Measurements of Bolometer Uniformity for Feedhorn Coupled TES Polarimeters


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Abstract.

We are developing feedhorn-coupled TES polarimeters to measure the polarization anisotropies of the Cosmic Microwave Background (CMB) radiation. These devices will be deployed in arrays of hundreds to thousands and will be measured using multiplexed SQUID readout electronics. Since multiplexed devices share common circuitry, a high degree of uniformity is required in the electro-thermal properties of the TES bolometers and readout circuits in order to simultaneously operate all channels with high sensitivity. Our cryogenic test bed can probe dozens of devices simultaneously, thus providing useful detector statistics on relatively short time scales. We describe the TES bolometer design and present dark (no optical loading) measurements of the electrical and thermal properties and uniformity of prototype bolometers across two 3-inch diameter production wafers, including (wafer uniformity in parentheses): TES transition temperature (standard deviation ∼ 1%), normal resistance (∼ 10%), thermal conductance (∼ 10%), time constant (∼ 20%), shunt resistance (∼ 5%), and noise properties.

Keywords: TES, bolometer, polarimeter, detector array, cosmology

INTRODUCTION

Polarization in the Cosmic Microwave Background (CMB) radiation is predicted to contain the subtle signature of an early period of inflationary growth in the Universe. Measurement of this signal would yield fundamental new insights into our understanding of the universe. However, in order to measure this faint signal – fluctuations of order $10^{-7}$ K [1] – arrays of hundreds to thousands of CMB polarimeter detectors will be needed. Focal plane array development has risen to meet this goal, advancing from focal planes consisting of a handful of detectors merely a decade ago to fielded (non-polarization sensitive) arrays of 960 detectors on the South Pole Telescope (SPT) [2] and three 1024 detector arrays on the Atacama Cosmology Telescope (ACT) [3]. Now a variety of technologies are under development to produce CMB polarimeter arrays for these and other telescope platforms [4].

One challenge in scaling detector arrays to these sizes is ensuring uniformity of the transition-edge sensor (TES) bolometer electro-thermal properties over the array with high yield. Bolometer homogeneity is critical for several reasons. Multiplexed readout of large arrays requires uniformity to simultaneously achieve optimal sensitivity on all detectors. In addition, only small margins are acceptable in detector electro-thermal properties to make them photon-noise limited since they are tuned for observing under the particular optical loading and thermal conditions of the experiment. Finally, uniform detector properties eliminate the need to individually tune bolometers and reduce the complexity of data excision during analysis, saving time and reducing errors during observing and analysis.

We have built a cryogenic test bed with which we have simultaneously measured the electro-thermal properties of dozens of detectors from two separate fabrication runs of prototype detectors on 3-inch silicon wafers (named CMB4 and CMB5). We measured and statistically characterized the uniformity of TES transition temperature $T_c$, normal resistance $R_n$, thermal conductance $G$, thermal time constant $\tau$, shunt resistance $R_{shunt}$, and noise properties. These results are presented below.
POLARIMETER AND TESTBED REVIEW

The polarimeter design and additional testing results are described in detail in other contributions to these proceedings [5, 6, 7, 8]. Here we provide a brief overview of the design. The optical beam of the polarimeters is defined by corrugated feedhorns. Corrugated gold-plated silicon platelet feedhorn arrays are being developed at NIST for integrating the polarimeters into monolithic silicon focal planes [10]. Waveguide feeds the radiation to a planar ortho-mode transducer (OMT) [6] that separates the radiation into orthogonal polarizations and couples it through a series of micro-strip quarter-wave stub filters that define the observation bandpass [8]. The micro-strip carries the radiation onto a TES bolometer island, where it transitions from superconducting into a lossy gold meander, which dissipates the radiation into heat measured by the TES. Each polarimeter currently comprises a total of three TES bolometers: one for each polarization and one dark (no optical coupling) for characterization and control of systematics.

Dark testing and statistical tests of prototype devices have been conducted in a large general-purpose cryogenic testbed at CU-Boulder. Sub-Kelvin refrigeration is provided by an adiabatic demagnetization refrigerator (ADR), which allows for a stable bath temperature ($T_{\text{bath}}$) down to $\sim 60$ mK. The polarimeters are magnetically shielded by single layers of Cryoperm™ [9] and superconducting niobium that attenuate and block DC and AC magnetic fields. Each bolometer electrical circuit consists of the TES, a shunt resistor to provide a voltage bias, an anti-aliasing Nyquist inductor, and a superconducting quantum interface device (SQUID) for coupling the bolometer signal (electrical current) to the readout electronics (all electrical components are fabricated at NIST). Currently, up to 128 bolometer signals can be measured simultaneously using a three-stage SQUID time-division multiplexing (TDM) system developed at NIST [11]. This CU testbed will be modified to incorporate an additional frequency-domain multiplexing (FDM) system [12] and will be opened for full optical testing of polarimeter arrays in the near future.

