Chapter 1

Background

Cryogenic detectors for photon detection have applications in astronomy, cosmology, particle physics, climate science, chemistry, security and more. In the infrared and submillimeter wavelengths, the most widely used sensor type is the bolometer, which employs a very sensitive thermometer to measure small temperature changes on a thermally isolated absorber. Over the past decade, however, interest has grown in superconducting microresonators for use as photon detectors because of their simplicity and potential to be multiplexed in large arrays. I have investigated and characterized a novel prototype device which incorporates elements of both bolometers and superconducting microresonators in its design. This resonator bolometer takes advantage of the scalability offered by the use of superconducting microresonator technology along with the versatility offered by the use of a thermally insulated island. Because of its unique potential, the resonator bolometer is proving promising for many different science applications. In order to discuss these further it will be necessary to first outline the basic operating principles of bolometer-based detectors and superconducting microresonators.

1.1 Introduction to bolometers

The bolometer concept is ubiquitous in infrared sensor design. The basic setup consists of an absorbing element with heat capacity C which is attached to a heat sink by thin legs which have a combined thermal conductance G (Fig. 1.1). The heat sink is well thermally sunk so as to maintain a constant base temperature from which the isolated absorbing element's temperature will deviate. When a power source P is turned on, the absorbing element's temperature rises to a limiting value of $T_{\mathrm{sink}} + P/G$ with time constant $\tau_{\mathrm{th}} = C/G$. A thermometer placed on the island measures this change. When the power source is turned off, the island temperature decays to the bath temperature with the same time constant.

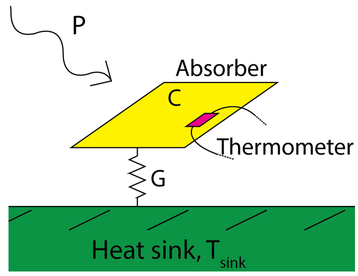


Figure 1.1: Schematic diagram of a bolometer pixel. A thermometer measures the temperature change associated with a change in incident power P on the absorber with heat capacity C. Heat escapes to the substrate via thin legs with combined thermal conductance G.

1.1.1 Bolometer modeling

The quantities C, G and the noise equivalent power in a bolometer may be calculated in terms of fundamental dimensions and properties of the device. The heat capacity of a slab of material of mass m, density ρ and specific heat c is given by

$$C = \frac{mc}{\rho}.$$

The thermal conductance of a wire with length l, cross-sectional area A and resistivity ρ is given by

$$G = \frac{\rho A}{l}.$$

Quantized fluctuations in the thermal energy flowing across the legs introduce phonon noise. The phonon noise contribution to the noise equivalent power is given by

$$\mathrm{NEP}_{\mathrm{phonon}} = \sqrt{4kT^2G}$$

in units of $\mathrm{W}/\sqrt{\mathrm{Hz}}$ [13].

1.2 Introduction to superconducting microresonators

Superconducting microresonators are of interest for use in sensitive photon detection [5], direct detection of dark matter [12] and quantum information experiments [14] among other applications [15]. Their simple fabrication process, involving a single deposition of a patterned superconducting film on an insulator substrate, and natural frequency domain multiplexing make them attractive candidates for large scale ($\sim 10^6$ pixel) arrays.

1.2.1 Microresonator electrodynamics

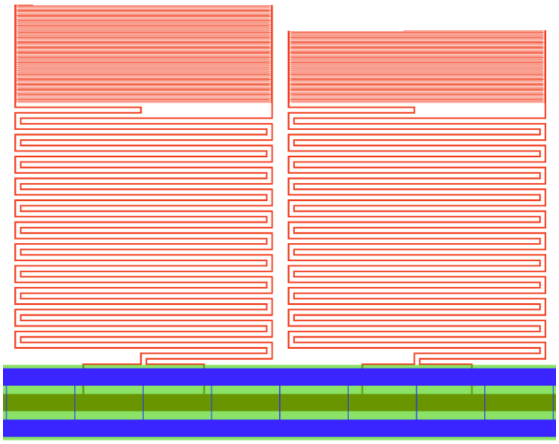
True to their name superconducting microresonators have zero resistance for direct currents when cooled below their superconducting transition temperature T_c. This supercurrent is carried by pairs of electrons, called Cooper pairs, with binding energy $2\Delta \approx 3.5 k_B T_c$ for $T \ll T_c$ [2]. However, for alternating currents energy may be stored as kinetic energy in the Cooper pairs and may be recovered without loss by reversing the electric field. Thin (10s to 100s of nanometers) superconducting films additionally permit energy to be transferred between Cooper pair motion and the magnetic field, since magnetic fields penetrate below the surface of superconductors a distance λ, called the London penetration depth, which is typically of order the thickness of the film. This reactive energy flow results in a surface kinetic inductance $L_s = \mu_0 \lambda$.

