Thermal Kinetic Inductance Detectors for Ground-Based Millimeter-Wave Cosmology

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Received: 6 November 2017 / Accepted: 25 June 2018 / Published online: 2 July 2018
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Abstract
We show measurements of thermal kinetic inductance detectors (TKIDs) intended for millimeter-wave cosmology in the 200–300 GHz atmospheric window. The TKID is a type of bolometer which uses the kinetic inductance of a superconducting resonator to measure the temperature of the thermally isolated bolometer island. We measure bolometer thermal conductance, time constant, and noise equivalent power. We also measure the quality factor of our resonators as the bath temperature varies to show they are limited by effects consistent with coupling to two-level systems.

Keywords TKID · Thermal kinetic inductance detector · Resonator bolometer · CMB · Cosmic microwave background · TLS · Two-level systems

1 Introduction
Measurements of the cosmic microwave background (CMB) polarization in search of a gravitational wave signal from an epoch of inflation are limited by a foreground of galactic dust [1]. Improving constraints on $r$, the tensor-to-scalar ratio, hinges on imaging galactic dust in the 200–300 GHz atmospheric window, where the brightness of dust relative to the CMB is enhanced relative to 95 or 150 GHz [2]. In this paper, we explore the thermal kinetic inductance detector (TKID) as a path to fill a 200–300 GHz focal plane, inspired by detector developments for X-ray spectroscopy [3–7]. TKIDs are bolometers whose thermometer exploits the temperature dependence of the kinetic inductance effect. As in a direct absorber kinetic inductance detector (KID) [8–10], the resonant frequency of an LC resonator shifts in response to the quasiparticle density in a superconducting inductor. However, in a TKID, rather than directly breaking pairs, photons are absorbed on a suspended island shared by the inductor and quasiparticles.
are produced thermally. Like KIDs, TKIDs can be frequency multiplexed by assigning each detector a different resonant frequency and weakly coupling the resonators to a shared readout transmission line.

The potential advantage of TKIDs is engineering freedom. In a KID, the function of electromagnetic absorption, conduction of optical power out of the detector and to the bath, and low-frequency readout are performed by the kinetic inductor which must be simultaneously optimized for all three functions. In a TKID, these functions can be separated into a load resistor, a silicon nitride membrane, and superconducting inductor, which can be independently optimized, at the cost of a many-layer fabrication process. Fortunately, the complexity of developing a new many-layer fabrication process can be mitigated by adapting a mature transition edge sensor (TES) process, such as the JPL process used for the Keck/BICEP detectors [11].

2 Methods

We fabricated a test chip to study the suitability of TKIDs for ground-based observations. Images of the mask and fabricated device are shown in Fig. 1. The test chip contains 5 TKIDs, one with an unreleased bolometer, and four with bolometer leg lengths 100, 200, 300, and 400 µm. The bolometer geometry is based on the design used for the Keck/BICEP program, which uses six parallel legs to mechanically suspend and thermally isolate a silicon nitride island [12]. To facilitate step coverage, the mechanical substrate of the bolometer island, low-stress silicon nitride, is 1/3 the thickness of that used for the Keck/BICEP TES bolometers, so we fabricated multiple leg lengths to measure the thermal conductivity (G) as a function of leg length for the thinner silicon nitride. The temperature sensing inductor on the island is a 16-mm-long, 1-µm-wide meandering trace of 50-nm-thick aluminum. On the island, niobium traces contact the inductor leads and run off along the island legs to an inter-

![Fig. 1](Image) Photograph of one bolometer island, showing the meandered aluminum inductor on the left and the gold heater resistor on a niobium washer on the right. Color banding around the bolometer release holes suggests the oxide etch stop has been consumed and up to ≈ 100 nm of the silicon nitride etched by the xenon difluoride (Color figure online)
digitated resonator capacitor. The silicon nitride layer under and around the capacitor is removed so that the resonator capacitor is deposited directly on the silicon wafer. To vary the resonant frequencies from 260 to 315 MHz, the number of fingers in the resonator capacitors is varied.