TES CHARACTERIZATION AND STATISTICS

The devices are currently fabricated as a single monolithic array of 68 polarimeters (204 TES bolometers), as depicted in Figure 1, before being diced into individual units. We currently install and simultaneously test 18 polarimeters (54 bolometers) per cooldown in the CU/NIST system. We have tested 108 TES bolometers spanning two production runs (CMB4 and CMB5), with 106 (98%) of the devices giving reasonable transition temperatures ($T_c$; Figure 1). Each production wafer included multiple polarimeter designs, with the most relevant design split for these tests being between devices with a relatively high thermal conductance (‘high-$G$’).
to the thermal bath ($T_{\text{bath}}$) to facilitate testing of optical properties of the polarimeters in the laboratory and those with low conductance (‘low-$G$’) to optimize the design for CMB observations. Overall, 102 (94%) of the bolometers were stable and capable of being simultaneously biased (with devices of the same design) on to their transition using a single TES bias current setting. The quoted failure rate ($\sim 6\%$) includes any failures due to the readout electronics.

As time-division multiplexed devices, large groups of the TES devices share a common bias voltage source (future TDM arrays are likely to have one bias source per production wafer). Therefore, these groups of devices require similar electro-thermal properties in order to be simultaneously biased onto their superconducting transition at near optimum sensitivities. Most notably, this requires similar values of $T_c$, $G$, and $R_n$. We find that all of our operable detectors are well within the acceptable range for these properties, including $T_c$ values with a standard deviation of $\sim 1\%$ across the measured parts of each production wafer and $\sim 2\%$ for all 106 TES bolometers tested between the two production wafers (Figure 1). The systematic difference between the mean $T_c$ values of CMB4 and CMB5 (14 mK) may be due, in part, to changes in heat sinking between the thermometer and detectors between the two tests.

$R_n$ is measured from the normal branch of the TES $I$-$V$ curve (sweeping the bias voltage while measuring current) and is found to be consistent amongst devices of a given production wafer to $\sim 10\%$, and $\sim 13\%$ across the two wafers combined (Figure 2). The thermal conductance at the transition temperature, $G(T_c)$, is determined from fits to the incident power, $P = K(T^c - T_{\text{bath}}^c)$, when biased to a common resistance on the transition at various bath temperatures. $G(T_c)$ is then calculated as the derivative with respect to $T$ at a value of $T_c$ for the best fit parameters determined for each TES. For low-$G$ devices at a common bias point of 0.7$R_n$, we find the mean and standard deviation of the distribution of fitted parameters are $n = 2.6 \pm 0.1$ and $K = 72 \pm 5\, \text{pW/K}^n$, resulting in $G(T_c)$ values that are consistent within $\sim 10\%$ (Figure 3). We note that the measured values of $R_n$ and $G(T_c)$ include $\sim 5\%$ random calibration error due to uncertainty in the shunt resistances, $R_{\text{shunt}}$ (Figure 2), which are measured from Johnson noise levels of the circuit while the TES is superconducting.

It is also important for bolometer arrays to have uniform time constants, $\tau$, which determine the frequency response ($f_{3db} = 1/(2\pi\tau)$) to modulated signals and potentially restrict aspects of the observing strategy (e.g. scanning speed). Detector time constants were measured on a subset of TESs by applying power over a range of frequencies using resistive heaters fabricated on the TES islands. The TES response to each frequency is determined by measuring the power in the Fourier transformed time stream at the heater modulation frequency. The response as a function of frequency is then fit as a single-pole filter to determine the detector time constants, which are found to be consistent within $\sim 20\%$ (Figure 2), with no significant outliers.

The noise spectral density of these devices at low frequencies is expected to be dominated by phonon noise,

$$\sqrt{\text{NEP}} = \sqrt{F_{\text{link}}k_BGT^2},$$  \hspace{1cm} (1)
CONCLUSIONS

We find the detector yield and measured uniformity of the detector electro-thermal properties very promising, validating the NIST fabrication process for future large-scale polarimeter arrays. We have plans to upgrade the cryogenic test bed for optical testing, including the capability to simultaneously measure the properties of hundreds of detectors per cooldown.

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