Invited Paper

Trap-integrated superconducting nanowire single-photon detectors for trapped-ion qubit state readout

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ABSTRACT

State readout of trapped-ion qubits is usually achieved by observing qubit-state-dependent fluorescence from the ion while driving an optical cycling transition with laser light. The integration of photon detectors for fluorescence detection into the ion trap itself may benefit the development of many-qubit setups for applications like quantum computing. Superconducting nanowire single-photon detectors (SNSPDs) are promising candidates for trap-integrated detectors for high-fidelity trapped-ion qubit state readout. However, the strong oscillating electromagnetic fields that are typically used to trap and manipulate ions can affect the function of the SNSPDs significantly. In this work, we demonstrate an improved design to integrate SNSPDs into linear rf ion traps that reduces the susceptibility of the SNSPDs to applied rf trapping potentials. Our measurement results represent an improvement in rf tolerance by an order of magnitude with an increase in operation temperature from 3.5 K to 6 K compared to previous work.

Keywords: SNSPD, ion trap, quantum computing, qubit state readout

1. INTRODUCTION

State readout of trapped-ion qubits is an essential operation for their use in quantum computation and communication.[1–3] It is usually achieved by observing qubit-state-dependent fluorescence from the ion while driving an optical cycling transition with a laser beam.[4] Photon detectors such as cameras or photomultiplier tubes can be combined with high-numerical-aperture optics to detect the presence or absence of fluorescence to infer the qubit state. Such experimental setups present challenges for scalability in applications like quantum computing. The integration of photon detectors for fluorescence detection into the ion trap itself may benefit the development of many-qubit setups.[5–8]

Superconducting nanowire single-photon detectors (SNSPDs) are promising candidates for trap-integrated detectors for high-fidelity trapped-ion qubit state readout. They offer high detection efficiencies,[9] low dark count rates,[10,11] sensitivity over a broad wavelength regime including the UV, which is particularly relevant for ion traps,[5,6,12,13] and scalable fabrication of arrays,[14] which would benefit large scale quantum computing applications.[3,15] Cryogenic temperatures required for SNSPD operations do not present a major obstacle as many ion trap experiments operate at cryogenic temperatures between roughly 4 K and 10 K. However, strong oscillating electromagnetic fields are needed to trap and manipulate ions, and can affect the function of the SNSPDs significantly.[5,6]

2. DESIGN

In this work, we demonstrate an improved design to integrate SNSPDs into linear ion traps.[12] The design is optimized for readout of calcium ions (Ca^+) at a fluorescence wavelength of 397 nm. The main components of the ion trap are shown in the scanning electron micrographs in Fig. 1. The rf electrodes are highlighted in light blue. An oscillating rf potential between 68 MHz and 72 MHz is applied to these electrodes by an external rf source driving a cryogenic resonant circuit. The resulting electric field from these electrodes is designed to confine a

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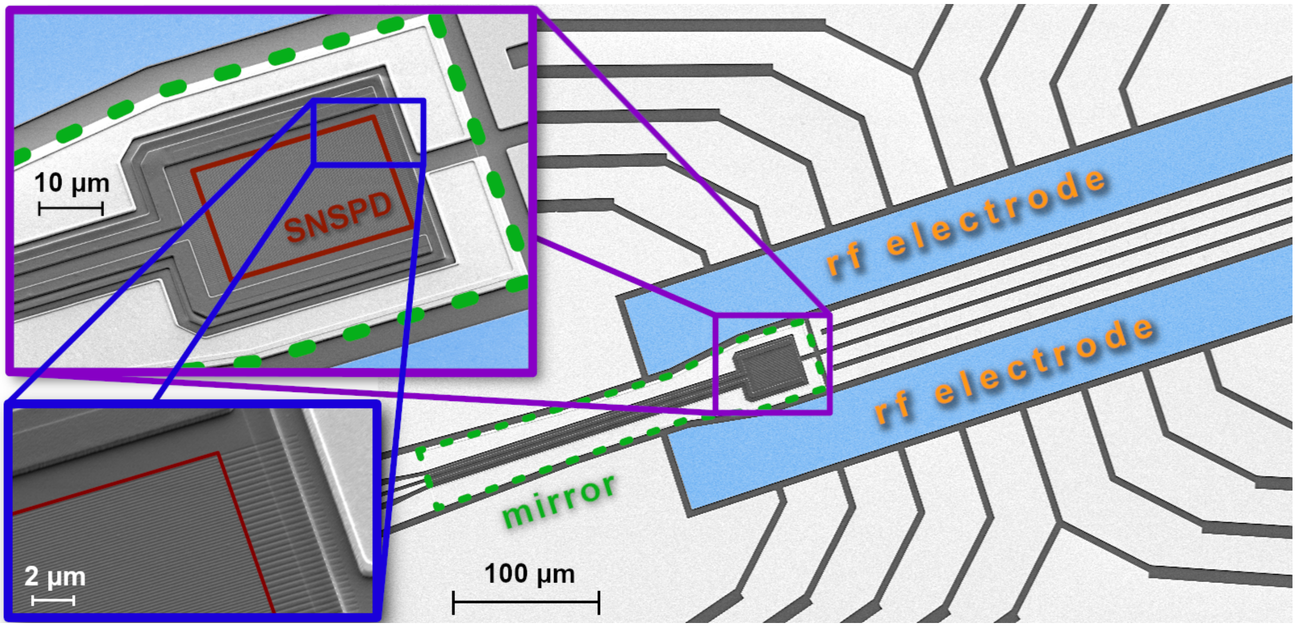

