Photon-Counting Superconducting Detectors for Submillimeter Astronomy

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Abstract. We are developing superconducting direct detectors (Single Quasiparticle Photon Counter, or SQPC) for submillimeter astronomy that could detect individual photons. These devices measure the quasiparticles generated breaking Cooper-pairs by photon absorption. This photoconductive type of device could yield high quantum efficiency, few μs response times, and sensitivities in the range of 10^{-20} W/Hz$^{1/2}$. Antenna coupling to a small absorber also suggests the potential for novel instrument designs and scalability to imaging or spectroscopic arrays. We describe device concept, fabrication and characterization of these detectors, issues related to their saturation and optimization. Presented measurements of the dark current, ultimately limiting the detector sensitivity, follow the expected exponential temperature scaling down to 210 mK and as small as 10 fA, corresponding to expected NEP of 10^{-20} W/Hz$^{1/2}$. Finally, we have developed practical readout amplifiers for these high-impedance cryogenic detectors based on the Radio-Frequency Single-Electron Transistor (RF-SET). We will describe a demonstration of a transimpedance amplifier based on closed-loop operation of an RF-SET, the use of an RF-SET to measure the photocurrent of an SQPC detector, and a wavelength-division multiplexing scheme for the RF-SET. These developments will be key ingredients in scaling to large arrays of high-sensitivity detectors.

1. Introduction

To take advantage of very low background photon rates, space-based far infrared or submillimeter-wave interferometers will require large advances in detector sensitivity and speed. Integration of photon-counting detectors with low power readout electronics to make large-format arrays is desired. The Single Quasiparticle Photon Counter (SQPC) is a type of superconducting direct detector, which has been proposed to meet these requirements [1].

2. Detector Concept and Fabrication

The SQPC is an antenna-coupled Superconducting Tunnel Junction (STJ) detector with integrated Radio Frequency Single-Electron Transistor (RF-SET) readout amplifier. STJs have been used for energy-resolving detection of single photons at wavelengths ranging from IR to X-ray. In an STJ detector, a superconducting-insulating-superconducting tunnel junction is biased below its superconducting gap. At temperatures well below the superconducting transition temperature, very little current flows since most electrons are bound in Cooper pairs. The number of thermally-generated unbound quasiparticles, and hence also the dark current and detector noise, decrease exponentially as the operation temperature is lowered. For Al-based STJs, operating temperatures of 250 mK or less are used.

When a photon is absorbed in a superconducting absorber linked to a junction electrode, it breaks Cooper pairs generating a current pulse. The integrated pulse charge measures the photon energy. At high count rates, overlapping pulses give a photocurrent proportional to the absorbed optical power. The tunneling time which sets the detector speed can be quite fast (≈ 1 μs) since the response is a non-equilibrium effect and not a thermal phonon relaxation.

2.1. Use of an STJ detector for low energy photons

Figure 1 shows how an STJ is adapted for detection of millimeter or submillimeter-wave photons in an SQPC. The optimal volume of the STJ detection electrode scales in proportion to the maximum photon energy. For submillimeter detection, dimensions of the absorber and junction need to be submicron. Efficient coupling of long-wavelength radiation to the small absorber is provided by an antenna structure. Sensitive and high-bandwidth readout of photocurrents through the small, high-impedance tunnel junction is provided by an integrated RF-SET. In our devices, we use Al-based STJs and absorber, and a Nb antenna. For photon frequencies between the superconducting gap frequencies of Al (100 GHz) and Nb (700 GHz), the normal-state resistance of the absorber is a well-matched impedance for absorbing energy at the center of the bow-tie antenna.

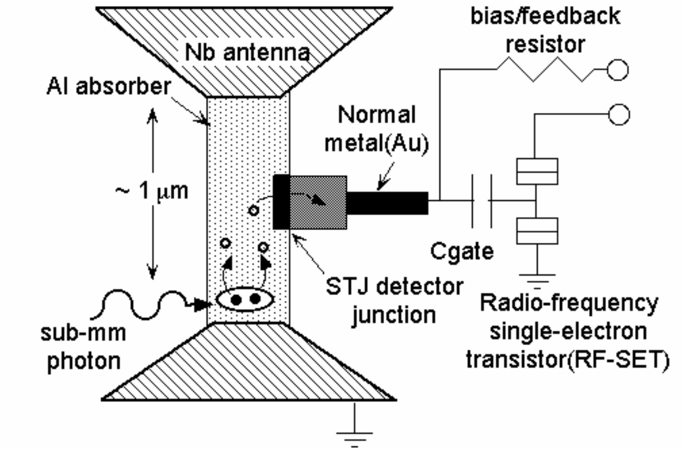

Figure 1. Single Quasiparticle Photon Counter (SQPC): A niobium bow-tie antenna provides coupling to submillimeter radiation. Absorption of a submillimeter photon breaks Cooper pairs in the aluminum strip joining the halves of the bow-tie, and gives a current pulse through a tunnel junction connected to an RF-SET readout amplifier.

A gold quasiparticle trap in the bias lead near the STJ allows in few nsec outdiffusion of collected quasiparticles away from the junction after tunnelling. This prevents backtunneling, which may otherwise slow the detector response time. Instead of one junction we actually use two junctions in parallel to form a dc Superconducting Quantum Interference Device (SQUID). This allows the critical current of the combined junctions to be easily suppressed nearly to zero, which is necessary for bias stability, and essential for achieving the lowest dark currents.

