CCAM: A NOVEL MILLIMETER-WAVE INSTRUMENT USING A CLOSE-PACKED TES BOLOMETER ARRAY

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Abstract

This thesis describes CCAM, an instrument designed to map the Cosmic Microwave Background (CMB), and also presents some of the initial measurements made with CCAM on the Atacama Cosmology Telescope (ACT). CCAM uses a CCD-like camera of millimeter-wave TES bolometers. It employs new detector technology, read-out electronics, cold re-imaging optics, and cryogenics to obtain high sensitivity CMB anisotropy measurements. The free-standing \(8 \times 32\) close-packed array of pop-up TES detectors is the first of its kind to observe the sky at 145 GHz. We present the design of the receiver including the antireflection coated silicon lens re-imaging system, construction and optimization of the pulse tube/sorption refrigerator cryogenic system, as well as the technology developed to integrate eight \(1 \times 32\) TES columns and accompanying read-out electronics into an array of 256 millimeter-wave detectors into a focal plane area of 3.5 cm\(^2\). The performance of the detectors and optics prior to deployment at the ACT site in Chile are reported as well as preliminary performance results of the instrument when optically paired with the ACT telescope in the summer of 2007. Here, we also report on the feasibility of the TES detector array to measure polarization when coupled to a rotating birefringent sapphire half wave plate and wire-grid polarizer.
CCAM was made possible through the efforts of many brilliant people. I am extremely grateful for the opportunity to have worked with them, and without their hard work and dedication, CCAM would not have been a success. I owe thanks to each of them, though it would be impossible to mention each by name. Without them, this thesis would not exist.

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Chapter 1

Introduction

1.1 Motivation

Over the course of history, people have questioned how the Universe began and, as a result, have developed numerous models to explain what they observed. The Big Bang is one such model though it is quantitative and based on physics. It asserts that the Universe began from a hot dense state and has been expanding ever since. This cosmological model predicts a Cosmic Microwave Background (CMB) that fills the Universe. In 1965, Arno Penzias and Robert Wilson [101] of Bell Telephone Laboratories detected this Cosmic Microwave Background which earned them the Nobel Prize in 1978.

After the discovery of the CMB by Penzias and Wilson, numerous experiments were built to observe anisotropies in the CMB. In 1989, the COBE satellite measured temperature anisotropies to one part in $10^5$ at angular scales $> 7^\circ$ [12, 121]. Subsequent measurements of the CMB focused on temperature anisotropies at scales $> 0.1^\circ$. These experiments revealed much about the early contents, geometry, and age of the Universe, as well as the history of star and galaxy formation. Figure 1.1 depicts how the resolution of CMB experiments has greatly increased since the CMB was discovered in 1965.

Improvements in technology now allow CMB anisotropies to be resolved at arcminute scales. These measurements of the CMB will be able to probe the expansion and structure formation of the Universe at new levels. For example, distortions in the CMB caused by the Sunyaev-Zel’dovich (SZ) effect [126, 125], can be an indicator of how gravity drove the formation of cosmic structure [7, 45]. Furthermore, the measurement and detection of
distinctive modes of CMB polarization will be able to further constrain cosmological parameters [123] and has the potential to establish the existence of primordial gravitational waves [105, 21].

This thesis describes a new instrument for measuring the anisotropy in the CMB, a possible way to extend the instrument so that it can also measure cosmic polarization, and results from initial celestial observations. The new instrument is called the Column CAMera (CCAM). It uses antireflection-coated cryogenic silicon lenses [74] to image the sky onto a 8×32 close-packed array of multiplexed TES detectors [85] to produce high resolution, sensitive, arcminute resolution spectrum measurements of the CMB and study the polarization of the CMB [52]. The technology pioneered by CCAM will be used in the Millimeter Bolometer Array Camera (MBAC) to observe the CMB at 145 GHz, 215 GHz, and 280 GHz.

The remainder of this chapter will discuss the scientific motivation behind CCAM as well as introduce the Atacama Cosmology Telescope (ACT) Project [39, 68]. The instrumental design of CCAM is presented in detail in Chapter 2. Chapter 3 describes the motivations for moving toward close-packed TES arrays and their associated multiplexed read-out. Here, an overview of the TES detectors, their biasing, and time-domain multiplexed SQUID amplifying read-out is provided as well as a complete description of how these components are assembled to form a free-standing array. The observations and performance tests conducted in Princeton are discussed in Chapter 4. Preliminary analysis and results from data acquired with CCAM in Chile are presented in Chapter 5. Chapter 6 discusses the construction, implementation, and performance analysis of a half wave plate/wire grid polarizer that aims to study polarization. Chapter 7 concludes with a summary of knowledge gained from the construction and data analysis of CCAM. Appendices on microfabrication recipes, array assembly run sheets, the sorption refrigerator assembly process, and usage of a cryogenic test bed are included at the end of this thesis. Electronic pinouts for both CCAM and the cryogenic test bed are also included for reference.
Figure 1.1: Some milestones in CMB measurements. In 1965, Penzias and Wilson’s microwave receiver at Crawford Hill, N.J. discovered the remnant redshifted photons from the Big Bang [101]. In 1992, the COBE DMR experiment mapped the whole sky with 7° resolution [36]. In 2003, the WMAP satellite produced an all sky map with sub-degree resolution [48]. In 2006, third year WMAP results were released which included maps of the polarization of the Cosmic Microwave Background [97]. The color scales in the maps range from -200 $\mu$K to 200 $\mu$K. This figure is a modification of a similar figure on the COBE and WMAP Science Teams taken from the NASA/WMAP mission website.
Black body spectrum intensity as a function of frequency and temperature $B(T)$ is given by:

$$B_\nu(T) = \frac{2\hbar\nu^3}{c^2} \frac{1}{e^{\hbar\nu/kT} - 1}$$

Figure 1.2: Black body spectrum of the CMB as measured by the FIRAS instrument [86, 36] aboard the COBE satellite in 1989 [37]. FIRAS measured the black body spectrum of the CMB between 60 GHz and 600 GHz during COBE’s first few days in space.

1.2 The Cosmic Microwave Background

From a few minutes into the expansion until today, the Universe has had $\approx 10^{10}$ photons for every baryon. When the Universe was too hot for hydrogen to form, there was frequent Thomson scattering of photons off free electrons. At the same time, Coulomb interactions tightly coupled the free electrons and protons. Both these interactions resulted in a tightly coupled photon-electron-baryon plasma. This plasma existed for $\sim 380,000$ years until redshift $z \approx 1100$, at which time there were no longer enough photons with energy sufficient to maintain hydrogen in an ionized state. The free electrons were then capable of forming neutral hydrogen while the photons were able to “decouple” from the matter. These photons free-streamed to us from the “surface of last scattering” giving us a picture of the early Universe.