Figure 1. Scanning electron micrographs of a linear ion trap with integrated SNSPD. The rf electrodes are false colored in light blue. The aluminum mirror under the SNSPD and parts of the SNSPD leads is highlighted with a green dotted line. The active area of the SNSPD is highlighted in the two magnified insets in red.

trapped ion in two spatial dimensions. The other non-highlighted electrodes of the trap are used to confine the ion in the third dimension and to transport it along the trap axis to different zones for state preparation and readout.

The ion can be moved above the integrated SNSPD to read its quantum state. Two laser beams are required to drive the optical cycling transition in Ca^+. If the ion qubit is in the "bright" quantum state when driven by these lasers, it will emit fluorescence at 397 nm that can be detected by the SNSPD. The trap-integrated SNSPD can be seen in the magnified insets of Fig. 1. The active area has a size of 20 µm by 30 µm and is highlighted with a red box. The meandering nanowires have a width of 90 nm and a pitch of 180 nm. They are barely visible in the largest magnification in the blue highlighted inset box.

When a photon hits a nanowire, it generates a hotspot that locally destroys the superconductivity of the nanowire. This leads to a sudden change of resistance in the nanowire, which results in a voltage pulse at the measurement electronics. In this way, single photons can be detected with efficiencies of over 98 %.[9]

However, the close proximity of the rf electrodes can impair the function of the SNSPDs significantly. The high rf fields required to trap an ion will induce rf currents in the SNSPD nanowires and bias leads. This modulates the bias current of the SNSPD and can degrade its performance or prevent it from operating. Electrical shielding can prevent these parasitic rf currents from being induced in the SNSPD. Simulation results suggested the use of an electrically grounded aluminum mirror under the SNSPDs for effective shielding. The mirror also results in increased system detection efficiency due to its reflective properties.[12] The mirror is highlighted in Fig. 1 with a green dotted box.

3. FABRICATION

The ion traps with integrated SNSPDs were fabricated in the NIST Boulder Microfabrication Facility on high-resistivity silicon wafers. After depositing 150 nm of SiO_2 in a plasma-enhanced chemical vapor deposition (PECVD) process, the 50 nm-thick aluminum mirrors are deposited in an electron-beam evaporation process and patterned in a liftoff process. A 212 nm PECVD SiO_2 layer separates the 10 nm niobium titanium nitride (NbTiN) layer from the grounded aluminum layer. The SNSPDs are patterned into the NbTiN layer with help of optical and electron-beam lithography and a reactive-ion etching (RIE) process with sulfur hexafluoride (SF_6). The active area of the SNSPD measures 20 µm by 30 µm. The ground contact to the aluminum mirror is achieved by etching vias into the SiO_2 layer with an RIE process based on trifluoromethane (CHF_3) with a subsequent deposition of a 20 nm gold layer to prevent oxidation of the aluminum. The electric contacts to the SNSPD, the mirror, and all trap electrodes are patterned in a liftoff process with 350 nm-thick gold. The SNSPDs are capped with a 130 nm SiO_2 layer that is deposited in a PECVD process and patterned with RIE based on CHF_3.

