The Quantum Capacitor Detector: A Single Cooper Pair Box Based Readout for Pair Breaking Photo-detectors

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We propose a sensitive new detector based on Cooper pair breaking in a superconductor. The quantum capacitor detector (QCD) exploits the extraordinary sensitivity of superconducting single-electron devices to the presence of quasiparticles generated by pair-breaking photons. This concept would enable single-photon detection at far-IR and sub-millimeter frequencies with detector sensitivities that exceed that of transition-edge-sensor bolometers (TES), kinetic inductance detectors (KID), and superconducting tunnel junction detectors (STJ). The detectors we propose are based on the single Cooper pair box (SCB), a mesoscopic superconducting device that has been successfully developed at JPL for applications in quantum computing. This concept allows for frequency multiplexing of a large number of pixels using a single RF line, and does not require individual bias of each pixel. The QCD is ideal for the sensitive spectrographs considered for upcoming cold space telescopes, such as BLISS for SPICA in the coming decade, and for the more ambitious instruments for the SAFIR / CALISTO and SPIRIT / SPECS missions envisioned for the 2020 decade.

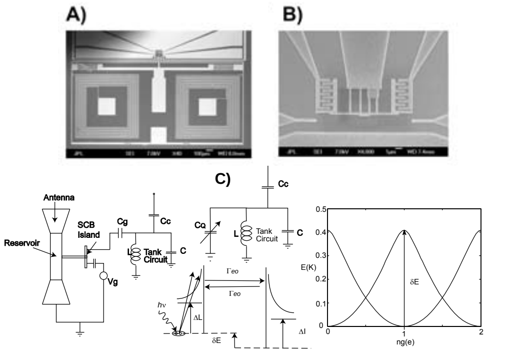

Figure 1. A) Scanning electron micrograph of multiplexed on-chip LC oscillators. B) Scanning electron micrograph of two side by side SCB structures. C) Concept of Quantum Capacitor Detector. *Nqp* quasiparticles are created by breaking Cooper Pairs in a reservoir by antenna coupled radiation. Quasiparticles will tunnel to the island of the SCB which acts like a potential well of depth δE with a rate *Γeo(Nqp)* and out of the well with a rate *Γoe* which is not a function of *Nqp*. The quantum capacitance of the island changes by a value proportional to the quantity *Pe=Γoe/(Γoe+Γeo)* and shifts the tank circuit resonance frequency and consequently the phase of an RF signal reflected off the tank circuit.

Radiation is coupled via an antenna to a small superconducting reservoir, where the absorbed energy generates quasiparticles by breaking Cooper pairs. The reservoir has a lower superconducting gap than that of the antenna, so quasiparticles generated in the antenna are concentrated in the reservoir. For a photon with energy $h\nu$ and a reservoir material with superconducting gap Δ, a number of quasiparticles $Nqp=\eta\, h\nu/\Delta$ is generated. Here $\eta \approx 0.57$ is the efficiency for conversion of the photon energy into quasiparticles. With the SCB biased at the degeneracy point, the box will behave as a potential well or "trap" for the quasiparticles with a depth $\delta E \sim E_C E_J/2$, where Ec is the charging energy given by $e^2/2C_\Sigma$, E_J is the Josephson Energy and C_Σ is the total capacitance of the island, including the two tunnel junctions and the gate capacitance. Quasiparticles tunnel onto the island with a tunneling rate $\Gamma_{eo}(nqp)$ which depends linearly on the density of quasiparticles in the reservoir $nqp=Nqp/\Omega L$, where ΩL is the reservoir volume. Quasiparticles will tunnel off the island with a rate Γ_{oe} which is approximately independent of the number of quasiparticles in the reservoir. At steady state, the probability of a quasiparticle being present in the island is given by $Po(Nqp)=\Gamma eo/(\Gamma eo+\Gamma oe,)$ and the resulting change in the average capacitance will be $CQ=(4E_C/E_J)(Cg^2/C_\Sigma)Po(Nqp)$. With the tank circuit tuned to its resonance frequency ωo, this change in capacitance will produce a phase shift $\delta\Phi \sim 2C_Q/(\omega_o Z_o C_C{}^2)$ in the reflected signal, where Zo is the characteristic impedance of the RF line (nominally 50Ω) and CC is the coupling capacitance to the tank circuit. Using measured values of Γoe and Γeo [12] we estimate the phase shift at 18mK due to a single quasiparticle tunneling event to be approximately 2.4 radians or 138 degrees, which is close to the measured values such as those shown in Figure 2.

