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A Concept for a Submillimeter-Wave Single-Photon Counter

R.J. Schoelkopf
Department of Applied Physics, Yale University, 15 Prospect St., New Haven, CT 06520-8284

S.H. Moseley and C.M. Stahle
Laboratory For Astronomy and Astrophysics, NASA/Goddard Space Flight Center, Greenbelt, MD 20771

P. Wahlgren and P. Delsing
Department of Microelectronics and Nanoscience, Chalmers University of Technology and Göteborg Universi
S-412 96 Göteborg, Sweden

***Abstract*—We discuss the design for a submillimeter-wave photometer, using a combination of superconducting and single-electron devices, which would have high quantum efficiency, very low noise-equivalent powers, and eventually even submicrosecond timing resolution. The absorption of above-gap photons occurs in a small strip of superconducting Al, whose normal-state resistance can be matched efficiently to an antenna of a higher gap (Nb) superconductor. The quasiparticles produced by photon absorption are then confined via Andreev reflection, and forced to tunnel through a small SIS tunnel junction. The tunneling time is much shorter than the known ($> 10\ \mu s$) quasiparticle recombination time, so collection efficiency will be high. The device sensitivity would be limited by the small subgap current in the high-quality $Al/AlO_x/Al$ tunnel junction at temperatures (100 mK) well below T_c. Scaling based on the larger junctions used in X-ray detector applications suggests that the total dark current can be < 0.1 pA, or of order 10^5 electrons/second, corresponding to an NEP of less than $10^{-19}\ W/\sqrt{Hz}$ at 500 microns (600 GHz). The photocurrent will be measured using a fast single-electron transistor (RF-SET), which allows a shot-noise-limited performance even for the very small currents delivered from this low capacitance and high impedance SIS junction. Results of initial fabrication and dc characterization of an integrated photodetector are also given.**

I. Introduction

How sensitive a direct detector does one need at submillimeter wavelengths? Heterodyne detectors (mixers) have in recent years achieved near quantum-limited performance [1] and are used for high resolution ($\delta\nu/\nu \sim 10^{-6}$) astronomical observations, while direct detectors are generally preferred for wide bandwidth applications. A heterodyne system is limited by its fundamental quantum noise (1/2 a photon per mode) when background temperatures are less than $T_Q = h\nu/2k_b$ (~ 25 K @ 1 THz), while an ideal direct detector is limited only by fluctuations in the photon background impinging on the device. For wideband (of order octave) observations from even the best ground-based sites, this background limit due to atmospheric emission [2] corresponds to noise-equivalent powers (NEP's) of about 10^{-15} or 10^{-16} watts Cryogenic bolometers (for a review, see [3]), wh ten operated below 0.3 K, can have sufficient se to easily reach this limit. Indeed, semiconducto ters [4] now achieve sensitivities of 10^{-17} W/√] ter.

However, there are also applications in extr astronomy in which require medium resolution $10^{-3} - 10^{-4}$) within some much wider total b and would be awkward to address using heter struments. Since the bandwidth is limited, ground flux is reduced, and detector sensitivit be correspondingly higher [5], $\leq 10^{-18}\ W/\sqrt{Hz}$ more, future space missions [6] with cooled optic spectral resolution might require drastically l levels [7], approaching even $10^{-21}\ W/\sqrt{Hz}$. Th direct detector is of course a true photon counte always background-limited when the number o per second exceeds whatever "dark" counts th registers in the absence of light. While good ph ters exist (e.g., photomultipliers) at shorter wa no device has yet approached this goal in the su ter.

