiconductors, and perovskite-based systems are redefining the limits of sensitivity, speed, and operational stability. SNSPDs, for example, leverage quantum phase transitions to nearly maximize detection efficiency at cryogenic temperatures. However, their historical reliance on ultralow-temperature operation ( $\leq 4$  K) and small active areas have limited clinical translation. Similarly, traditional X-ray detectors based on amorphous selenium ( $\alpha$ -Se) or silicon face inherent compromises between radiation hardness, energy resolution, and fabrication costs [3]. The emergence of perovskite semiconductors and GaN technologies now offers pathways to address these limitations through tunable bandgap engineering and robust optoelectronic properties.

These innovations carry profound implications for medical imaging. Improved single-photon sensitivity facilitates earlier detection of pathological changes like tumor angiogenesis or neurodegenerative protein aggregation. Low-dose X-ray detection, in turn, benefits pediatric and screening applications. Furthermore, detectors capable of operating in high-noise or high-radiation environments promise to expand imaging modalities into intraoperative and radiotherapy settings. By integrating nanoscale material engineering with system-level signal processing, next-generation detectors are poised to transform medical imaging into dynamic, functional, and molecular-level quantification. This paradigm shift not only elevates diagnostic precision but also lays the groundwork for personalized therapeutic strategies.

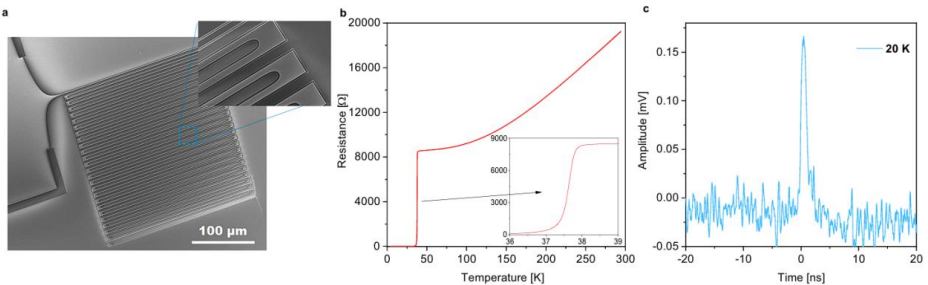
## 2 Single Photon Detector

### 2.1 Advances in Superconducting Single-Photon Detectors for Enhanced Medical Imaging

The single-photon detection technique has expanded rapidly and has become a high-end technology. In 2023, the team led by Ilya Charaev planned and executed an experiment. Through a helium-ion-beam-based irradiation process, the researchers developed a new superconducting microwire-base single-photon detector with MgB<sub>2</sub>, as shown in Figure 1. In the realm of material fabrication, the researchers use the method of Hybrid Physical-Chemical Vapor Deposition to grow MgB<sub>2</sub> thin films on the 6H-SiC substrate. Identified by x-ray reflectivity (XRR) and scanning transmission electron microscopy (STEM), the thickness of the superconducting core was about 7nm. The researchers also successfully modulated the defect density with the helium ion irradiation. This approach limited the variation of the affected switching current and normal state resistance to less than 5%. In terms of device processing, the research

team implemented a SNSPD meander framework with a filling factor of 0.28 and a width of 1-5  $\mu\text{m}$  using electron-beam lithography. Furthermore, the films were patterned using argon ion beam etching with a 300V beam voltage. After fabrication, the research team quantified the transmission properties of the microwires, determining a switching current of 673  $\mu\text{A}$  and a critical temperature of  $37.6\pm 0.3\text{K}$  from the peak position of the temperature derivative of resistance,  $dR(T)/dT$ . Moreover, spontaneous voltage pulses emerged under dark conditions when the device was biased near its switching current. The absolute magnitude of these dark counts exhibited comparability to conventional NbN-based SNSPDs. In the experiment, the  $\text{MgB}_2$ -based superconducting single-photon detectors demonstrated a  $2\times$  higher operating temperature (20 K vs.  $<10$  K for NbN) with 14.1% system detection efficiency at 3.7 K (6.8% at 20 K) without optical cavity assistance, achieved  $16\times$  larger active area ( $400\times 400\ \mu\text{m}^2$ ) and  $10\times$  faster reset time (1.2 ns) compared to conventional SNSPDs, while maintaining a dark count rate  $<2\times 10^3$  cps at 20 K under  $0.96I_c$  bias [4].