4. RESULTS

The ion traps with integrated SNSPDs were characterized in a Gifford-McMahon cryocooler setup with a base temperature of 2.6 K. The measurement setup is shown in Fig. 2. Up to six ion trap chips are mounted on copper sample holders. They are electrically connected to a printed circuit board (PCB) by wirebonds. Six rf resonators with resonance frequencies between 68 MHz and 72 MHz are connected to the PCB, one resonator for each trap chip, and can be driven by an external rf source. The SNSPDs are biased through the dc port of a bias tee with a low-noise voltage source. Voltage pulses due to photon detection events can be measured by connecting the ac port of the bias tee to low-noise amplifiers, followed by a notch filter at the rf frequency (to remove extraneous rf pickup), a lowpass filter, and either a counter or an oscilloscope. The ion traps are flood illuminated with LEDs with a center wavelength of 395 nm.

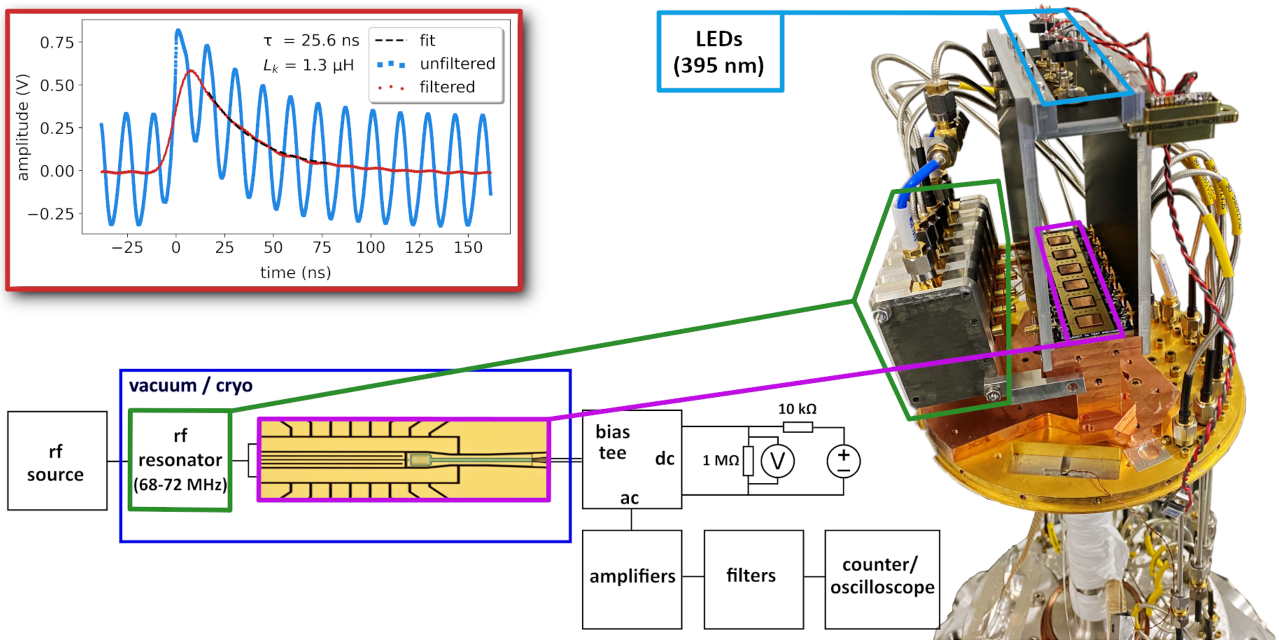

Figure 2. Measurement setup for the characterization of the rf tolerance of trap-integrated SNSPDs. An external rf source in combination with an rf resonator generates realistic rf trapping potentials in the ion traps. The SNSPDs are biased and read out through a bias tee. They are flood illuminated with LEDs with a center wavelength of 395 nm. The inset shows a filtered and unfiltered SNSPD pulse shape recorded with an oscilloscope at the output after amplification at $T = 2.6$ K. The pulses are fitted to calculate the kinetic inductance L_k. Data available at Ref. 16.

The pulse shapes of individual SNSPD count events were recorded with a high-speed oscilloscope to determine the kinetic inductance L_k and observe the influence of the rf potentials on the output signal. The kinetic inductance was calculated to be $L_k = 1.3\,\mu$H by fitting the measured pulse decay to get the time constant $\tau = 25.6$ ns and by using the relation $L_k = \tau \cdot R$ with $R = 50\,\Omega$. Filtered (red) and unfiltered (blue) pulse traces are depicted in the inset of Fig. 2 for an rf tolerance measurement with an rf voltage peak amplitude of 44 V_{peak}. Because the rf signal couples into the readout line, filters are necessary to enable reproducible counting. Otherwise, the counter can be triggered multiple times by a single SNSPD output, due to the presence of rising edges at the rf frequency. This problem can be avoided by using a notch filter at the rf frequency and lowpass filter after amplification of the output signal as shown in Fig. 2.