In the past few years, several novel bolome tures and/or readout schemes have been develo can address this range of sensitivities. Bolome use a voltage-biased superconducting transition sor (TES) combined with a SQUID readout, fo have demonstrated [8] electrical NEP's of 10^{-17} and have even been used for detection of indi tical and near-IR photons [9]. Another promis for achieving these very high sensitivities is th "NIS" microbolometer [10], in which an antenn normal metal strip is used as the absorber, an tron temperature is readout using a normal- superconductor tunnel junction. These NI ters have demonstrated electrical NEP's of a W/√Hz, and the predicted performance at 100 the order of $10^{-19}\ W/\sqrt{Hz}$. An exciting superc technology for single-photon detection are sup ing tunnel junction (STJ) detectors, where t pulse in a superconductor-insulator-supercondu junction, due to the breaking of many Cooper-p photon absorption in one of the electrodes, can determination of photon energy. These STJ de been used for spectroscopy of individual photo ray [11] down to near-IR [12] wavelengths.

In this paper, we introduce a device, calle

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Corresponding author: rob.schoelkopf@yale.edu

Quasiparticle Photon Counter (SQPC) for convenience, which combines demonstrated elements of both superconducting and single-electron (SET) technologies to produce a direct-detector with expected sensitivities of 10^{-20} $W/\sqrt{Hz}$ or better. It is not a bolometer, but rather a non-equilibrium device which would first be operated as a photoconductor, but might eventually produce a true single-photon counter at submillimeter wavelengths with sub-microsecond speed and high quantum efficiency. Furthermore, the detector has a integrated readout scheme which has low power dissipation, small size, and a potential for multiplexing to produce large scale arrays. We first present the device configuration and basic operating principles, then discuss the dynamics of the response to a photon absorption, address the expected noise sources in the system and their optimization, continue with initial results from fabrication and dc characterization of the first such devices, and discuss the prospect of performing true single-photon counting at submillimeter wavelengths.

II. Device Concept and Geometry

The basic configuration of the SQPC device is shown in Figure 1. A small strip of Al is connected to the terminals of a planar antenna fabricated from a higher-gap superconductor, such as Nb or NbTiN. Photons in the frequency range between the gap frequencies of the Al and the antenna (~ 100-700 GHz, for Al and Nb) which impinge on the antenna will break Cooper-pairs in the Al strip. The quasiparticles produced will be trapped within the Al absorber due to Andreev reflection, and either recombine or tunnel through the submicron-area $Al/AlO_x/Al$ tunnel junction, located to one side of the absorber. The junction is of submicron area, so that its capacitance is small (fF), its normal-state resistance is high (kΩ), and its leakage current, when biased below the superconducting gap voltage, can be picoamps or less.

The photocurrent across the SIS detector junction is measured using a capacitively-coupled high-speed quantum electrometer, namely a radio-frequency single-electron transistor (RF-SET) [13], as a transimpedance amplifier. The RF-SET is also fabricated from ultrasmall Al tunnel junctions, and integrated on chip. The RF-SET is optimized for measuring signals from large impedance sources, and can attain bandwidths of over 100 MHz for small source capacitances. The SIS junction is biased through a cooled feedback resistor, with the current return provided through the absorber and antenna.

When photons are absorbed, the quasiparticles tunnel across the junction, causing an increase in the current, so that the device operates as a photoconductor. In this mode, a readout using a conventional field-effect transistor would probably be possible. Because the RF-SET is in fact capable of counting a pulse consisting of only a few electrons on microsecond timescales or faster, however, and because the expected dark currents of less than a picoamp correspond to electron-counting rates (f=I/e) of less than 10^6 per second, one might eventually be able to resolve individual photon absorptions. Although of course a single pair-breaking photon event leads to the production of two quasiparticles, we refer to this integrated detector as a Single Quasiparticle Photon Counter,

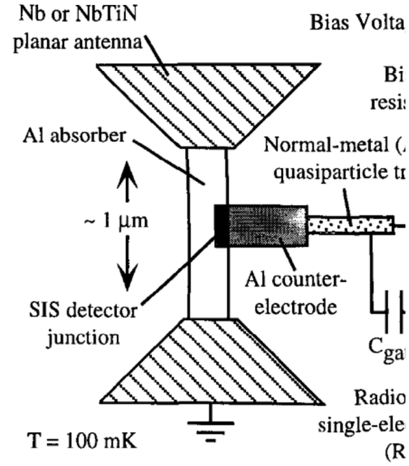

Fig. 1. Schematic layout of ultra-sensitive submilli detector and photon counter.

or SQPC.