Additionally a dissipative component to the conductivity is present due to the small fraction of electrons not bound up in Cooper pairs, called quasiparticles, which behave as normal electrons (i.e. they do not carry the supercurrent). The presence of quasiparticles and the finite inertia of the Cooper pairs result in a complex conductivity $\sigma(\omega) = \sigma_1(\omega) - i\sigma_2(\omega)$ as described by the Mattis-Bardeen theory [10]. Any energy input $E > 2\Delta$ which breaks a Cooper pair into quasiparticles will introduce a corresponding perturbation in the complex conductivity $\delta\sigma$. This perturbation may be measured very precisely by constructing a resonant circuit.

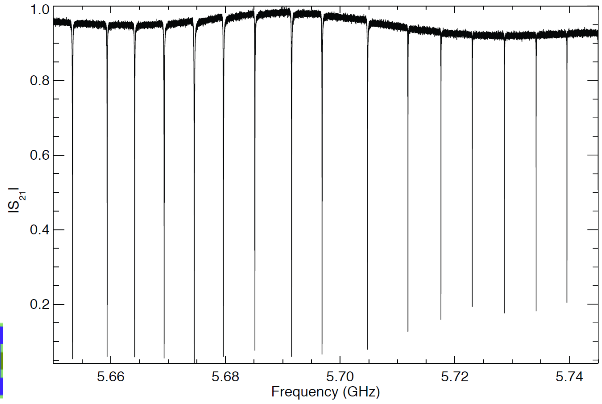
1.2.2 Principles of operation

Superconducting microresonator detectors are typically either a quarter-wave transmission line resonator or a lumped-element circuit. A single coplanar waveguide (CPW) transmission line is coupled to every pixel in the array. The superconducting material is carefully chosen so that the resonators exhibit very low loss in each oscillation; quality factors of $Q \sim 10^5$ are readily obtainable. Since the device studied in this paper utilizes the lumped-element pixels, I will focus my discussion on that design. A lumped-element pixel consists of a capacitor and inductor in series which are capacitively coupled to the transmission line (Fig. 1.2a). By varying the capacitor area, the capacitance and thus the characteristic resonant frequency of the pixel may be varied in a controlled manner according to $\omega = (LC)^{-1/2}$.

When sufficient energy is absorbed by the resonator, the resistance and reactance change according to the change in conductivity $\delta\sigma$ as described above. By varying the frequency of the current on the feedline and thus sampling many points near and within the resonance, the dissipation and phase changes may be quantified and the original absorbed energy determined. Because the phase and dissipation directions are orthogonal, one can use one or the other or both to determine the optical signal change.



(a) Lumped-element pixels (Image courtesy of C. McKenney)



(b) Sample normalized signal amplitude readout

Figure 1.2: (a) An example of the lumped-element design. The interdigitated capacitor, top, can be varied in size to control the resonant frequency of the pixel. In the center, the meandered inductor, which acts as the photon absorber, takes up most of the pixel area. The coplanar waveguide, along which the microwave signal travels, is visible at the bottom. (b) Signal transmission vs. frequency using standard scattering matrix notation. Each dip in transmission indicates attenuation from a resonant pixel coupled to the transmission line.

1.2.3 Frequency multiplexing

By tuning each pixel to a different resonant frequency, multiple pixels may be read out simply by varying the AC frequency on the feedline (Fig. 1.2b). Only this single feedline is required to read out the entire array. Pixels may be engineered to be closely spaced in frequency, in principle allowing hundreds to thousands of pixels coupled to a single feedline. Furthermore, the readout technology required for such large arrays already exists. One example is the CASPER ROACH processing board shown in Fig. 1.3 [4]. One system is currently being used to read out the 32 x 32 pixel ARray Camera for Optical to Near-infrared Spectrophotometry (ARCONS) [11].

1.2.4 Photon absorption

Most often either direct radiation coupling or an antenna structure which focuses radiation to the sensitive part of the resonator is used to absorb photons. In the direct detection case, the inductor serves as the photon-sensitive area, and absorbed photons directly break Cooper pairs and thus modify the inductance and resistance. For wavelengths $\lambda \gg s$, the spacing between lines of the inductor, the absorbing area acts as a sheet resistance, whose value depends on the fraction of the pixel area covered by superconducting film. The array is back-illuminated, with light first passing through the silicon substrate before contacting a pixel, for better impedance matching between the pixels and free space.