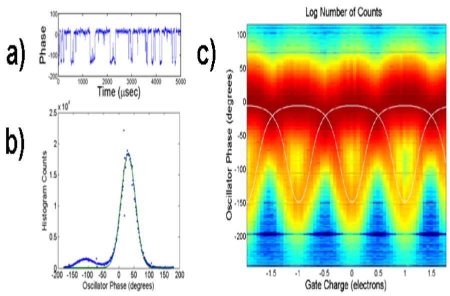

Figure 2. Measurements of the phase of the reflected signal from an SCB embedded in an LC tank circuit. A) Measurement of the phase as a function of time at the degeneracy point. The jumps correspond to a single quasiparticle tunneling on and off the island. Note the large phase shift (140 degrees) a quasiparticle can cause. B) Histogram of phase measurements showing an rms phase noise of 33 degrees or 1.8x10-3 radians/Hz1/2 given a measurement bandwidth of 100 kHz C) Plot of phase histograms as a function of gate voltage. The position of the peaks trace the phase as a function of gate voltage for an SCB with and without an extra quasiparticle. White curves are theoretical estimates of quantum capacitance.

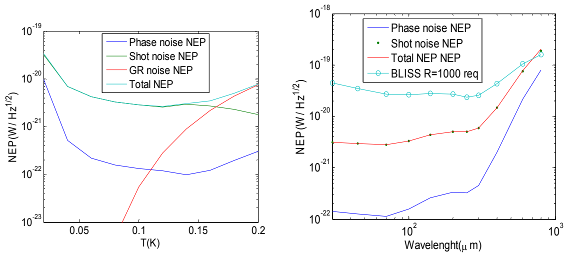

Figure 3. Left: NEPs from various noise sources calculated for devices optimized for BLISS (with 100μm loading, R=1000) as a function of temperature. Right: NEPs of various noise sources as a function of wavelength as compared to the requirements for a BLISS type spectrometer with R=1000 . The operating temperature was chosen to be 0.08K.

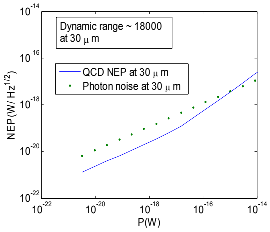

Figure 4. NEP of QCD detector as a function of loading power at 30μm as compared with the photon noise at the same wavelength. We define the saturation as the power at which the NEP becomes equal to the photon noise. The dynamic range is the ratio between the saturation power and the BLISS loading at that wavelength. The dynamic range at 30 μm is over 18000. Note that the detector still works for powers above the saturation, except that it will add noise over the photon noise.

Wavelenght(μm)	Loading (10^{-19}W)	Required NEP (10^{-20}W/Hz$^{1/2}$)	QCD NEP (10^{-21}W/Hz$^{1/2}$)	Saturation power(10^{-17}W)	Dynamic Range
30	1.62	4.51	3.13	300	18552
45	1.46	3.51	2.96	200	13661
70	1.34	2.69	2.83	100	7477
100	1.81	2.62	3.32	60.0	3314
140	2.94	2.81	4.37	43	1463
200	3.78	2.67	5.07	25.4	674
250	3.64	2.35	4.96	24.2	667
300	4.97	2.53	5.97	15.0	302
400	19.5	4.38	14.9	7.83	40
600	165	10.36	78.4	5.22	3
800	540	16.13	204	2.63	0.5

Table 1. Summary of predicted performance of QCD detector under loading conditions appropriate to BLISS

In conclusion, we proposed here a new type of Pair-Breaking detector with readout based on the Quantum Capacitor of a Single Cooper Pair Box. We present measurement of quasiparticle tunneling rates on SCBs that provide input to our model predicting the performance of the detector. We predict this detector will fulfill the stringent requirements of future Far Infrared missions using cold telescopes in space.

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