A subsequent study characterizing SNSPDs was published by the research group under the leadership of I. Charaev. The report first implemented the high-temperature SNSPD based on high-temperature superconducting copper oxide nanowire. The researchers created thin flakes by mechanically exfoliating large BSSCO crystals in order to prepare the material. Subsequently, defects were introduced into the enclosed BSSCO flake using a beam of  $\text{He}^+$  ion to define the SNW patterns. The material was then covered with hexagonal boron nitride slabs for protection. After that, molecular beam epitaxy (ALL-MBE) can be used to grow the LSCO-LCO bilayer films atomic-layer-by-layer. A typical SNW meander structure for SNSPDs, measuring 60  $\mu\text{m}$  in length and 100 nm in width with a filling factor of 0.28, was therefore defined using electron-beam lithography. Defects were introduced into the crystal lattice using the  $\text{He}^+$  ion beam to implement single-photon response. A variable-temperature cryostat was used during measurements to ensure thermal stability. After measuring, the BSSCO SNW had a respective critical temperature of 69.8K, while the one of LSCO-LCO SNW was 34.4K. For the retrapping current  $I_h$  and the switching current  $I_c$ , the BSSCO SNW has an  $I_h$  of 516  $\mu\text{A}$  and an  $I_c$  of 883  $\mu\text{A}$ , while the LSCO-LCO SNW has an  $I_h$  of 36.3  $\mu\text{A}$  and an  $I_c$  of 86.7  $\mu\text{A}$ . In conclusion, the research demonstrated single-photon detection at temperatures as high as 25K in high- $T_c$  cuprate SNWs. The work developed a scalable fabrication method for high- $T_c$  quantum sensors, demonstrating how to incorporate them into on-chip photonic quantum information circuits [5].



**Fig. 1.** Superconducting  $\text{MgB}_2$  microwire-based single-photon detectors [4].

## 2.2 GaN-Based X-Ray Photon Detectors for High-Sensitivity Medical Diagnostics

In 2024 the research team led by Yiqiao Wei published a similar experiment implementing a low-energy x-ray SPD based on GaN which can analyze photon energy and respond quickly, over breaking the performance bottleneck of traditional GaN-based detectors. By employing an optimized GaN-on-GaN homoepitaxial growth process, the researchers achieved a fully vertical p-i-n photodiode with decreased dislocation density. Simultaneously, the slant mesa termination structure effectively alleviated the maximum of the electric field and ulteriorly lowered the leak current. Furthermore, researchers optimized p- and n- type ohmic contact and therefore achieved a low parasitic resistance of  $0.74 \text{ m}\Omega\cdot\text{cm}^2$ . Ulteriorly, the researchers combined a reset charge sensitive amplifier with a shaping amplifier. This circuit cascade transformed the original photo-carriers into quasi-Gaussian output pulses, thus implementing a linear correlation between pulse characteristics and photon energy. Turing to the quantitative result, the dark current is as low as  $\sim 7\text{pA}$  at  $-200\text{V}$  at RT, and the  $150^\circ\text{C}$  current is  $9 \text{ pA}$ , which indicates an excellent temperature stability. The reaction time of approximately  $1.0 \text{ }\mu\text{s}$  and the photon energy falling within the researched range of approximately  $10\text{-}20 \text{ keV}$  allow for photon energy resolution with a good carrier collection ratio. Significantly, the detector demonstrates robust tolerance to both elevated temperatures and radiation exposure. In conclusion, the experiment is the first to implement the low energy x-ray SPD based on Gallium nitride, which bridged the critical research gap in this field, and created a solid foundation for the development of the next generation of high-stability and high-sensitivity detectors [6].