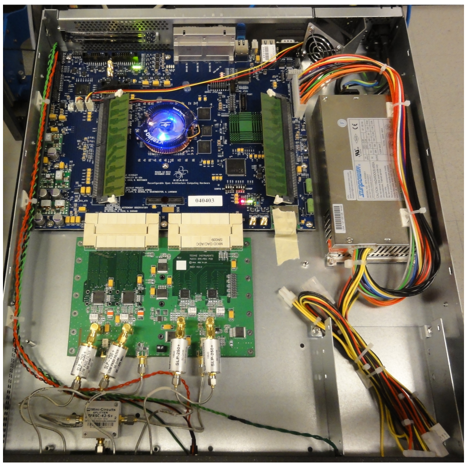


Figure 1.3: A Reconfigurable Open Architecture Computing Hardware (ROACH) board used to read out large superconducting microresonator arrays.

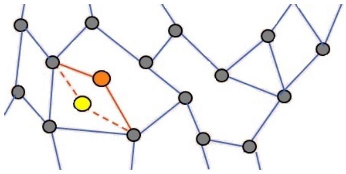


Figure 1.4: Two level systems, in which an atom may quantum tunnel between two local minima in potential energy, are hosted in a thin amorphous surface layer on the crystalline substrate. They introduce excess noise in the position of the resonant frequency in a resonant circuit.

1.2.5 Two level systems

In practice, superconducting microresonators exhibit excess noise in the frequency (phase) direction not predicted by superconductivity theory. This noise arises from the presence of an amorphous surface layer on the crystalline substrate on which the superconducting material is deposited. This layer appears when the atoms on the surface of the crystal contact air and form bonds with molecules in the air. Because of irregularities in the structure of this surface layer, under the presence of a strong electric field an atom or group of atoms may quantum tunnel from one local minimum in potential energy to another (Fig. 1.4). The moving atoms carry a dipole moment so that these two level systems (TLS) contribute randomly to the dielectric constant of the capacitor in the resonant circuit and thus the capacitance and the resonant frequency. While a microscopic theory of the noise introduced by TLS does not yet exist, the effect is well-documented in experiments [3, 5, 8] and a semi-empirical model has been developed by Gao et. al. [7]. This model may be used to design devices which minimize the TLS noise.

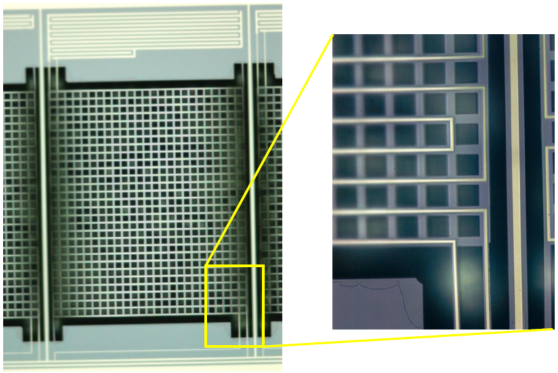
1.3 The resonator bolometer

Superconducting microresonators are revolutionary devices but they do not come without limitations. They must operate at temperatures $T \ll T_c$, where the surface inductance dominates. To operate in the 1 - 4K temperature range, desirable for its simple cooling requirements compared to sub-Kelvin temperatures, superconductors with $T_c \sim 15K$ must be used. However, superconductors with such high transition temperatures have short quasiparticle lifetimes [9]. The quasiparticle lifetime, or the time it takes for quasiparticles to recombine once formed, limits the sensitivity of a detector. For constant illumination, a shorter lifetime implies fewer quasiparticles at a given time and thus a smaller signal. Thus microresonators must operate at sub-Kelvin temperatures to remain sensitive.

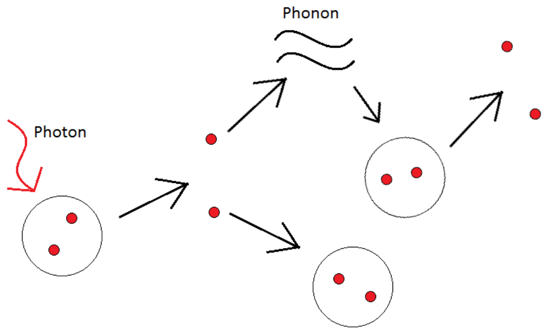
Along with my collaborators at Caltech and NASA's Jet Propulsion Laboratory I have investigated placing the sensitive portion of the resonator on a thermally insulated island as a way to circumvent this obstacle. In the resonator bolometer, the inductor is placed on the bolometer island, where it acts as both the photon absorber and the thermometer measuring the energy trapped on the island. The rest of the circuit is deposited directly onto the substrate (Fig. 1.5a). This design effectively extends the quasiparticle lifetime because thermal energy released from the recombination of a pair of quasiparticles is trapped on the island, where it may break another Cooper pair (Fig. 1.5b). The magnitude of the signal is thus governed by heat flow from the bolometer island legs to the substrate instead of by the quasiparticle recombination time. In contrast, in a superconducting film deposited directly on the substrate, the emitted thermal energy, or phonon, simply escapes to the substrate, and only incident photons break Cooper pairs.