As the Universe aged and expanded, the CMB radiation cooled to the $2.7253 \pm 0.066$ mK [86, 36] seen today. Figure 1.2 shows the CMB’s spectrum as measured by the FIRAS (Far-Infrared Absolute Spectrophotometer) instrument [86, 36] aboard the COBE (Cosmic Background Explorer) satellite in 1989 [37]. The spectrum measured by the FIRAS instrument matches a blackbody spectrum to the limits of the measurement.
1.2.1 The CMB Power Spectrum

Temperature anisotropies in the CMB provide a way to examine small fluctuations in gravitational potential that existed in the Universe 13.7 billion years ago. To quantify these CMB temperature anisotropies, $\Delta T_{\text{cmb}}(\theta, \phi)$, they are often expressed by a series of spherical harmonics, $Y_{\ell m}^\ast$, with amplitudes, $a_{\ell m}$. The temperature anisotropy can then be described by,

$$\Delta T(\theta, \phi) = T_{\text{cmb}} = \sum_{\ell=1}^{\infty} \sum_{m=-\ell}^{\ell} a_{\ell m} Y_{\ell m}(\theta, \phi),$$

(1.1)

where $\theta$ and $\phi$ are the spherical coordinates and $\ell$ is the spherical harmonic multipole number. Smaller values of $\ell$ correspond to larger spatial scales on the sky. The angular power spectrum is then defined as

$$C_{\ell} = \langle a_{\ell m} a_{\ell m}^* \rangle = \frac{1}{2\ell + 1} \sum_{m=-\ell}^{\ell} |a_{\ell m}|^2.$$  

(1.2)

By measuring and analyzing features of the CMB power spectrum, one can constrain both cosmological parameters and the models they can viably support.

1.2.2 Current Status of CMB Power Spectrum Measurements

Recent measurements by experiments such as ACBAR(2004) [71], CBI(2004) [108], VSA(2004) [28], BOOMERanG(2005) [63], and WMAP(2006) [48] have led to an excellent determination of the CMB power spectrum for multipoles of $\ell \sim 800$ as shown in Figure 1.3. These measurements have allowed many models of structure formation in the Universe to be ruled out, current models to be constrained, and fundamental cosmological parameters to be determined to high accuracy. For an excellent overview of the major cosmological parameters and their current values as determined by the WMAP Science Team, see [122].

Although these measurements have led to rapid progress in our understanding of the Universe, they focus on large scale ($\ell < 800$) features. Figure 1.4 shows the current state of small scale (large $\ell$) angular power spectrum measurements, which have yet to be quantified as accurately as the large scale power spectrum shown in Figure 1.3. On small angular scales of a few arcminutes and less ($\ell > 2000$), the CMB anisotropy is dominated by secondary effects resulting from distortions of the CMB as it passes through the Universe (thus free-streaming is an approximation). Studying these effects can provide new insights on the early Universe and structure formation [65, 123].
Figure 1.3: Current measurements of the CMB angular power spectrum. The data shown come from the ACBAR (2004)[71], BOOMERanG (2005)[63], CBI (2004)[108], VSA (2004)[28], and WMAP (2006)[48] instruments. Notice the larger error bars for multiple moments of $\ell > 800$. Figure courtesy of the WMAP Science Team from the NASA/WMAP website.

One such effect which distorts the CMB signal is the thermal Sunyaev-Zel’dovich (SZ) effect [126, 125]. The SZ effect is the scattering of CMB photons from the surface of last scattering off free electrons in the ionized plasma inside galaxy clusters. The probability of CMB photons inverse-Compton scattering off free electrons is on the order of one percent for any given photon. This scattering of photons results in a unique spectral distortion of the CMB spectrum. The scattered photons cause a shift away from the “SZ null” (~ 220 GHz), which appears as a cold patch at frequencies below the SZ null and a hot patch above the SZ null [115]. This distortion is represented in Figure 1.6.

Measurements of the CMB SZ distortion are capable of probing structure formation in the early Universe. Furthermore, subtraction of the measured SZ distortions will allow the CMB power spectrum to be resolved to finer accuracy. The MBAC observing frequencies were chosen to straddle the SZ null so the distortions resulting from the SZ effect can be analyzed and subtracted from the measured signal to increase the accuracy of CMB power spectrum measurements.
Figure 1.4: Current measurements of small scale temperature anisotropies as measured by ground-based and balloon-borne CMB experiments. The colored lines show the best fit (red) and the 68% (dark orange) and 95% confidence levels (light orange) based on fit of the $\Lambda$CDM model to the WMAP data [122]. The $\Lambda$CDM model of the early Universe assumes a nearly scale-invariant spectrum of primordial perturbations, and a flat Universe. Figure courtesy of the WMAP Science Team from the NASA/WMAP website.

Figure 1.5: The thermal SZ effect. The thermal SZ effect is the result of high energy electrons in the plasma inside clusters of galaxies distorting the CMB through inverse-Compton scattering.
1.3 Polarization Anisotropies in the CMB

Recent measurements of the CMB power spectrum support the model in which the early Universe went through an epoch of inflation [123, 122]. This model also suggests that an intrinsic polarization signature, a magnitude smaller than the temperature anisotropy, should be observable in the CMB. In 2002, the existence of a polarization signal in the CMB was confirmed by the DASI instrument [69, 77]. Subsequent instruments such as BOOMERanG [88], CAPMAP [8], CBI [109], and WMAP [97] have confirmed the existence and begun to quantify the polarization anisotropy of the CMB. Figure 1.7 illustrates recent measurements of the polarization from these experiments for $\ell < 1400$.

The polarization signature of the CMB is generated when free electrons Thomson scatter a quadrupole radiation pattern in their rest frame. There is more to it than this however. To create an observable polarization signal, a low optical depth and a sufficient number of available scatters is required. Otherwise, the scattered radiation is isotropized. Thus, observable CMB polarization resulting from Thomson scattering of quadrupole radiation is...
Multipole moment $l$

200

-0.05

0.00

0.05

0.10

0.15

400 600 800 1000 1200 1400

$(l+1)C_l^{EE}/2 (K_2)$

WMAP

DASI 05

CBI 05

B 03

CAPMAP

Figure 1.7: Recent polarization measurements for $\ell > 40$. The solid curve is the best fit EE spectrum for the parameters that best fit the TT data. The black boxes are the WMAP data; the triangles are the BOOMERanG data; the squares are the DASI data; the diamonds are the CBI data; and the asterisk is the CAPMAP data.

generated in the $\sim 10,000$ years ($\Delta z \sim 200$) after photons began to free-stream, but before decoupling between the photons and matter ended.

As mentioned above, only a quadrupole moment in the intensity of incident radiation can lead to polarization. This can be understood by examining the cross-section:

$$\frac{d\sigma_T}{d\Omega} = \left( \frac{e^2}{mc^2} \right)^2 |\hat{k} \cdot \hat{k}'|^2 \propto \cos^2 \theta,$$

(1.3)

where $\sigma_T$ is the Thomson scattering cross-section, $\hat{k}$ and $\hat{k}'$ are the incident and scattered polarization directions respectively, and $\theta$ is the angle formed by $\hat{k}_1$ and $\hat{k}_2$. As a result of the $\cos^2 \theta$ dependence, an electron in a quadrupolar field will oscillate preferentially in one direction and therefore emit polarized radiation. Figure 1.8 illustrates how Thomson scattered quadrupole radiation can produce polarization but dipole radiation can not.

If gravitational waves existed during the inflationary epoch, an additional polarization signal would be produced [21]. Gravitational waves generate the quadrupole pattern that the electrons see. This results in polarization containing both a curl-free component and a curl component [21, 105, 119, 120]. In rough analogy to electromagnetism, the curl-free polarization is called $E$-mode polarization, and the curl component is called $B$-mode.
Figure 1.8: (a) Depiction of Thomson scattering. This illustrates the dependence on the direction of scattered radiation in which a non-zero differential cross-section can be observed. (b) If there exists a local quadrupole anisotropy in the plane perpendicular to the line of sight, Thomson scattering will produce a net linear polarization along the “cold” axis of the quadrupole.