## 2.3 Quantum Parametric Mode Sorting for Noise-Resilient Biomedical Sensing

In another experiment, the researchers blended the QPMS technique with single photon detection to achieve high-efficiency noise suppression. The experimental architecture integrates two key optical modulators: a digital micromirror device (DMD) and a spatial light modulator. This hybrid system generates structured illumination beams encoded with Walsh 2D patterns, which are subsequently projected as target images. Then the researchers used InGaAs-SPD (Indium Gallium Arsenide single-photon detector) to count the photons for direct detection (DD), while for QPMS detection, the signal is coupled into periodically poled lithium niobate (PPLN) module and a Si-SPAD detects it. Furthermore, amplified spontaneous emission (ASE) noise in-band with the signal was introduced to emulate real-world environmental interference. The result turned out that the QPMS technique achieves selective photon conversion though employment of spectrally broad pump pulses whose bandwidth is precisely aligned with the phase-matching regime of the nonlinear frequency conversion stage. The study resolved a key challenge in single-photon compressed sensing by mitigating the effects of low-photon and high-noise environments using the QPMS technique. Moreover, it pioneers the achievement of 94% classification accuracy under signal-to-noise ratio (SNR) conditions where the signal intensity is 500-fold weaker than background noise,

establishing a new benchmark for optical sensing robustness. The proposed methodology delivers a high-fidelity solution with extreme noise immunity, achieved through adaptive signal conditioning algorithms. This capability proves critical for field-deployable monitoring systems and biomedical imaging applications, where sub-shot-noise detection is mandatory to resolve weak signals under ultra-low SNR conditions [7].

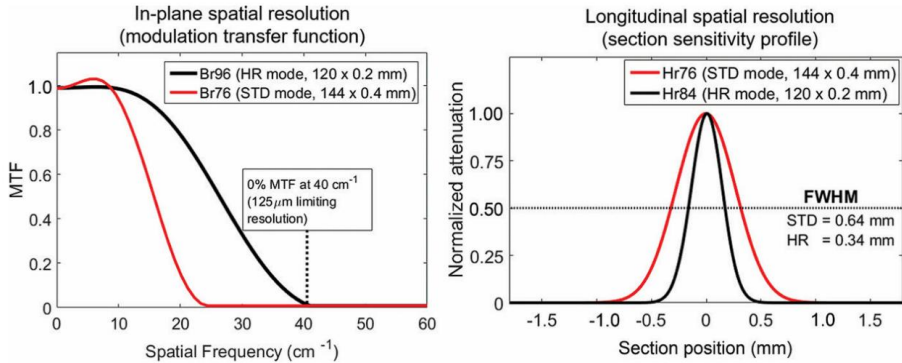
#### **2.4 SNSPD-Enhanced Diffuse Correlation Spectroscopy for Non-Invasive Blood Flow Monitoring**

Turning to the application, a team led by Nisan Ozana has published a paper developing a diffuse correlation spectroscopy (DCS) methodology incorporating SNSPDs. In the experiment, the research team operated DCS at 1064 nm laser source with the assistance of SNSPDs contrary to 850 nm DCS devices, which implemented greater photon availability and slower autocorrelation function decay. By replacing traditional Si-SPADs with SNSPDs, the researchers achieved a photon detection efficiency (PDE) of approximately 88%. Furthermore, at the 1064 nm wavelength, the light power can be up to 100 mW compared to 38 mW at 850 nm. In the execution of the experiment, 11 subjects participated in the study and were tested with the two techniques synchronously. The index of blood flow (BFi), average photon counts are measured to compare the two techniques. As a result, the SNSPD-DCS achieved a significantly higher number of photons than that of conventional DCS (average gain  $13 \pm 6$ ) and an SNR gain of  $16 \pm 8$  for  $\tau = 4 \mu\text{s}$ . Moreover, the researchers estimated sensitivity to the brain via Monte Carlo Simulation. The results demonstrated that for the 1064-nm SNSPD-DCS, the sensitivity of brain blood flow has increased by 31.6% at 35-mm SD separation. In conclusion, the research was the first to apply SNSPD in biomedical monitoring in humans, which broke through the bottleneck in the SNR of traditional DCS. Furthermore, the researchers synergize 1064 nm wavelength and SNSPDs to implement enhanced tissue penetration depth and superior temporal resolution, significantly enhance the application potential of DCS in critical care settings [8].