A standard measurement procedure for the characterization of SNSPDs is the acquisition of a count rate vs. bias current curve. For this, the bias current through the SNSPD is increased, while a counter is used to observe any voltage pulses from the SNSPD at the ac port of the bias tee. When the bias current exceeds the switching current (current at which the critical current density is exceeded), superconductivity in the nanowire is destroyed and the SNSPD cannot count photons. In addition to every measurement with flood illuminated SNSPDs, the dark count rate (DCR) of the SNSPD is measured by running the same measurement procedure without illumination.

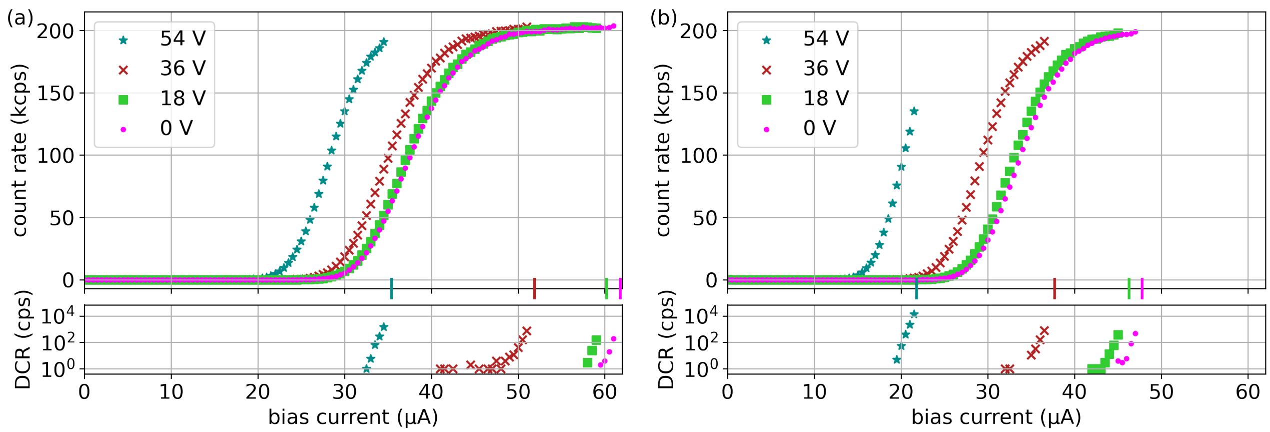

Figure 3. Count rate and dark count rate (DCR) in counts per second (cps) as a function of bias current for different rf voltage peak amplitudes at a temperature of (a) 4.5 K and (b) 6 K. The plotted count rates are corrected for the measured DCR and the DCR is plotted on a logarithmic vertical axis. The switching currents for the different measurements are indicated by correspondingly colored vertical makers on the horizontal axes. Data available at Ref. 16.

Measurement results of a trap-integrated SNSPD are shown in Fig. 3 at temperatures of 4.5 K and 6 K. The different curves were measured at different rf voltage peak amplitudes (corresponding to different strengths of confining potential), which are large enough to trap a wide variety of relevant ion species. A large plateau region can be observed at a temperature of 4.5 K with low rf voltage peak amplitudes. Such a plateau is interpreted as a regime of saturated internal detection efficiency. Small bias current fluctuations due to induced rf currents will not impair the photon count rate if the SNSPD is biased at such a large plateau. However, larger rf voltage peak amplitudes reduce the switching current significantly. The detectors could still be operated in this regime, but the maximum count rates and therefore the system detection efficiency might be reduced. The SNSPD's performance at a temperature of 6 K is still very promising, although the maximum count rate is significantly reduced for the highest rf voltage peak amplitude.

5. CONCLUSION

We presented an improved design of ion trap-integrated SNSPDs for the state readout of trapped-ion qubits. The use of the superconductor NbTiN for the SNSPDs allows us to operate the ion traps at a maximum temperature of 6 K while achieving much higher SNSPD critical currents compared to previous work.[6] The improved design reduces the susceptibility of the SNSPDs to rf potentials on the trap using an aluminum ground plane beneath the SNSPD. The next steps will be an optimization of the optical stack for the SNSPDs to increase their system detection efficiency and the optimization of the fabrication process to fabricate ion traps for tests with real ions.

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REFERENCES

[1] Kielpinski, D., Monroe, C., and Wineland, D. J., "Architecture for a large-scale ion-trap quantum computer.," *Nature* **417**, 709–11 (2002).

[2] Monroe, C. and Kim, J., "Scaling the Ion Trap Quantum Processor," *Science* **339**, 1164–1169 (2013).