2.2. *Integrated Readout Amplifier*

At detector readout frequencies (<< 100 GHz), the aluminum is superconducting, and the tunnel junction has a subgap differential resistance higher than 100 MΩ, and a capacitance lower than 1 fF. An ideal transimpedance amplifier for a high impedance photoconductor is the RF-SET [2]. A Single Electron Transistor (SET) is a very sensitive electrometer based on the Coulomb blockade effect with sub-femtofarad input capacitance. An RF-SET integrates the SET with a LC circuit resonant at ≈ 1 GHz to impedance match the typical 50 kΩ SET output impedance to a 50 Ω High Electron Mobility Transistor (HEMT). Signal bandwidths of 100 MHz can be obtained [3].

To make an RF-SET transimpedance amplifier, we feed the room temperature output voltage of the RF-SET amplifier system back to the input gate of the SET via a cryogenic, 60 MΩ resistor integrated at the detector bias point.

3. Optimization of device parameters and experimental results

Apart from efficiency of antenna coupling, the fundamental factors determining SQPC sensitivity are: (i) detector responsivity, (ii) shot noise of the dark current, (iii) noise of the RF-SET expressed as an equivalent voltage noise at its input, (iv) Johnson noise in the feedback resistor, and (v) impedance of the detector in parallel with the feedback resistor. We have investigated each of these issues, and predict Noise Equivalent Power (NEP) ≈ 10^{-20} W/√Hz could be obtained with our existing SQPC prototypes based on the demonstrated levels of performance measured for each factor.

3.1. *Detector Responsivity*

The responsivity of the SQPC is ideally equal to $e/\Delta_{Al} \approx 5000$ A/W. Efficient collection of photon-generated quasiparticles depends on making the tunneling time short by

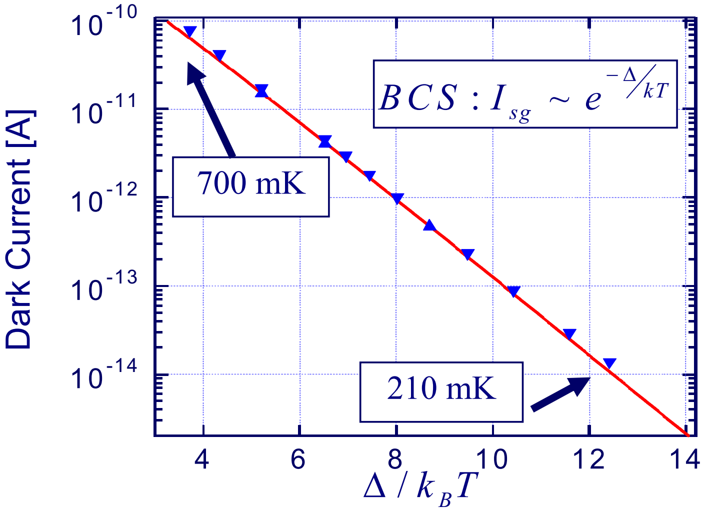

Figure 2. Data and theory for I_{sg} of one of our detectors at $V_{bias}=50\ \mu V$.

confining the quasiparticles to a small absorber volume, and on avoiding sources of quasiparticle recombination. At low operating temperatures, thermal recombination rates are orders of magnitude slower than our few μs tunneling times.

3.2. Dark Currents

We have investigated dependence of dark current on device parameters. Several different detectors were cooled down to temperatures as low as 210 mK. For junctions with a Josephson energy $E_J = I_c\Phi_0 /2\pi$ smaller than kT, we observed extra suppression of the critical current by thermal fluctuations. We were able to show that the supercurrent can be suppressed to less than 0.1% on its initial value with a few Gauss of magnetic field through the SQUID loop. BCS theory predicts that the subgap current, I_{sg}, due to thermally excited quasipartcles should decrease exponentially with temperature. Our measurements have shown that I_{sg} corresponds to the BCS value and that it continues to scale exponentially. At 210 mK, we measured $I_{sg} \approx 10$ fA, as shown in Figure 2. This implies that a shot noise limited detector would have an NEP ≈ 10^{-20} W/√Hz.

3.3. RF-SET voltage noise

Nearly quantum-limited charge noise ≈ 10^{-6} *e*/√Hz has been demonstrated for RF-SETs with small input gates [4]. However, just as for dc SQUIDs, it is difficult to maintain quantum-limited sensitivity while providing strong coupling to an input signal. For SQPC readout, the figure of merit is the voltage noise, equal to the charge noise divided by the input gate coupling capacitance. As gate capacitance is increased, the voltage noise at first drops, but then levels off or increases as the charge noise of the RF-SET starts to degrade due to co-tunneling effects. We have obtained SET voltage noise of 30 nV/√Hz with a 0.5 fF gate, and have been able to maintain a voltage noise close to this value during closed-loop transimpedance amplifier operation [5].

4. Multiplexing for arrays

An advantage for the SQPC is the multiplexing capability of RF-SETs. Multiplexing schemes will be crucial to the development of large-format arrays of SQPCs, or other low-temperature detectors. RF-SETs have a natural wavelength division multiplexing capability. Each RF-SET is connected to one coaxial line by an rf tank circuit with a unique resonance frequency. A directional coupler allows rf carriers to be applied at each resonance frequency and reflected powers to be monitored by a single HEMT following amplifier at 4 K. RF-SETs can be individually or simultaneously powered and read out. We have made a two-channel rf multiplexing demonstration using discrete inductors for the rf tank circuits [2]. We have designed a 50-channel system with components based on measured parameters of our lithographic circuits [6].

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