The resonators are weakly coupled to a readout transmission line through a second small interdigitated capacitor on one side of the resonator, and through the parallel plate capacitance of the resonator to the ground of the chip holder to complete the circuit. The parallel plate capacitance to ground acts on both sides of the resonator, and on the coupling capacitor side it acts to weaken the coupling. This was not accounted for in the design, so the devices are more weakly coupled than intended with coupling $Q_c = 80,000-140,000$ rather than $20,000$.

Rather than integrating an antenna directly into this chip, power is deposited onto the bolometer island via a resistive heater and DC current source. This calibrates the leg thermal conductivity and detector noise directly in units of watts. On the tested chip, two released bolometers (100 and 400 $\mu$m legs) and the unreleased bolometer were fully functional. Of the remaining two bolometers, one resonator was broken and one heater was left disconnected from the cryostat wiring.

The devices were fabricated on a high-resistivity silicon substrate $\approx 500 \mu$m thick. A 40-nm silicon dioxide film and 300-nm low-stress silicon nitride film are deposited on top of the wafer, which form the membrane layer. E-beam evaporated liftoff aluminum 50 nm for the inductor is deposited on top of this. The gold resistor layer is 200 nm thick, e-beam evaporated, and patterned with liftoff. Next, the silicon nitride and silicon dioxide are etched to expose silicon and define the island and the region where the capacitor will be deposited. The niobium layer for the capacitor and wiring is 400 nm thick and patterned with liftoff. Finally, holes in the island are drilled by deep reactive ion etching and the island released with xenon difluoride.

3 Results

The film properties of the aluminum are measured via a test structure on one side of the chip consisting of niobium leads running to an aluminum inductor identical to the inductor on the bolometer islands. The transition temperature of the aluminum film is 1.32 K and the sheet resistance is 0.23 $\Omega/\Box$, which implies a thin-film Mattis–Bardeen kinetic inductance of 0.24 pH/$\Box$ [13]. The niobium to aluminum contact is zero resistance up to the critical current of $\approx 100 \mu$A.

To measure the bolometer thermal conductance to the bath, the resonator is first calibrated by sweeping the bath temperature, while measuring the resonant frequency with a small readout excitation of $-110$ dBm (0.01 pW). Then, the bath is returned to base temperature and the island heater power is swept while measuring the resonant frequency to measure the island temperature. The measured conductances are 26 and 64 pW/K for the 400- and 100-μm detectors, respectively, at an island temperature of 0.38 K. 0.38 K operating temperature compromises between quality factor ($Q_{i,MB} \approx 10^4$) and noise equivalent power (NEP) in an ideal aluminum TKID.

To measure the responsivity as a function of frequency of the 400-μm leg bolometer, a function generator supplied a DC offset and a sine wave chirp with a logarithmic
sweep in frequency to the island heater. The frequency of the resonator was monitored using the technique described in Sect. 3.2. The power spectrum of the response is shown in Fig. 2. The response is a good fit to a one pole model with 3 dB frequency 28.6 Hz or a heat capacity of 0.14 pJ/K.

### 3.1 TLS

The power and temperature dependence of the resonator quality factors show substantial loss consistent with the behavior of two-level systems (TLS). We follow standard methods to model the resonator and the temperature and power dependence of TLS [9,14,15]. A model for $S_{21}$ of a resonator is fit to extract the resonator quality factor $Q_r$ and complex coupling quality factor $Q_e$. The internal resonator quality factor is estimated by $Q_i^{-1} = Q_r^{-1} - \text{Re}Q_e^{-1}$. The internal quality factors are then fit to a sum of contributions from TLS (Eq. 1), Mattis–Bardeen quasiparticles from the measured $T_c$, and a constant $Q_i$ for loss due to other sources. Power dependence is captured by the terms $P_g$, the generator power, and $P_c$, the generator power above which TLS is saturated.