The resonator bolometer design thus allows for a broad class of superconducting materials to be used in fabrication. It additionally enables a straightforward decoupling of the meander from photon detection; a separate absorber could easily be placed on a bolometer island with a resonator inductor, with the resonator detecting the thermal energy produced by this absorber.

This design has many potential science applications. The ability to operate at temperatures above 1K makes the resonator bolometer attractive for space-based instrumentation because of the greatly simplified cryogenic setup. It is especially suitable for high-background applications such as Earth observation in the far-infrared because of the tunability of the dynamic range enabled by the use of high-T_c superconductors. The investigation into the viability of the bolometric island as a coupling mechanism is important for further development of superconducting microresonator-based designs for gamma ray, X-ray and particle detectors.



(a) Resonator bolometer pixel



(b) Energy recycling in a resonator bolometer pixel

Figure 1.5: (a) A resonator bolometer pixel. The inductor is on a wire mesh grid released from the substrate and connected to it via six legs (see closeup). The capacitor (top) and the CPW (bottom) are both directly on the substrate. (b) Energy recycling in a resonator bolometer pixel. An incident photon breaks a Cooper pair into its constituent quasiparticles, which quickly recombine. The energy from recombination is emitted as a phonon. Since the phonon is trapped on the isolated island, it is available to break another Cooper pair. Overall, a given input power causes more quasiparticles to exist at a given time than if the sensitive portion of the pixel were not thermally isolated, so that the signal is larger.

1.3.1 Fabrication

In order to begin investigating the feasibility of the resonator bolometer concept, a prototype array was fabricated at NASA's Jet Propulsion Laboratory (Fig. 1.6). This array consists of a single row of 16 pixels in two frequency bands. The chosen superconducting material is NbTiN, with a T_c of approximately 14 K. The NbTiN was deposited and patterned on a layer of silicon nitride on the silicon substrate. Next, trenches in the silicon were etched to isolate neighboring pixels. Finally, the silicon was etched away from underneath the grid mesh to suspend the inductors and thus thermally isolate them.

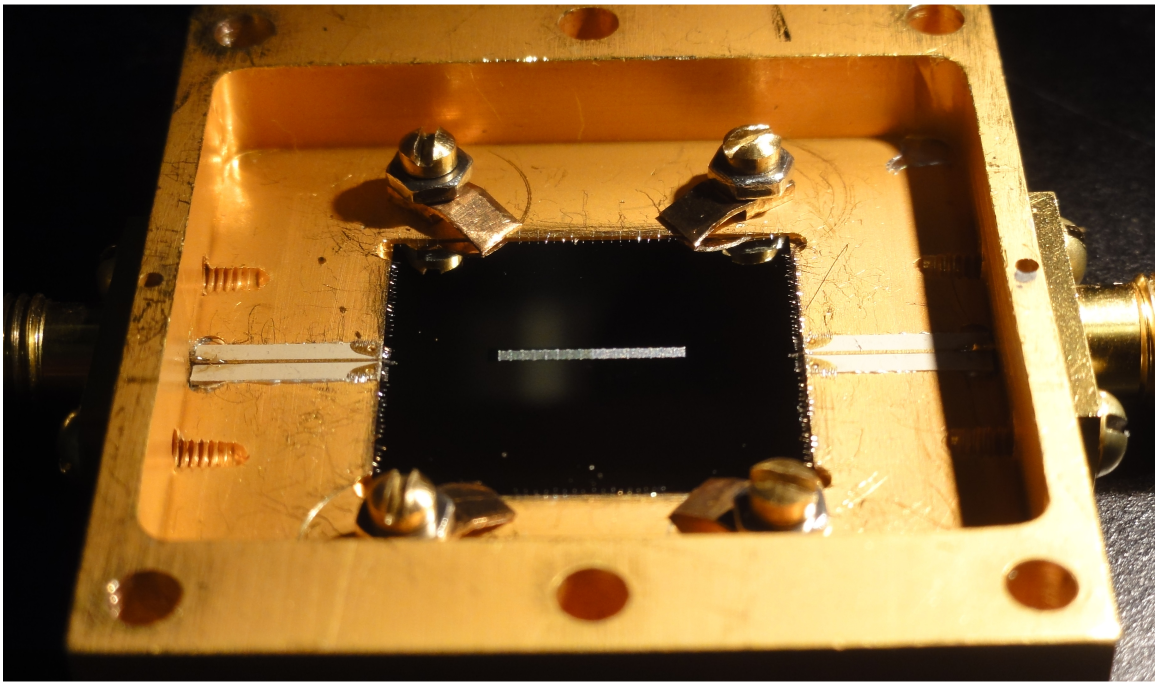


Figure 1.6: The prototype resonator bolometer array studied. The 16 pixels in a row in the center of the substrate are read out by a single transmission line, visible to the left and right of the substrate. The substrate itself is well thermally sunk by multiple wire bonds around its edges.