#### **2.5 Photon-Counting CT Systems: Revolutionizing Medical Imaging Resolution and Efficiency**

Another report on applications of SPD is made by the research team led by Kishore Rajendran. The report systematically investigated the technical characteristics of photon-counting detector (PCD) CT systems. This analysis revealed superior performance in spatial resolution (150  $\mu\text{m}$  vs. 250  $\mu\text{m}$  conventional), noise suppression (15% lower noise power spectrum (NPS) amplitude), multi-energy discrimination (5-material decomposition), and temporal resolution (83 ms gantry rotation). These technical merits collectively establish a quantitative foundation for evaluating the feasibility of deploying PCD CT in clinical practice. In the experiment, the researchers used dual-source PCD design with gantry rotation time of 0.25 seconds to implement 66-msec temporal resolution, supporting multi-energy CT performance. With high-spatial-resolution (HR) collimations, the full width of the section sensitivity profile at

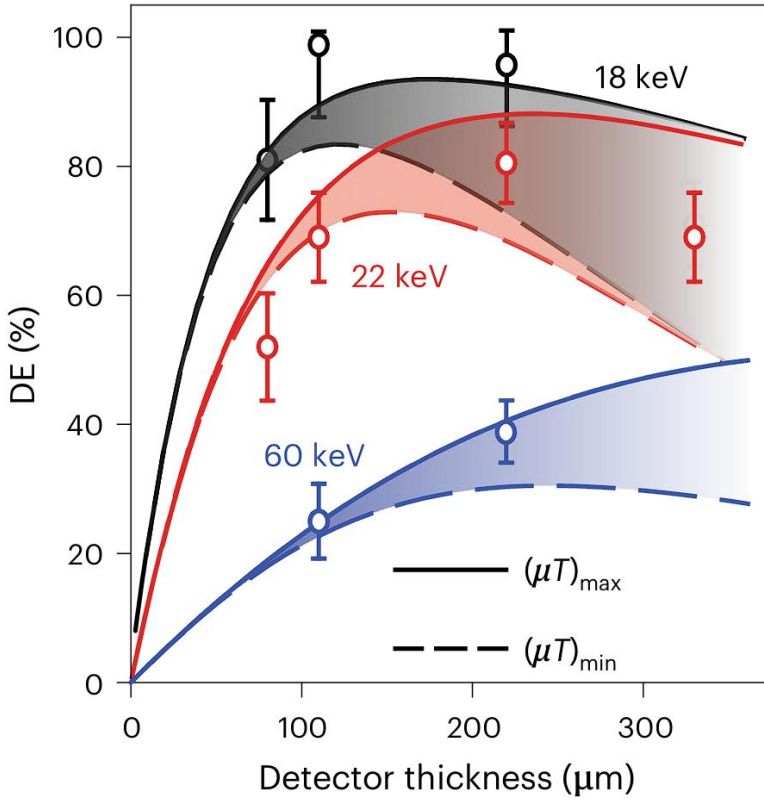
half maximum values for the smallest section thickness that was available was 0.34 mm (0.2 mm nominal), as shown in Figure 2. Quantum iterative reconstruction algorithm (QIR) was also applied to reduce the image noise. In summary, clinical PCD CT technical performance has been improved in the previously listed aspects [9].



**Fig. 2.** Modulation transfer functions and section sensitivity profiles for the STD and HR collimations of the photon-counting detector CT system [9].