Figure 1.9: Illustrations of polarizations produced by $E$- and $B$-modes. $E$- and $B$- modes have distinctive properties when reflected across an axis through the centers of their patterns. $E$-modes remain unchanged after reflection while $B$-modes are reversed. Image by Seljak and Zaldarriaga.
polarization. Figure 1.9 illustrates the different polarization patterns produced by $E$-mode and $B$-mode polarization.

While $B$-modes can be differentiated from the intrinsic $E$-mode pattern, foregrounds can additionally yield $B$-mode polarization. This $B$-mode signal would be greater than $B$-mode polarization produced by primordial gravitational waves for $\ell \gtrsim 200$. A way $B$-mode polarization created during the inflationary epoch can be separated from gravitationally lensed foregrounds is by examining the different angular power spectra and their correlations with the temperature and $E$-mode spectra [93, 66].

### 1.3.1 Cross Correlation Power Spectra

All CMB polarization is generated from Thomson scattering. The only difference between observable CMB polarization signals is the source of the quadrupole pattern. The $E$-modes can be generated by both spatial energy fluctuations and gravitational waves while the $B$-modes can only be generated by gravitational waves, weak gravitational lensing from foregrounds, and direct emission of polarized radiation from electrons and dust. To distinguish the source of observed anisotropies, measured CMB signals are represented by the five power spectra $C_{\ell}^{TT}$, $C_{\ell}^{EE}$, $C_{\ell}^{TE}$, and $C_{\ell}^{BB}$. The $C_{\ell}^{TT}$ describes the temperature anisotropy power spectrum formed from the temperature two-point correlation function. The $C_{\ell}^{EE}$ power spectrum characterizes the autocorrelation of $E$-mode polarization. The cross power spectrum, $C_{\ell}^{TE}$, describes the cross-correlations between $E$-mode polarization and temperature anisotropies. This spectrum is important because both temperature anisotropies and $E$-mode polarization originated from primordial density fluctuations. Finally, the $C_{\ell}^{BB}$ power spectrum represents the autocorrelation of the $B$-modes. Figure 1.10 illustrates the relative strengths of the $C_{\ell}^{TT}$, $C_{\ell}^{EE}$, $C_{\ell}^{TE}$, and $C_{\ell}^{BB}$ power spectra for $r = 0.3^1$ as a function of multipole moment.

### 1.4 Goals of ACT, MBAC, and CCAM

Although the data from experiments such as WMAP [48] have provided a wealth of information about the early Universe, their angular resolution and sensitivity have only allowed for accurate measurements of CMB power spectra for $\ell \sim 800$. As detectors, signal read-out,

\begin{footnote}
1 The tensor to scalar ratio, $r$, gives the ratio between the temperature anisotropies produced by gravitational waves and by density perturbations at $\ell = 2$.
\end{footnote}
Figure 1.10: Angular CMB power spectrum as a function of $\ell$ for the temperature (TT), the temperature-polarization cross-correlation (TE), and the $B$-mode polarization (BB) spectra. This illustrates the relative strength of each power spectrum. Estimates on signals from gravitational lensing and emission of polarized radiation from electrons and dust are also given. The short-dashed blue line is the predicted $B$-mode signal from gravitational lensing of $E$-modes. The two long dash lines are estimates for a combination of polarized synchrotron and dust emission from our galaxy at 65 GHz averaged over 75% of the sky. The top green dashed line represents the predicted $E$-mode signal while the bottom blue dashed line depicts the estimated $B$-mode signal. The cosmic variance is shown as a light swatch around each predicted signal [97]. Figure courtesy of the WMAP Science Team from the NASA/WMAP website.
cryogenics, and optics technology have advanced, it is now possible to observe and further constrain CMB anisotropies for multipoles $\ell \gg 800$.

Telescopes in the 5-10 meter range are required to measure the CMB power spectrum at arcminute scales. The Atacama Cosmology Telescope (ACT) [39, 68] is a custom designed 6 meter telescope dedicated to observing small scale anisotropies of $\ell \sim 10,000$ over a $100 \deg^2$ patch of sky with $0.03^\circ$ resolution when coupled to the MBAC receiver. The goal of ACT is to achieve less than $1 \mu K$ systematic error per 1.7' at 145 GHz. To do so, the MBAC receiver is equipped with antireflection-coated cryogenic silicon lenses to image the sky onto a $32 \times 32$ close-packed array of multiplexed TES detectors. MBAC will utilize three detector cameras to observe in three separate frequencies. The three frequencies, 145 GHz, 215 GHz, and 280 GHz, were specifically chosen to minimize atmospheric foregrounds at the ACT site in northern Chile, as well as straddle the SZ null allowing us to probe structure formation, produce high sensitivity SZ cluster surveys, and subtract the SZ signal from the CMB power spectrum.

The new technology being pioneered with MBAC prompted us to build a prototype receiver containing all of MBAC’s critical components, but at a single frequency of 145 GHz. In the summer of 2007, CCAM became the first receiver to integrate multiplexed TES detectors into a free-standing close-packed array to make millimeter-wave measurements of the CMB. In addition, a polarizer has been constructed to mate with CCAM and has the potential to make polarization measurements of the CMB. This thesis provides detailed information on the design, as well as challenges that arose, and their subsequent solutions during the construction of CCAM’s detector array, optics, SQUID read-out electronics, polarizer, and cryogenics. This description of CCAM’s construction is directly applicable to the manufacturing of MBAC and future experiments.
Chapter 2

The CCAM Instrument

2.1 Introduction

The CCAM instrument consists of a $8 \times 32$ close-packed array of Transition Edge Sensor (TES) detectors [76, 56] used for measuring the temperature anisotropy of the CMB at 145 GHz. With CCAM, and also described in this thesis is an external polarizer for detecting the polarization anisotropy of the CMB.

CCAM was built as a prototype receiver to test the detector array, optics, cryogenics, and read-out electronics. In our implementation, all these systems were new to the field of CMB measurement. In the winter of 2005, CCAM was mounted on a spare set of WMAP mirrors to observe the sky with an unfolded $1 \times 32$ column of detectors from the roof of Jadwin Hall in Princeton University. This allowed us to test the cold optics, read-out electronics, and detectors in Princeton, NJ, rather than on the ACT telescope, which was under construction in Vancouver, BC at that time. To avoid saturating the detectors when observing through the New Jersey atmosphere, an 11.5% neutral density filter was placed in the optical path at 4 K.\footnote{The neutral density filter is described in more detail in Chapter 5, Section 4.2.} Data gathered from that observing season is described Chapter 5, Section 4.2. CCAM was then prepared for installation on ACT by removing the neutral density filter, assembling and installing the $8 \times 32$ detector array, and decreasing the size of the Lyot stop’s aperture to improve the focal quality when coupled to the ACT optics. In the summer of 2007, CCAM became ACT’s first light instrument. In the fall of 2007, the MBAC (Millimeter Bolometric Array Camera) receiver is planned to observe on ACT at...
145 GHz with a 32×32 array of TES detectors, using the knowledge gained with CCAM. In the following year, MBAC is planned to measure the temperature anisotropy of the CMB in three frequency bands (145 GHz, 220 GHz, and 265 GHz) using three independent 32×32 close-packed arrays of TES detectors.