$$Q_{TLS} = Q_{TLS_0} \sqrt{1 + \frac{P_c}{P_g}} \frac{h f}{2 k T} \tanh \left( \frac{h f}{2 k T} \right)$$

As shown in Fig. 3, $Q_i$ is strongly limited by a TLS consistent loss where $Q_i$ increases with power and temperature. The limiting performance in the unreleased devices may be due to side wall coating during the niobium liftoff step, visible as flags of metal, or resist along the lines of the capacitor. Subsequent unreleased devices fabricated using etch-back to pattern the niobium capacitor show low temperature and power $Q_i > 60,000$.

The released devices show much lower $Q_i$. We are currently considering two possibilities. Chemical damage is one possibility, as the long distance ($\approx 100 \mu m$) between release hole and edge of the island necessitated a long exposure to xenon difluoride (15 pulses, 45 s/pulse, 3 torr). The island can be reengineered to reduce this distance to 15 $\mu m$. A second possibility is mechanical damage due to stress on the island during and after the release process.
3.2 Noise

To characterize NEP, the resonator frequency is tracked by continuous network analysis. Once per millisecond, a chirp generated by a software radio sweeps in frequency across a 1 MHz bandwidth centered on the resonant frequency of one detector, from high to low frequency. A 1 ms chirp is slow compared to the time constant of the resonator ($\approx 10 \mu s$) but fast compared to the time constant of the island ($\approx 5 \text{ ms}$). The ratio of the Fourier transforms of the received signal and input chirp is proportional to the transfer function $S_{21}$. The position of the resonance in each transfer function sweep is fit to produce a resonator frequency timesstream sampled at 1 kHz. Fluctuations in gain and phase of the readout are removed by fitting a baseline of the transfer function away from the resonance. The wide bandwidth of the sweep compared to a single tone readout allows the resonator to be tracked across large temperature changes corresponding to frequency shifts of many resonance widths.

We find this a practical technique for reading out and characterizing single resonators, but for chirp rates slow compared to the resonator ring down time, a time multiplexing penalty makes it impractical for large numbers of resonators. An example of the continuous network analysis from the chirp readout scheme is shown in the left panel of Fig. 4. To measure the NEP of the detector, the resonator frequency is monitored while calibrating resonator frequency into power by applying a sine wave of known frequency and power to the island heater. The resulting noise power spectrum is shown in the right panel of Fig. 4 and reaches $\approx 200 \text{ aW/}\sqrt{\text{Hz}}$. This is a few times the single-mode photon noise under the South Pole atmosphere, and an order of magnitude larger than the phonon noise expected for the 0.38 K island temperature.

4 Discussion

The noise of the resonators in excess of the expected phonon and readout noise has many possible sources. The presence of the 35 Hz line consistent with the pulse tube
motor stepping frequency suggests there is electrical interference from the pulse width modulated driver reaching the TKIDs. This is potentially broadband and could be raising the entire noise floor, which we will test in the future by replacing the pulse width modulated stepper motor driver with a linear driver. Other possible external sources of noise include the magnetic environment [16] and the infrared environment [17], which we can test by improving the magnetic and radiation shielding around the chip holder. TLS noise may also contribute to the noise floor, but the magnitude is likely separable from environmental effects through a lack of resonator–resonator correlations.

We view these detectors as a promising avenue for millimeter-wave detectors, with many aspects remaining to be studied before they are suitable for deployment in a telescope. We intend to optically couple the detectors with antenna arrays, such that the aluminum inductor will be exposed to millimeter-wave radiation, and could potentially directly absorb power not processed by the antenna and band-pass filter. Simple estimates based on the area of the inductor suggest this will be comparable to that experienced by antenna-coupled TES detectors. We plan to measure this direct stimulation after integrating antennas into a future iteration of the TKID chip.

Acknowledgements This work was supported by JPL’s Research and Technology Development Fund for Projects R.17.223.057 and R.17.223.058.

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