Progress in the development of a 5x5 array of Quantum Capacitance Detectors for far-infrared radiation

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Electron Beam Lithography by
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Single Cooper-Pair Box

Electrostatic gate charge

\[ n_G = \frac{C_G V_G}{2e} \]

Charging energy

\[ E_C = \frac{e^2}{2C_\Sigma} \]

Josephson coupling

\[ E_J = E_{j\text{max}} \cos \left( \frac{\pi \Phi}{\Phi_o} \right) \]

\[ H = 4E_C \sum_n (n-n_G)^2 |n\rangle\langle n| - \frac{E_J}{2} \sum_n (|n+1\rangle\langle n| + |n\rangle\langle n+1|) \]
Energy levels, Coulomb Staircase and Quantum Capacitance

- In the absence of Josephson coupling, Energy is given by parabolas centered at integer values of Cooper Pair Charge
  \[ E = (Q - 2ne)^2 = (C_g V_g - 2ne)^2 \]

- As the gate voltage is increased, Cooper Pairs tunnel to minimize the energy and the charge on the island changes in a stepwise fashion

- The capacitance of the island \[ C_Q = 2e \frac{d\langle n \rangle}{dV_g} \] has peaks at the degeneracy points where the charge in the island is changing fast

- The Josephson Coupling introduces splittings in the energy levels

- Eigenvectors are symmetrical and anti-symmetrical combinations of the charge states

- The larger \( E_j \), the “rounder” the charge staircase and the smaller the capacitance peaks

- In the absence of tunneling, only one parabola would exist (n=0) and the capacitance would be constant as a function of the gate voltage

- The variable capacitance is due to the quantum nature of the system and is called the quantum capacitance
• If there are quasiparticles present in the leads, they could tunnel in and out of the island

• When they tunnel, they shift the effective gate voltage by $e/C_g$ (or $n_g=0.5$)

• Coulomb staircase and quantum capacitance curve shifts by $n_g=0.5$ each time a quasiparticle tunnels in or out.
The Quantum Capacitance Detector

- Radiation coupled by an antenna breaks Cooper pairs in the reservoir (absorber)
- Quasiparticles tunnel onto the island with a rate $\Gamma_{\text{in}}$ proportional to the quasiparticle density in the reservoir
- Quasiparticles tunnel out of the island with a rate $\Gamma_{\text{out}}$ 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 $P_0(N_{qp}) = \frac{\Gamma_{\text{in}}}{\Gamma_{\text{in}} + \Gamma_{\text{out}}}$
- The resulting change in the average capacitance will be $C_Q = \frac{(4E_c/E_J)(C_g^2/C_2)P_0(N_{qp})}{(\omega_0Z_0C_e^2)}$
- This change in capacitance will produce a phase shift $\delta\Phi \approx 2C_Q / (\omega_0Z_0C_e^2)$
Measurement Technique

- λ/2 resonator capacitively coupled to a feedline
- SCB is the variable capacitor at the end of resonator
- Change in resonance frequency due to change in quantum capacitance should be large (1MHz)
- Single pixel resonator (green dots)
- Resonance frequency = 3.328118 GHz
- Qi = 220000; Qc= 360000; Qt=136000
Simulated response

- SCB capacitance x gate voltage (in units of Cooper Pair charge) for different coupled optical signal power
Simulated response

- transmission through feedline x gate voltage (in units of Cooper Pair charge) for different coupled optical signal power
Simulated response

- amplitude of transmission peak as a function of signal power

![Graph showing the amplitude of transmission peak as a function of signal power.](image-url)
Simulated response

- responsivity as a function of signal power
Left: NEPs from various noise sources calculated for devices optimized for $\lambda = 100\mu$m, optical loading $10^{-19}$ W and 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 spectrometer with R=1000 and the expected optical loading at L2 for a cold (4.2K) telescope. The operating temperature was chosen to be 0.1K at which the GR noise contribution is negligible.
Theoretical Sensitivity vs. Signal Power

- Detector is background limited over a wide range of operation
QCD 25 pixel array
Only one pixel illuminated
SEM pictures

- Nb $\lambda/2$ resonator, Au antenna with Al absorber with Nb plug for quasiparticle trapping
  - SCB - Al/AlOx/Al
Optical characterization

- Blackbody source
- Aperture
  - 2 mm diameter
- 1.5 THz band pass filter
  - 10% band
- 3 THz low pass filter
- HDPE lens
- Silicon lens
- Sample

Legend:
- 4K
- Still Temp.
- MC Temp.
Antenna design

• Double-dipole antenna

• Frequency = 1.5THz \ (\lambda = 200\mu m)
Antenna design

- Resonance @ 1.5 THz
- 30% bandwidth
- $Z = 32\Omega$
Quantum Capacitance signal $\times$ optical power

![Graph showing quantum capacitance signal multiplied by optical power at different optical powers (3 pW, 0.7 pW, 30 fW, 5 fW, 0.4 fW, 4 aW) as a function of gate voltage.]
• Applied ramp with amplitude such that 10 peaks were visible
• Ramp frequency 100Hz
• Signal on spectrum analyzer had peak at 1kHz
• Measured amplitude of 1kHz peak as a function of black body power
Quadrature signal response

- Plotted amplitude of 1kHz peak as a function of power
- Fit response with empirical formula (green line)
Quadrature signal response

- Calculated responsivity from response fit and from data points
Quadrature signal response

- Calculated NEP from responsivity and noise
NEP x power

- NEP 6\times10^{-18} W/Hz^{1/2} at the lowest power 3\times10^{-18} W
• Applied ramp with amplitude such as 10 peaks were visible
• Ramp frequency 100Hz
• Signal on spectrum analyzer had peak at 1kHz
• Measured amplitude of 1kHz peak using lock-in amplifier
• Took data passively while cooling and warming black-body
• Fit response with empirical formula (green line)
Responsivity (dV/dP)

- Took the derivative of fitted response with respect to signal Power (green line)
- Dots are responsivity just taking the derivative of data points
Measured noise and response peak
Noise equivalent power – noise averaged between 920 and 980 Hz
Conclusion

- Achieved NEP $3 \times 10^{-18}$ W/Hz$^{1/2}$ at 1aW
- Actual NEP might be lower, since it depends on the power reaching the device. Any (likely) misalignment would entail a lower power than calculated and hence a lower NEP.
- Resonance peaks should be deeper (as they were in single pixel design)
- Working on resolving this issue
- Should gain an instant factor of 12 when resonance is ideal
- New Si lenses to illuminate 4 pixels
- Working on Fresnel lenses to illuminate all pixels