2.2 Optics

2.2.1 Telescope

The imaging properties of the telescope can be described by the effective focal length and the focal ratio. The effective focal length, \( f \), is the effective distance over which the telescope converges light. The focal ratio, \( F \), is defined as \( F \equiv f/D \) where \( D \) is the diameter of the mirror. The greater \( F \) is, the less light per unit area reaches the focus. A pictorial representation of \( f \) and \( F \) are shown in Fig 2.1 (left).

ACT is an off-axis compact Gregorian telescope constructed by AMEC\textsuperscript{2} Dynamic Structures \textsuperscript{3}. The mirrors shapes and positions have been optimized with the Code V\textsuperscript{3} software package. The ACT primary mirror is a 6 meter off-axis parabola with a focal ratio \(( F \leq 1)\) to keep the telescope compact. The primary mirror feeds the 2 meter secondary mirror, which creates a fast Gregorian focus \(( F \sim 2.5 \) at the input to the receiver), keeping the camera window for the cryostat from being too large. ACT has an effective focal length of \( f=5.2 \) m. Figure 2.1 (right) depicts the rays from ACT’s primary and secondary mirrors converging onto the focal plane.

To deflect extraneous loading by ambient temperature sources and to sharply define the aperture illumination pattern there is a cold Lyot stop\textsuperscript{4} inside the cryostat at an image of the primary. Also, each mirror is surrounded by a reflective aluminum guard ring to ensure that the light passing through the Lyot stop does not have an ambient temperature component. In addition, a fixed ground screen ensures the ground loading is constant and smaller than atmospheric loading. Instead of having moving or rotating chopping optics in the optical path, which would introduce undesired systematic effects, the entire telescope

\textsuperscript{2}AMEC Dynamic Structures Ltd. (currently called Empire Dynamic Structures), Telephone: (604) 941-9481

\textsuperscript{3}Optical Research Associates, http://www.opticalres.com/ Telephone: (626) 795-9101

\textsuperscript{4}A Lyot stop is a cold aperture stop that blocks light that does not reflect off the primary mirror.
Figure 2.1: Right: A simple on-axis Gregorian telescope to illustrate $f$ and $F$. The effective focal length $f$ determines how wide an angle the telescope can view. The focal ratio $F$ of a telescope is the ratio between the effective focal length and the diameter of the mirror. Thus, for a given aperture, low focal ratios indicate wide fields of view. Left: Side view of the ACT telescope. Recall, ACT is an off-axis Gregorian telescope to minimize scattering and blockage.
scans in azimuth at approximately 2 degrees/second. Figure 2.2 shows photographs of the telescope taken at the ACT site on Cerro Toco.

The plate scale of a telescope describes the ratio between degrees on the sky and spacing on the focal plane. It is given by:

\[
\text{Plate Scale} = \frac{1}{f} = 6.8' / \text{cm},
\]  

(2.1)

where \( f \) is the effective focal length. In other words, in CCAM positions separated by approximately 6.8' on the sky, will be separated by 1 cm in the focal plane.

Figure 2.2: Photographs of the ACT telescope at the site on Cerro Toco. The opening from the uninstalled ground screens provides a good view of the actual telescope. The completed ground screen will fully shield the telescope from ground emission. Photograph courtesy of A. Hincks.
<table>
<thead>
<tr>
<th>Component</th>
<th>Cold Spacing (cm)</th>
<th>Temperature</th>
<th>Warm Spacing (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cryostat window</td>
<td>-4.534</td>
<td>297 K</td>
<td>-4.534</td>
</tr>
<tr>
<td>WMAP focus</td>
<td>0.000</td>
<td>...</td>
<td>0.000</td>
</tr>
<tr>
<td>8 cm$^{-1}$ Lowpass Filter</td>
<td>50 K</td>
<td>0.491</td>
<td>0.493</td>
</tr>
<tr>
<td>Lens 1 front</td>
<td>3.006</td>
<td>4 K</td>
<td>3.016</td>
</tr>
<tr>
<td>Lens 1 back</td>
<td>3.576</td>
<td>4 K</td>
<td>3.588</td>
</tr>
<tr>
<td>7 cm$^{-1}$ Lowpass Filter</td>
<td>4.878</td>
<td>4 K</td>
<td>4.894</td>
</tr>
<tr>
<td>Lens 2 front</td>
<td>24.893</td>
<td>4 K</td>
<td>24.975</td>
</tr>
<tr>
<td>Lens 2 back</td>
<td>25.663</td>
<td>4 K</td>
<td>25.747</td>
</tr>
<tr>
<td>Bandpass Filter Center</td>
<td>29.046</td>
<td>4 K</td>
<td>29.141</td>
</tr>
<tr>
<td>Lens 3 front</td>
<td>31.790</td>
<td>800 mK</td>
<td>31.893</td>
</tr>
<tr>
<td>Lens 3 back</td>
<td>32.760</td>
<td>800 mK</td>
<td>32.867</td>
</tr>
<tr>
<td><strong>Detectors</strong></td>
<td><strong>38.254</strong></td>
<td><strong>300 mK</strong></td>
<td><strong>38.379</strong></td>
</tr>
</tbody>
</table>

Table 2.1: CCAM warm and cold optical component spacing. The temperature corresponding to each cold component is also given. The WMAP focus is the location of the focus when CCAM was mounted on the spare WMAP mirrors in the winter of 2005.

2.2.2 Cold Optics Overview

Figure 2.3 shows top and side views of sample light rays through CCAM’s cold optical elements. Figure 2.4 is a schematic of CCAM’s optics tube.

Radiation enters the dewar window and passes through a lowpass filter mounted on the 50 K radiation shell lid. A Cryoperm,\(^5\) shell encases the the 4 K copper optics tube and acts both as the 4 K radiation shell and as a magnetic shield. The 4 K optics tube is light-tight and heavily baffled to ensure the radiation incident on the 800 mK optics and the detectors is free of external radiative loading. The baffling is painted “black” with a mixture (by weight) of 88% Stycast 2850FT\(^6\), 3% Catalyst 9, and 9% finely ground charcoal to further reduce unwanted scattering of rays [75]. The 4 K bandpass filter holder also acts as the Lyot stop, which defines the illumination pattern on the primary mirror. The 800 mK optics, which contain the last lens and additional baffling are thermally isolated from the 4 K optics by three 6.4 mm diameter and 250 µm thick G-10 posts. A copper cone also painted black, and superinsulation “fingers” (superinsulation is discussed in Section 2.3.7) block 4 K radiation outside the optical path from entering between the 4 K and 800 mK optics juncture. The warm and cold spacings between optical components are listed in Table 2.1.


Figure 2.3: The CCAM optical path. Radiation enters from the left and passes through two lowpass filters. Light then travels through two silicon lenses, lens 1 and lens 2. The third filter is the bandpass filter. The final lens, lens 3 images the sky onto the detectors. The 40 K filter, 4 K filter, and bandpass filter were manufactured by collaborators in Peter Ade’s group at Cardiff University. See Section 2.2.3 for an in depth description of CCAM’s filters. Ray tracing figure courtesy of J. Fowler.