## 2.6 Perovskite X-Ray Detectors: Cost-Effective and Stable Solutions for Medical Imaging

Another report showed another application of SPD. The report proposed a perovskite X-ray detector uses uniformly thick methylammonium lead iodide single-crystal sheets to apply long-term consistent performance and single photon counting. Firstly the MAPBI3 films were grown on indium tin oxide substrates covered with poly triaryl amine (PTAA) as a hole-transporting layer using a space-confined inverse-temperature crystallization technique for material preparation. Then the extensive post-drying of crystal at ambient temperature in a drybox filled with nitrogen successfully eliminated the influence of the solvent's persistent residual solvates and improved the X-ray detection capabilities, especially in the normalized SNR. When designing the device structure, the PTAA and electron-transporting layer were used to establish an internal electrical field, which made the transport layers' charge selectivity optimal. Simultaneously, by optimizing the layer thickness, the researchers balanced x-ray absorption (10-30 keV) and carrier mobility-lifetime ( $\mu\tau$ ), as is shown in Figure 3. This optimization significantly enhanced the detector's performance. Finally, the zero-bias operation greatly improved the lifetime of the XPV devices, enabling them to maintain their traits while in the air for at least a year and a half by avoiding unstable performance arisen from the ion migration. The results validate the promise of hybrid lead halide perovskites as an affordable medical x-ray imaging technique when used in photovoltaic mode [10].



**Fig. 3.** Detection efficiency over detector thickness of MAPbI<sub>3</sub> SC XPV detectors [10].

### 3 Conclusion

Recent advancements in single-photon detection technologies are driving transformative progress across medical imaging modalities. Among these, superconducting detectors have achieved a paradigm shift through the development of MgB<sub>2</sub> and copper oxide (BSCCO/LSCO) nanowires. Specifically, the MgB<sub>2</sub>-based SNSPD developed by Charaev's team operates at 20 K, twice the temperature of traditional NbN systems. It maintains a dark count rate below  $2 \times 10^3$  cps. This breakthrough is attributed to helium-ion-beam irradiation and electron-beam lithography, which enable a  $16 \times$  larger active area ( $400 \times 400 \mu\text{m}^2$ ) and rapid reset times of 1.2 ns. When applied to DCS, these SNSPDs leverage 1064 nm illumination, demonstrating a cerebral blood flow sensitivity improvement of 31.6% over conventional 850 nm systems. Such advancements underscore their potential for non-invasive hemodynamic monitoring in clinical settings.

Simultaneously, innovations in wide-bandgap semiconductors are addressing limitations in X-ray detection. The GaN-based single-photon detector developed by

Wei's team employs a vertical p-i-n structure with slant mesa termination, suppressing dislocation density and reducing dark currents to  $\sim 7$  pA at  $-200$  V. By integrating optimized ohmic contacts and readout circuits, this detector achieves linear energy response in the 10–20 keV range, enabling precise photon energy discrimination. These improvements lay the groundwork for high-sensitivity, radiation-tolerant imaging systems.

Complementing these developments, perovskite-based detectors bridge cost and performance gaps. Rajendran's team demonstrated year-long stability in methylammonium lead iodide (MAPbI<sub>3</sub>) single-crystal films through inverse-temperature crystallization in space and PTAA heterojunction engineering. Operating at zero bias, these detectors mitigate ion migration while balancing X-ray absorption (10–30 keV) and carrier mobility-lifetime ( $\mu\tau$ ) via layer thickness optimization. The resulting enhancements in normalized SNR demonstrate their potential for low-dose pediatric and diagnostic imaging.

At the system level, QPMS techniques have revolutionized noise suppression. By combining DMDs with nonlinear frequency conversion in PPLN, QPMS delivers 94% classification accuracy even under a 500:1 noise-to-signal ratio. This capability is particularly critical for subcellular-scale tracking in high-noise environments. In parallel, photon-counting CT (PC-CT) systems have advanced through dual-source designs, achieving 150  $\mu\text{m}$  spatial resolution and 83 ms temporal resolution. When combined with quantum iterative reconstruction (QIR) algorithms, these systems reduce NPS amplitudes by 15%, enhancing multi-energy discrimination for precision oncology and vascular imaging.

Looking ahead, the clinical translation of these technologies requires addressing key challenges. These include improving SNSPD detection efficiency, scaling perovskite film fabrication, and refining adaptive noise suppression in QPMS. As quantum sensing converges with advanced signal processing, medical imaging is transitioning from anatomical visualization to functional and molecular-level quantification. Ultimately, these innovations promise to enable earlier disease detection and personalized therapeutic strategies, marking a shift toward precision medicine.

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