[3] Bruzewicz, C. D., Chiaverini, J., McConnell, R., and Sage, J. M., "Trapped-ion quantum computing: Progress and challenges," *Applied Physics Reviews* **6**(2), 021314 (2019).

[4] Dehmelt, H. G., "Monoion oscillator as potential ultimate laser frequency standard," *IEEE Transactions on Instrumentation and Measurement* **IM-31**(2), 83–87 (1982).

[5] Slichter, D. H., Verma, V. B., Leibfried, D., Mirin, R. P., Nam, S. W., and Wineland, D. J., "UV-sensitive superconducting nanowire single photon detectors for integration in an ion trap," *Optics Express* **25**, 8705–8720 (2017).

[6] Todaro, S. L., Verma, V. B., McCormick, K. C., Allcock, D. T. C., Mirin, R. P., Wineland, D. J., Nam, S. W., Wilson, A. C., Leibfried, D., and Slichter, D. H., "State readout of a trapped ion qubit using a trap-integrated superconducting photon detector," *Physical Review Letters* **126**, 010501 (2021).

[7] Setzer, W. J., Ivory, M., Slobodyan, O., Van Der Wall, J. W., Parazzoli, L. P., Stick, D., Gehl, M., Blain, M. G., Kay, R. R., and McGuinness, H. J., "Fluorescence detection of a trapped ion with a monolithically integrated single-photon-counting avalanche diode," *Applied Physics Letters* **119**, 154002 (2021).

[8] Reens, D., Collins, M., Ciampi, J., Kharas, D., Aull, B. F., Donlon, K., Bruzewicz, C. D., Felton, B., Stuart, J., Niffenegger, R. J., Rich, P., Braje, D., Ryu, K. K., Chiaverini, J., and McConnell, R., "High-fidelity ion state detection using trap-integrated avalanche photodiodes," *Physical Review Letters* **129**, 100502 (2022).

[9] Reddy, D. V., Nerem, R. R., Nam, S. W., Mirin, R. P., and Verma, V. B., "Superconducting nanowire single-photon detectors with 98% system detection efficiency at 1550 nm," *Optica* **7**, 1649–1653 (2020).

[10] Wollman, E. E., Verma, V. B., Beyer, A. D., Briggs, R. M., Korzh, B., Allmaras, J. P., Marsili, F., Lita, A. E., Mirin, R. P., Nam, S. W., and et al., "UV superconducting nanowire single-photon detectors with high efficiency, low noise, and 4 k operating temperature," *Optics Express* **25**(22), 26792 (2017).

[11] Chiles, J., Charaev, I., Lasenby, R., Baryakhtar, M., Huang, J., Roshko, A., Burton, G., Colangelo, M., Van Tilburg, K., Arvanitaki, A., Nam, S. W., and Berggren, K. K., "New constraints on dark photon dark matter with superconducting nanowire detectors in an optical haloscope," *Phys. Rev. Lett.* **128**, 231802 (2022).

[12] Hampel, B., Slichter, D. H., Leibfried, D., Mirin, R. P., Nam, S. W., and Verma, V. B., "Trap-integrated superconducting nanowire single-photon detectors with improved rf tolerance for trapped-ion qubit state readout," *Applied Physics Letters* **122**, 174001 (2023).

[13] Crain, S., Cahall, C., Vrijsen, G., Wollman, E. E., Shaw, M. D., Verma, V. B., Nam, S. W., and Kim, J., "High-speed low-crosstalk detection of a $^{171}\mathrm{Yb}^{+}$ qubit using superconducting nanowire single photon detectors," *Communications Physics* **2**(1), 97 (2019).

[14] Hampel, B., Mirin, R. P., Nam, S. W., and Verma, V. B., "A 64-pixel mid-infrared single-photon imager based on superconducting nanowire detectors," *Applied Physics Letters* **124**, 042602 (2024).

[15] Wineland, D. J., Monroe, C., Itano, W. M., Leibfried, D., King, B. E., and Meekhof, D. M., "Experimental issues in coherent quantum-state manipulation of trapped atomic ions," *Journal of Research of the National Institute of Standards and Technology* **103**(3), 259–328 (1998).

[16] Hampel, B., Slichter, D. H., Leibfried, D., Mirin, R. P., Nam, S. W., and Verma, V. B., "Data for "Trap-integrated superconducting nanowire single-photon detectors for trapped-ion qubit state readout"," *National Institute of Standards and Technology* (https://doi.org/10.18434/mds2-3216) (2024).