Cryostat Window

CCAM uses a 760 μm thick,\(^7\) 15.2 cm diameter, polypropylene sheet for its vacuum window. Figure 2.5 is a cross section of the window aperture. The window circumference is secured by a vacuum greased O-ring seal and twelve 8-32 bolts to ensure the window/cryostat junction is vacuum tight.

The window bows inward under vacuum. The maximum sag, \(y_{sag}\), from a circular window under a uniform pressure \(P\), of thickness \(t\), and radius \(a\), can be expressed as:

\[
y_{sag} = \frac{Pa^4(\frac{5+\nu}{2+\nu})}{64D},
\]

(2.2)

where

\[
D = \frac{Et^3}{12(1-\nu^2)},
\]

(2.3)

and \(\nu\) is Poisson’s ratio and \(E\) is the modulus of elasticity of the window material. For polypropylene, \(\nu = 0.42\) and \(E = 0.9\) GPa [59]. If we take the applied pressure to be 1 atm, the calculated maximum deflection of the window is 0.8 cm. When measured in the lab, the measured bowing under \(1\times10^{-6}\) Pa vacuum was approximately 1 cm, in close agreement with our calculation.

\(^7\)The thickness of the polypropylene before being on the vacuum.
Figure 2.4: Schematic of CCAM’s optics tube. Radiation enters from the left and passes through the cryostat window. It is subsequently filtered by two low pass filters with cutoff frequencies of 240 GHz and 210 GHz. The different cutoff frequencies ensure higher harmonic radiation leakage is blocked. Light then travels through two silicon lenses, Lens 1 and Lens 2, and heavy baffling to reduce unwanted reflections. The bandpass filter holder acts as our cold Lyot stop. All the baffling and lens holders are made of OFHC copper. The final lens, Lens 3 images the sky onto our detectors. For calibration purposes, an infrared emitter is placed near the Lyot stop that can provide constant precise pulses of radiation.
Figure 2.5: Cross section of CCAM’s window mounting scheme. A Buna-N O-ring, (part number: AS568A-259) keeps the window vacuum tight. This particular O-ring was chosen for its working temperature range of: -5°C to 120°C. Under vacuum, the measured bowing in the lab for the originally 760 µm thick polypropylene sheet is ∼1 cm.

The polypropylene window thickness was determined by balancing the absorption and reflection losses in our frequency band with the ability to hold vacuum and minimize bowing of the window. Figure 2.6 shows the calculated reflection, absorption, and transmission of our window as a function of frequency over our band.

2.2.3 Millimeter-Wave Filtering

Filter Basics

Various types of filters can be used to selectively transmit radiation of different frequencies. When an electric field, \( E \), is incident upon a conductive wire, only the component of \( E \) parallel to the wire can induce an electromagnetic force along the wire causing electrons to oscillate. A fraction of the incident power from the wave will be transmitted, and the remaining power will be reflected by the oscillating electrons. However, the perpendicular component of the \( E \) fails to produce a force along the wire as it passes by the wire. By manipulating the configuration of the conductive sections, a certain pattern can constrain which frequencies are transmitted.

Two types of metal mesh filters, capacitive and inductive, are depicted in Figure 2.7. A capacitive mesh filter is comprised of a grid of conducting squares. The inductive filter is the conductive mirror image of the capacitive filter, i.e., a grid of conductive lines. Since the
Figure 2.6: Left: the computed transmission (shown in red) of the 760 $\mu$m polypropylene window as a function of frequency. Right: the computed absorption (shown in blue) and reflection (shown in green) of the window as a function of frequency. CCAM’s bandwidth is depicted in grey. The plots were created using the properties of polypropylene given in [73].

capacitive mesh’s conductive regions are isolated squares, the current is confined in these squares and thus only short wavelength radiation is reflected. On the other hand, inductive metal mesh filters act as highpass filters. The configuration of the inductive metal mesh filter allows electrons to move across the length of the filter. This enables long wavelength radiation to excite currents and be reflected. However, the short wavelength radiation will have a high transmittance. Since the grids are symmetric under rotation of 90 degrees, the wave’s polarization does not affect the transmission and reflection coefficients.

Often filters are stacked to form multiple element filters. For example, [130, 99] use multiple types of filters to create bandpass filters allowing only a small band of frequencies to be transmitted.

**CCAM Filters**

Two lowpass and one bandpass metal-mesh filters [3], made by Carole Tucker in Peter Ade’s laboratory at Cardiff University provide CCAM’s bandpass filtering and infrared blocking. The two lowpass filters are mounted on the 50 K and 4 K stages of the optics tube to reject high-frequency radiation and reduce the thermal load on the 4 K, 800 mK, and 300 mK stages of the cryostat. Unfortunately, metal-mesh filters suffer from resonant leaks at harmonics of the cutoff frequency. To block these leaks, the two lowpass filters have different cutoff
Figure 2.7: The two images show the geometry of inductive and capacitive mesh filters. The inductive type of metal mesh filter allows high frequencies to pass (highpass filter), while the capacitive mesh filter allows low frequencies to pass (lowpass filter). These filters have the advantage that their transmission is independent of polarization.

Frequencies (240 GHz and 210 GHz) to block the others’ harmonic transmission leaks. In addition, these filters block the harmonic leaks of the third filter, the band-defining edge or bandpass filter. This filter, held at 4 K, limits the incident radiation on the detectors and defines our band.

Each filter is 10.8 cm in diameter and 0.3 cm thick. They are secured in place by the mounting scheme depicted in Figure 2.8. The 210 GHz lowpass and bandpass filters are mounted at a 1.5° angle, see Figure 2.8 to reduce potential standing waves. To ensure that the filters are thermally sunk to their respective thermal stages, each filter is compressed by 0.1 mm between its copper mount base and mount lid. In addition, a 1 mm diameter indium wire placed under the filter and around the filter edge creates a thermal and light-tight seal between the mount and filter.

The bandpass and 210 GHz lowpass filters were measured on M. Halpern’s Fourier Transform Spectrometer (FTS) at the University of British Columbia. The 240 GHz lowpass filter spectrum was acquired on J. Ruhl’s FTS at Case Western University. The transmission of all three filters and their combined properties are shown in Figure 2.9.

For incoherent detectors such as ours, we can quantify our filters by their band center, $\nu_0$, where the band center is the mean frequency weighted by the corrected transmission function. Given a filter’s transmission spectrum, the band center can be determined by:

$$\nu_0 = \frac{\int \nu f(\nu)d\nu}{\int f(\nu)d\nu},$$

(2.4)

*Space limitations did not allow the 240 GHz lowpass filter to be tilted at an angle.*
Figure 2.8: Filter mounts. Each filter is 10.8 cm in diameter, and 0.3 cm thick. The filters are mounted at a 1.5° angle to reduce standing waves. To ensure that the filters are thermally sunk and completely cool, the filter is compressed by 0.1 mm between the copper mount base and copper mount lid. In addition, a 1 mm diameter indium wire creates a thermal and light tight seal between the mount and filter.

where \( f(\nu) \) is the measured transmission spectrum that has been corrected for the FTS source (\( \nu^2 \) for a Raleigh Jeans source). The calculated bandwidth, \( \Delta \nu \), from the measured filter spectra can additionally provide a qualitative sense of the filters’ properties. Unfortunately, discrete features such as high frequency spikes affect the overall normalization. Thus, bandwidth calculations based on measured spectra such as the span in frequency at half the maximum (FWHM) should not be considered quantitatively robust. Table 2.2 lists the calculated properties of the CCAM filters from the spectra shown in Figure 2.9.