Experts will recognize that this devic STJ detector, carried to an extreme limit photon charge pulses consist of only on trons, and utilizing antenna coupling ratl absorption. An SET has previously been with a doped Si absorber to yield very low $W/\sqrt{Hz}$) at shorter wavelengths, but s have natural "bandgaps" of meV. Finally, ton counting by absorption directly in a s SET, where a multiplication process gives for each absorbed photon, was also discu [15], although the issues of quantum efficie able high-speed readout were not resolved

III. Input Coupling, Quantum Eff Responsivity

In this device, the input coupling and tion can be separately optimized. The im Al absorber strip at frequencies well abo proaches the normal state impedance. If th impedance is impedance-matched to the a incident power is absorbed by the Al str excess quasiparticles and high quantum ef for an absorber resistance of about 15 Oh ical antenna impedance, $Z_{ant} \sim 75$ Ohm efficiency should be greater than 50% (in t of the antenna). The use of a planar super tenna also allows [16] low-loss tuning circ the impedance match, or the incorporatio ters to select the desired band for the dete

If the photo-produced quasiparticles ca collected, (see section on quasiparticle dy then two quasiparticles are measured per ton. Note that this is twice the quantum- sivity of an ordinary SIS direct-detector [1 quasiparticles contribute to the tunnel cur figuration. When the photon energy exce pect the net result to be the production of 4 quasiparticles. Thus the number of quasiparticles produced per photon, $2h\nu/2\Delta$, scales as the photon energy, although with some discretization. The current responsivity is then approximately constant with frequency, with a value of $e \times h\nu/\Delta/h\nu = e/\Delta$, or about 5×10^3Amps/Watt for an aluminum absorber. However, the main advantage over an ordinary SIS direct-detector, where the radiation is coupled directly *across* the junction, is not responsivity. In the usual configuration, the conditions of efficient matching, which requires R_N of order the impedance of free space, and very low leakage current cannot be simultaneously met.

IV. Quasiparticle Dynamics and Timescales

In order to preserve the efficient collection and measurement of the quasiparticles produced by the incident photons, we require a certain hierarchy of timescales within the detector, namely that the diffusion of the quasiparticles within the absorber, and their tunneling out through the SIS junction, should all take place on a timescale which is short compared to the recombination time. Even for absorber films with the resistivities of several $\mu\Omega - \mathrm{cm}$ that might be required to achieve a few ohms/square and efficient matching to the absorber, the diffusion constant should be in the range 1-10 cm^2/s. This implies diffusion times, $\tau_d = L^2/D$, of 1-10 nanoseconds over the one μm absorber. Since the diffusion time is much shorter than the tunneling time out of the absorber, the quasiparticles will effectively sample the entire volume of the absorber, and the fraction of the absorber which is covered by the detector SIS junction is not important.

The time required for an individual quasiparticle to tunnel from the absorber simply depends on the product of the volume of the absorber and the normal state resistance of the tunnel junction. This process is identical to charge collection in shorter-wavelength STJ detectors, which is well understood [18]. The tunneling time, τ_t, in the normal state is $\tau_t = 2eR_N N_F V$, where e is the electron's charge, R_N is the normal-state resistance of the junction, N_F is the density-of-states of the Al (per eV per volume), and V is the total volume of the absorber. In the superconducting case, with bias voltages much less than the gap, there are only small corrections of about a factor of two. For an absorber approximately 1 μm x 1 μm x 200 Å thick, the volume is approximately 10^{-14} cm^3, and the tunneling time for a 10 kΩ junction would be about 1 μs. We note that this is similar to the times found in X-ray STJ detectors; the Yale group [19] finds $\tau_t \sim$ 1 μs, for an absorber volume about 10^4 times larger, and a resistance about 10^4 times smaller. If film thickness in the SQPC was decreased to 100 Å and linewidth reduced to 0.2 μm, the volume and hence the time could perhaps be an order of magnitude still smaller. One could further decrease the tunneling time by reducing the junction resistance, but this would come at the expense of an increased dark current and a decreased sensitivity (see next section). A normal-metal wiring layer (Au) is placed within a few microns of the detector junction counter-electrode. This helps to ensure that after tunneling, the quasiparticles diffuse away from the junction and are lost, before they have