<table>
<thead>
<tr>
<th>Filter Properties</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Bandwidth ( \Delta \nu )</td>
<td>21.20 (GHz)</td>
</tr>
<tr>
<td>Band center ( \nu_0 )</td>
<td>145.73 (GHz)</td>
</tr>
<tr>
<td>Band FWHM</td>
<td>17.46 (GHz)</td>
</tr>
<tr>
<td>Max Trans. ( T_{max} )</td>
<td>0.93</td>
</tr>
</tbody>
</table>

Table 2.2: Calculated properties of the CCAM filters from the measured filter spectrum data.
Figure 2.9: Measured individual filter transmission and computed composite transmission for the three filters used in CCAM. The transmission of the bandpass filter was averaged between 100 and 120 GHz. The composite transmission is shown in red.
Atmospheric Filtering

The altitude (5200 m) and dry air above the ACT site on Cerro Toco make it an optimal site for CMB observations. Water vapor in the atmosphere is a large source of contaminating radiation at our observing frequency. The CCAM filter band and central frequency was chosen to maximize the CMB signal through the atmospheric transmission. Figure 2.10 shows a model of the transmission spectrum at the Atacama site. Over-plotted are our bandwidth and the composite transmission through our three filter stack.

Figure 2.10: Model transmission spectrum for the ACT telescope site during the winter for observations at 45° elevation. The opacity in our band is a function of the altitude of the observing site and the precipitable water vapor (PWV). The PWV for the Atacama site (5200 m) was extracted from the ALMA (5000 m) [114] and APEX (5100 m) sites using software based on the ATM model written by Juan Pardo. Over-plotted in blue is the CCAM composite filter transmission, taken from Figure 2.9. “Winter months” are from June to November.
2.2.4 Lenses and AR coating

The following work in this subsection comes from a paper by J. Lau, J. Fowler, T. Marriage, L. Page, J. Leong, E. Wishnow, R. Henry, E. Wollack, M. Halpern, D. Marsden, and G. Marsden.

CCAM uses three cold antireflection (AR) coated, high resistivity (HR) silicon (> 10,000 $\Omega$-cm bulk resistivity) lenses [74]. The lenses were manufactured by Nu-Tek Precision Optical Corporation.\(^9\) The lens shapes and spacings were optimized by J. Fowler using the Code V software package. Each lens is plano-convex and antireflection coated on both sides with 0.3 mm thick Cirlex\(^{10}\) brand polyimide. The first two lenses are held at 4 K and the final lens, which focuses the image onto the detector array, is held at 800 mK.

There are many advantages to using HR silicon as a lens material: it can be machined; it has a high index of refraction, which is optically advantageous; and it has a high thermal conductivity, allowing for straightforward cooling of the lenses to cryogenic temperatures. Furthermore, HR silicon has a low loss tangent in the submillimeter region [100]. However, the high index ($n_s = 3.42$) in the submillimeter region [73] leads to a reflection at each silicon/vacuum interface of approximately $R = [(n_s - 1)/(n_s + 1)]^2 \approx 30\%$ per surface. This is prohibitively large, especially for multi-lens cameras. Nevertheless, the benefits of silicon have motivated the development of antireflection coatings, [113, 89] where the referenced AR solutions are in IR and thus easier than mm-wave bands due to the thickness of the AR layer. The following details the development and testing of a simple antireflection coating that reduces reflection to $< 1.5\%$ per lens at the design wavelength while maintaining $> 90\%$ transmission at $\nu < 300$ GHz.

At a fixed wavelength the ideal, normal-incidence antireflection coating for a substrate of index $n_s$ in vacuum has an index of refraction of $n_c = \sqrt{n_s}$ and is $t_c = \lambda_0/(4n_c)$ thick. Our $\sim 20$ GHz bandwidth is narrow enough that single-layer quarter-wave antireflection coatings would suffice. Thus, for our frequency of 145 GHz, the ideal antireflection coating has $t_c = 279 \mu m$ and index $n_c = 1.85$.

The coating is a machined piece of Cirlex polyimide glued to silicon with Stycast 1266 epoxy\(^{11}\) and Lord Ap-134 adhesion promoter.\(^{12}\) For the curved lens surface, a piece of

---


\(^{10}\)Fralock, Division of Lockwood Industries, Inc., http://www.fralock.com/ Telephone: (800) 372-5625

\(^{11}\)Emerson and Cuming, http://www.emersoncuming.com/ Telephone: (978) 436-9700

Cirlex approximately 1 cm thick is machined to the curved shape and then held in a Teflon gluing jig\textsuperscript{13} shaped to match the lens surface while the epoxy cures.

**Material Properties and Construction Details**

The low-frequency (∼1 kHz) dielectric constant and loss reported in the Kapton polyimide data sheet\textsuperscript{14} suggested that polyimide and silicon could be combined in an AR configuration. To ensure accurate modeling and to test for sample dependent effects, we measured the dielectric properties with a Fourier Transform Spectrometers (FTS), summarized in Table 2.3.

Cirlex is a black, pressure-formed laminate of Dupont Kapton polyimide film, readily available in sheets up to 597 mm × 597 mm and thicknesses from 0.2 mm to 3.175 mm, with thicker constructions possible. In the 100–400 GHz range, at room temperature, we found that the complex dielectric constant is well modeled as \( \tilde{\epsilon} = 3.37 + i[0.027(\nu/150)^{0.52}] \) with \( \nu \) in GHz. At 150 GHz the loss tangent is given by:

\[
\tan \delta = \frac{\text{Im}(\tilde{\epsilon})}{\text{Re}(\tilde{\epsilon})} = \frac{0.027}{3.37} = 0.008. \quad (2.5)
\]

To test the cryogenic properties of Cirlex, E. Wollack placed a 250 µm thick sample in a Bruker IFS 113 FTS that operates between 300 and 3000 GHz. Fitting a single complex dielectric constant across this frequency range, we measure \( \tilde{\epsilon} = 4.0 + i0.06 \) (\( \tan \delta = 0.015 \)) at 5 K, and \( \tilde{\epsilon} = 3.6 + i0.1 \) (\( \tan \delta = 0.030 \)) at room temperature. Note that when the temperature is reduced, the loss tangent decreases and the real part of the dielectric constant increases.

We also performed tests using a vector network analyzer to confirm the temperature-dependent behavior of Cirlex. Thin slabs (∼0.02 cm) of Cirlex were inserted into WR-10 waveguide and tested at 90 GHz both at room temperature and in a liquid nitrogen bath. The full complex scattering matrix was measured over the WR-10 band (75–110 GHz). The boundary conditions on the electric and magnetic field at both ends of the sample lead to expressions for the scattering parameters. The expressions depend on the length of the sample and its permeability and permittivity, and we inverted them to derive the complex dielectric constant [135, 58]. At 77 K, \( \text{Re}(\tilde{\epsilon}) = 2.95 \) (\( \tan \delta = 0.002 \)) and at room temperature, \( \text{Re}(\tilde{\epsilon}) = 3.05 \) (\( \tan \delta = 0.017 \)). Though we have not corrected for the dimensional change of the sample upon cooling (≈2% shrinkage), it is clear that the loss decreases.