TABLE I
Device Parameters and Noise Sources for SQPC Detect

Device Parameters	Optimal Device	Initi
Junction Resistance, R_N	10 kΩ	
Dynamic Resistance, R_d	> 1 GΩ	
Total Capacitance	1 fF	
Dark Current @ V = 50μV	< 50 fA	4
Electrons/second	$< 3 \times 10^5$	3
Noise Sources		
Shot Noise (A/$\sqrt{\mathrm{Hz}}$)	1×10^{-16}	1
Johnson Noise (A/$\sqrt{\mathrm{Hz}}$)	1×10^{-16}	2.5
SET Charge Noise (e/$\sqrt{\mathrm{Hz}}$)	2×10^{-6}	5
SET Voltage Noise (V/$\sqrt{\mathrm{Hz}}$)	6×10^{-10}	1.5
Effective Current Noise [20] of SET (A/$\sqrt{\mathrm{Hz}}$)	$< 10^{-18}$	1.5
Readout Bandwidth	> 10 MHz	
Responsivity (e/Δ)	5,000 A/W	5,0
Predicted NEP (W/$\sqrt{\mathrm{Hz}}$)	$< 3 \times 10^{-20}$	3

an opportunity to tunnel back into the absorber

Very long recombination times, τ_R, have be ously observed [21] in Al films at these low temp and times greater than 10 μs are observed in devices. But for the very dirty, thin films such a sorber, the times will need to be determined. N less, we expect that the recombination time will b 1-2 orders of magnitude longer than the sub-mic tunneling time. So the desired hierarchy of ti $\tau_d \ll \tau_t \ll \tau_R$, should be well-satisfied, and t be an efficient collection, with nearly all the qu cles produced by the photons resulting in excess t current across the detector junction.

V. Noise Sources and Detector Sensit

Since the SQPC will operate as either a phot tor or photon counter, the intrinsic limit on the ity will ultimately be determined by the numbe counts per second, or the leakage current of th tector junction. Again, a main advantage of t geometry we have chosen is that the detector jun be very high in resistance. Furthermore, the lea rent of Al/AlO$_x$/Al tunnel junctions in the subg and at temperatures well below T_c can be a smal of the tunneling current in the normal state, V Al STJ devices operated at 0.25 K, subgap cur times lower are commonly observed, and ratios o been observed [22] below 0.1 K. Whether these to-normal state conductance ratios can also be with the very small area tunnel junctions of t will have to be demonstrated. However, if a ra can be obtained, then the leakage current of a with a normal state resistance of 10 kΩ, when b low the gap, can be much less than a picoamp (1). This corresponds to an electron counting rat only 10^5 electrons per second. The minimum d photon flux in a 1 second integration would be a square-root of this number, or a few hundred ph second, and is equivalent to NEP's of 10^{-20} W/