\textsuperscript{13}Teflon was used as the glue jig material because the glued lens could easily be removed.

\textsuperscript{14}Dupont, http://www2.dupont.com/Kapton.html Telephone: (800) 967-5607
Our observations of Cirlex are consistent with a smooth 20% increase in Re(\(\tilde{\epsilon}\)) from 100 GHz to 1 THz. In our calculations we used the value in Table 1, which corresponds to a best fit of the room-temperature data over the 90–300 GHz range. Table 2.3 shows that two similar samples exhibited losses differing by approximately 30%. Surface effects may be to blame, but we also note that the difference has low statistical significance.

Stycast 1266 is a two-component, low viscosity epoxy made by Emerson Cuming. We measured its properties with a cured sample machined to be flat and 0.64 cm thick. These properties are given in Table 2.3. The index of refraction is similar to that of Cirlex, but the loss is two to three times larger. To adhere the Cirlex to the silicon we coated the silicon with Lord Ap-134 adhesion promoter before applying the Stycast. The adhesion promoter is needed to ensure the coating can endure multiple cryogenic cycles. We used high purity, high resistivity silicon for our lenses and test samples. Recall that the complex dielectric constant for a weakly conducting dielectric is:

\[ \tilde{\epsilon}(\nu) = \text{Re}(\tilde{\epsilon}) + \frac{i}{2\pi\nu\epsilon_0\rho}, \]

in the MKS system, where Re(\(\tilde{\epsilon}\)) is the real part of the dielectric constant, \(\epsilon_0 = 8.85 \times 10^{-14} \ (\Omega \text{ cm Hz})^{-1}\), and \(\rho\) is the resistivity. For a \(\rho = 5000 \Omega\text{-cm}\) sample at 150 GHz, this corresponds to 11.67 + i(0.0024), close to the measured value. Prior studies of the loss in high-resistivity silicon show a complicated temperature dependence [100]. However, the loss is always smaller at 4 K than at room temperature for potential optical components.

Some care must be exercised when measuring the optical properties of silicon because both heating and ultraviolet light raise its conductivity. The nitrogen source used in the Case FTS was a critical improvement over the mercury arc lamp used in the initial mea-

<table>
<thead>
<tr>
<th>Material</th>
<th>Relative dielectric constant (\tilde{\epsilon}^{a,b})</th>
<th>(\tan\delta^c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silicon ((\rho \sim 5000 \Omega\text{ cm}))</td>
<td>11.666 + i[0.0026((\nu/150))^{-1}]</td>
<td>2.2 \times 10^{-4}</td>
</tr>
<tr>
<td>Cirlex (0.25 mm)</td>
<td>3.37 + i[0.037((\nu/150))^{0.52}]</td>
<td>0.011</td>
</tr>
<tr>
<td>Cirlex (10 mm)</td>
<td>3.37 + i[0.027((\nu/150))^{0.52}]</td>
<td>0.008</td>
</tr>
<tr>
<td>Stycast 1266</td>
<td>2.82 + i[0.065((\nu/150))^{0.27}]</td>
<td>0.023</td>
</tr>
</tbody>
</table>

Table 2.3: Dielectric properties of the materials for AR coating.

\(a\) The values are fit to transmission measurements in the frequency range \(100 \leq \nu \leq 420 \text{ GHz}\). Throughout, \(\nu\) is in GHz.

\(b\) All results are at ambient temperature.

\(c\) The loss tangent is measured at 150 GHz. Results have a relative uncertainty of 10%, or 15% on the thinner Cirlex sample.
measurements at UBC. The arc lamp produced UV and heated the silicon samples to 70°C or higher. We have observed that both effects affect the resistivity of the silicon (and hence its optical transmission); heating to 70°C alone reduced the resistivity by a factor of five.

In our experience, when a plastic sheet is glued to a glass, quartz or silicon substrate and cooled to liquid nitrogen temperatures, differential thermal contraction can shear apart the substrate. Silicon and Stycast 1266 thermally contract from 296 K to 4 K with $\Delta L/L = 2.2 \times 10^{-4}$ and $110 \times 10^{-4}$, respectively [9, 41]. We expect Cirlex to have a coefficient of thermal expansion comparable to that of a plastic, i.e. approximately that of Stycast 1266 and ten to one hundred times that of silicon. Through repeated testing, we have found that the composite structure does not fracture upon cooling if a thin layer of adhesion promoter is applied before the epoxy.

We experimented with multiple antireflection-coated samples to test their robustness, including five flats—four 100 mm in diameter and one over 200 mm in diameter—and three plano-convex lenses. Both the 100 mm and the 200 mm flats were dunked from room temperature into liquid nitrogen over fifty times without damage. The lenses have been cryogenically cycled over ten times between room temperature to less than 4 K in a dewar, also without damage.

**Measurements and Modeling**

We have measured both the reflection and transmission of the AR-coated samples. The reflectometer is quick and straightforward to use, though it is limited to only one frequency. The transmission measurements are necessary to understand the indices and the absorption losses, and they can be made at a wide range of frequencies.

**Reflection measurements**

We built the reflectometer shown in Figure 2.11 in order to measure the reflection of the samples. Samples are mounted in 10.16 cm diameter holes on a 53.9 cm diameter, 1.23 cm thick rotating 6061 aluminum plate. Care is taken to ensure that the sample surface is in the same plane as the aluminum plate (±25 μm) and that the sample holder does not cause extraneous reflections. The diode detector, which measures total power, and a temperature-compensated 144.00 GHz source are each mounted at a 27° angle from normal incidence. The feed horns for the source and receiver are aligned so that the electric field is oriented
normal to the plane of incidence (TE mode). As the disk rotates, the receiver successively views 6061 aluminum, a sample to be measured, or Eccosorb through an empty sample holder. The signal is synchronously binned and averaged over \( \approx 1000 \) rotations of the plate. The data are then scaled by taking Eccosorb to have negligible reflection \( (R = 0.001) \) and 6061 aluminum to reflect perfectly.

To calibrate the reflectance \( R \), we placed silicon flats of known thicknesses (4–7 mm) into the reflectometer. The extremely narrow-band light source produces interference between reflections from the front and back of the silicon flats, so that \( R \) varies between 5 and 70\%, depending on the sample thickness. A single model of the reflection that incorporates the incident angle, polarization, sample thickness, frequency, and properties of silicon fits all the data with 1\% mean residuals. Figure 2.12 illustrates the ease of interpreting the raw reflectometer measurements. All lenses are measured with the flat side parallel to the aluminum plate.