The actual NEP of the detector, including

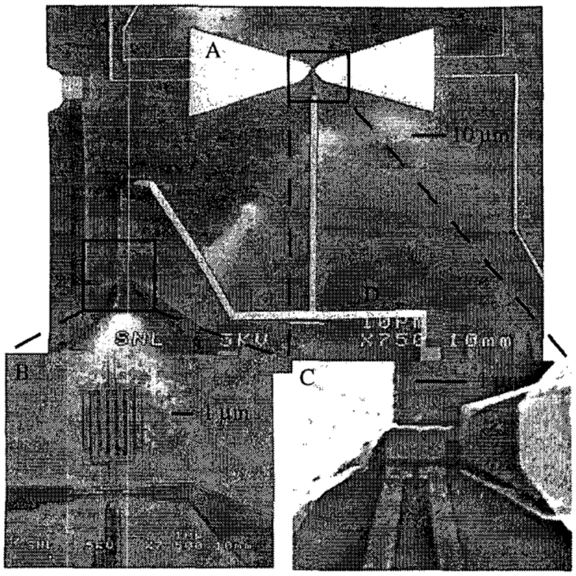

Fig. 2. SEM micrograph of completed photodetector, fabricated with multi-layer direct-write e-beam lithography. Shows A) chip layout including Pb bowtie antenna and Al absorber, B) integrated single-electron transistor with interdigitated finger capacitor, C) two SIS detector junctions with SQUID loop to allow suppression of critical current, and D) Au wiring/quasiparticle traps.

added in the readout, is determined by computing the total effective current noise (in Amps/$\sqrt{\text{Hz}}$), and dividing by the responsivity,

$$NEP = \frac{i_n}{R} = (i_{Shot}^2 + i_{Johnson}^2 + |e_n/Z_{tot}|^2)^{1/2}/R, \quad (1)$$

where R is the responsivity (in Amps/Watt), i_{Shot}^2 is the shot noise of the dark current, $2eI_{dark}$, $i_{Johnson}^2$ is the current noise of the bias resistor, $4k_bT/R_b$, e_n is voltage noise of the SET $e_n = q_n/C_{gate}$ (q_n is the charge noise of the SET), and Z_{tot} is the total impedance of load. This load impedance is equal to the parallel combination of the junction dynamic resistance, R_d and the total capacitance to ground of the node connected to the SET, $C_{tot} = C_{junc} + C_{gate} + C_{parasitic}$, so that $Z_{tot} = R_d/(1 + \jmath\omega R_d C_{tot})$. The noise contribution of the SET therefore increases above the RC frequency of the load, and depends on the total capacitance. In the first design, we plan to use an off-chip, but cooled, feedback resistor, so C_{tot} will be a picofarad or more, at the expense of considerable bandwidth. With an on-chip resistor, perhaps even consisting another junction or a series array, the total capacitance can be maintained at only a few femtofarads. In the above we assume that i_n of the SET itself is negligible, since the gate resistance of this type of interdigitated capacitor on Si [23] is greater than 10^{18} Ω. The feedback resistors are assumed to have only Johnson noise, be cooled to 100 mK, and to have initial and final values of 100 and 250 MΩ, respectively.

Some representative numbers for both the device parameters and the terms contributing to the total NEP (Eq 1) are given in Table 1. In initial experiments, an ordinary SET, operated at low frequencies where $1/f$ noise limits the charge noise to several times 10^{-5} elec be used. The RF-SET has demonstrated of about 15 micro-electrons/$\sqrt{\text{Hz}}$ (1.5×10 simultaneous bandwidths of greater thar simple design improvements are expected noise of only a few micro-electrons/$\sqrt{\text{Hz}}$. ' sitivity means that the readout can be lin damental shot noise of the leakage curre bandwidths could be comparable to the The main advantage of the RF-SET read voltage noise, since high-quality field-effec attain $\sim$ nV/$\sqrt{\text{Hz}}$. The bandwidth of a due to their 1,000 times higher capacitan greater than about a hundred hertz for th impedance of the SIS detector. In additio dissipation and operating temperature o simplify the scaling to a large number c nels. Si FET's must be kept at 100 K, an implement with 100 mK detectors in larg

VI. Fabrication and Initial

Several integrated devices of the design have been fabricated in the Swedish Na tory, and an electron micrograph of one detectors is shown in Figure 2. The fabric cluded several steps of direct-write elect raphy and thermal evaporation. First, th contacts were deposited. The Al absorbe of 16 Ω), detector junctions, and SET ar in the next lithography step. The SE detail B) were made using a standard do oration technique through this resist pat area of approximately 80 x 80 nm, capa 0.2 fF per junction, and resistance $\sim$ 50 sorber strip was also fabricated at the the detector junction made during the Finally, the Pb bowtie antenna layer wa deposited over the absorber. Low resista absorber to antenna was made through regions under antenna. All of the elem were electrically functioning.

The detector junction was actually (se ure 2) split into *two* separate junctions, of about 100 x 300 nm. Separate counter two detector junctions are extended to f ducting loop with an area of several squa junctions thus form a SQUID, which allo supercurrent of the parallel combination with a magnetic field of only a few Gau depress the superconducting gaps. The junction combination had an R_N of 1 kΩ, (at T = 50mK) is shown in Figure 3. T the subgap current are taken with for two magnetic fields, and demonstrates the m supercurrent. The bottom trace in Fig modulation of the SET with the voltag gate, and allows determination of the g $C_{gate} = 0.55 fF$.

The subgap current of this first device 100 times smaller than the normal-state

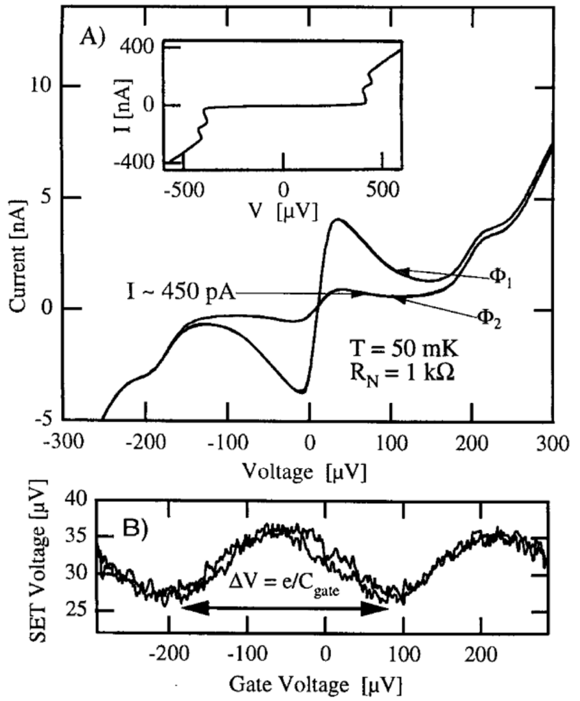

Fig. 3. Data from dc characterization of device such as that shown in Figure 2. A) Current-voltage characteristic of double-junction SIS detectors, for two different values of applied magnetic field. Inset shows I-V on larger scale. B) Response of integrated SET to voltage applied to the input gate. The observed periodicity allows a determination of the gate capacitance, $C_{gate} = 0.54$ fF.

in this first characterization the influence of external noise or stray light cannot be ruled out. The junctions also displayed some non-ideal behavior, which could be due to nonequilibrium effects from the wiring layers, or bad alignment. Even this relatively high leakage current should yield a very sensitive detector, however. The expected sensitivity, given the measured dc characteristics, is detailed in Table 1, and would be at the state-of-the-art for direct detectors, with an NEP of a few 10^{-18} W/$\sqrt{\text{Hz}}$. Future designs for true photon counting will have to investigate the leakage current and minimize it, as well as reduce the parasitic capacitance to allow high speed operation.

VII. Summary

In conclusion, we have presented the concept for and demonstrated the fabrication of a combined superconducting/single-electron device which can serve as a far-IR direct detector with sensitivities as much as 100 times better than present state-of-the-art bolometers, and response times of less than 1 μs. Furthermore, this SQPC is in essence a photoconductor, rather than a thermal (bolometric) detector. When comparing a device which utilizes a bandgap against a true bolometer, the simple expectation is that the performance will increase more rapidly (dark current should scale exponentially) with a decrease in operating temperature than in tl detector. Initial devices which incorporate an readout using a fast RF-SET have been fabri even these unoptimized designs should give NEl 10^{-18} W/$\sqrt{\text{Hz}}$. Eventually, devices of this type proach 10^{-20} W/$\sqrt{\text{Hz}}$, and even yield a true sin counter in the submillimeter band.

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