Silicon flats and plano-convex silicon lenses were subsequently AR coated on both sides using the procedure detailed above. The reflection was measured before and after coating. The results shown in Table 2.4 demonstrate that both the flat and shaped silicon can be AR coated to achieve as little as 1.5\% reflection.
Figure 2.12: Four overlaid reflection plots from the reflectometer. Two samples are shown both before and after (denoted by primes) applying antireflection coating. The reflectometer measures aluminum in regions labeled $a$, and Eccosorb or a mounted sample at positions $b1-b5$. In the above plot, only $b2$ has a sample mounted. The stability of the measurement from one sample to another is good, as shown by the almost perfect overlap of the data.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Thickness$^a$ (mm)</th>
<th>$R_{uncoated}$</th>
<th>$R_{coated}$</th>
<th>Epoxy Thickness$^b$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat 5</td>
<td>5.0</td>
<td>0.59</td>
<td>0.009</td>
<td>&lt; 0.03</td>
</tr>
<tr>
<td>Flat 6</td>
<td>7.0</td>
<td>0.05</td>
<td>0.05$^c$</td>
<td>&lt; 0.2</td>
</tr>
<tr>
<td>Flat 7</td>
<td>4.1</td>
<td>0.38</td>
<td>0.005</td>
<td>&lt; 0.03</td>
</tr>
<tr>
<td>Lens 1</td>
<td>5.7</td>
<td>0.28</td>
<td>0.016</td>
<td>&lt; 0.07</td>
</tr>
<tr>
<td>Lens 2</td>
<td>7.7</td>
<td>0.61</td>
<td>0.015</td>
<td>&lt; 0.03</td>
</tr>
<tr>
<td>Lens 3</td>
<td>9.7</td>
<td>0.47</td>
<td>0.015</td>
<td>&lt; 0.06</td>
</tr>
</tbody>
</table>

Table 2.4: Reflection of silicon before and after AR coating.

$^a$Center thickness is given for the plano-convex lenses. All lenses have edge thickness of $\sim$ 3 mm.

$^b$This is the total epoxy thickness, not per side.

$^c$Due to the large epoxy layer, the coating was less successful.
Transmission measurements

Since we are primarily concerned with maximizing transmission through the lenses, the transmission spectra were also measured at room temperature on the Case Western FTS. The spectrometer uses the black body emission of Eccosorb foam submerged in liquid nitrogen as a light source. The detector is a composite bolometer with a Haller-Beeman NTD germanium thermistor and a 4 x 4 mm nickel-chromium coated sapphire absorber. Liquid helium cools the bolometer to 4 K. Spectra were obtained between 100 and 425 GHz. The small aperture of the Winston cone feeding the bolometer sets the lower frequency limit, and a 15 cm$^{-1}$ capacitive-inductive grid lowpass filter in the optical system sets the upper limit. The interferometer scans continuously from $-21$ cm to $+21$ cm optical path difference (OPD). Bolometer data are digitized at 40 samples per second by a 16-bit data acquisition board [20]. Acquiring each spectrum requires eight minutes. In analyzing the interferograms, we have discarded data outside $\pm 18.4$ cm OPD and apodized the rest using a window function with Hann-like taper and a half-maximum at $\pm 13.5$ cm optical path difference. The results are insensitive to the details of the window, the shape of which is a compromise between suppressing noise and not suppressing the real variations in the transmission spectra of thick dielectric samples.

The transmission model (like the reflection model used in the previous section) assumes that light consists of plane waves normally incident on infinite, planar samples. The formalism uses the characteristic matrix of stratified dielectric media, given in §1.6 of Born and Wolf [15]. Unfortunately, the transmission cannot readily be expressed as a function of frequency for any system with two or more layers of dielectric. The light incident on the samples has a focal ratio of $f/4$, slow enough that we can ignore wavefront curvature and polarization effects in the model. Two other effects must be considered, both of which tend to suppress in real FTS data the extremes of the idealized channel spectrum. First, it is necessary to treat the model as if it had been taken on the FTS by apodizing its “interferogram” with the same window applied to the data. More importantly, the model must sample the exact same frequencies as the measurements do, where the frequency step size is the inverse of twice the maximum optical path difference (in this measurement, the frequencies are spaced at 0.8 GHz). With these precautions, we find an excellent match between the measured and modeled transmission spectra of the coated (and uncoated) flat samples.
We were unable to measure the transmission of lenses directly. It was possible to obtain a spectrum of the transmitted light, but this spectrum included the confounding factor of the lens’s optical power. This optical gain factor can be computed in principle, but it requires detailed knowledge of the complete FTS optical system. Worse, it is not robust against small variations in the lens placement. For example, one sample’s spectrum differed by a factor of two between successive tests in which the lens was moved in the FTS beam by less than 5 mm. We find that the primary value of lens transmission measurements is to check for high transmission at the target frequency $\nu_T$ and at $3\nu_T$. 

![Image](image_url)

**Figure 2.13:** The room temperature transmission $T$ of the coated 4 mm-thick silicon flat (Flat 7), both modeled (blue) and measured on the FTS (green). The measurement is the ratio of a sample to a reference spectrum. The lower curve shows that the difference (measurement minus model) is within 5% of zero through the well-measured range. The high transmission near 133 and 400 GHz is due to the AR coating being $\lambda_0/4$ and $3\lambda_0/4$ thick. The slow reduction in $T$ with increasing frequency is due to increasing loss in the coating and glue. This sample was made before precise values of the index of Cirlex and Stycast 1266 were known. Thus, the center of the pass band window, 133 GHz, is 12 GHz below our target frequency.
Rather than trying to interpret the lens results, we measured the transmission of the two coated flats labeled Flat 6 and 7 in Table 2.4. Figure 2.13 shows the transmission spectra for one of these samples along with a model. The measurement is the ratio of a sample to a reference spectrum, which are averages over two and six spectra, respectively. The model is not a fit to the coated transmission data but is determined instead by the Cirlex, Stycast, and silicon properties given in Table 2.3 and by measurements of the component thicknesses. The one exception is the silicon loss. The coated flats have somewhat lower resistivity (between 1300 and 3500 Ω-cm, as measured by the vendor) than the un-coated silicon samples (all specified to exceed 5000 Ω-cm); both sets have poorly constrained resistivity. To handle the uncertain silicon loss, we have treated the resistivity of the sample as an unknown and varied it to fit the measured transmission.

**Lens holder design**

From 293 K to 10 K, \( \frac{\Delta L}{L} = 2.2 \times 10^{-4} \) for silicon while \( \frac{\Delta L}{L} = 32.6 \times 10^{-4} \) for copper [104]. Thus, the difference in thermal contraction between silicon and copper over 10 cm is approximately 300 μm. This difference in thermal contraction requires our lens mounts to secure the lenses both thermally and mechanically in the copper optics tube without breaking them. The final design depicted in Figure 2.14, utilizes Spira-Shield gaskets that encircle the lens. These tin/lead plated beryllium copper spiral gaskets apply a outward radial force during cooling to keep the lens stationary. The high thermal conductivity of the gasket provides an additional conductive path between the copper lens mount and silicon lens. Figure 2.14 Figure 2.15 shows photographs of an actual AR coated silicon lens and the Spira-Shield gasket used in the lens mounts.

To ensure the lens mount adequately cooled the antireflection coated silicon lens, a temperature sensor was varnished onto the center of a spare antireflection coated lens and cryogenically cycled. The thermalization time constant between the copper and silicon lens was found to be negligible.

---

Figure 2.14: Cross sectional view of the lens mount scheme. The lens rests flush against the bottom copper mount, and is kept in place with two Spira-Shield gaskets. One Spira-Shield gasket runs around the circumference of the lens where the lens is not AR coated. The other Spira-Shield gasket provides force against the top edge of the lens and also runs around the circumference, thermally connecting the copper mount lid to the lens.

(a) ~100 mm diameter AR coated silicon lens.

(b) Spira-Shield gasket

Figure 2.15: Left: Photograph of an AR coated silicon lens. The lens shown is ~100 mm in diameter. Right: Photograph of the Spira-Shield gasket. The Spira-Shield gasket is used in the lens holder to thermally cool and mechanically hold the silicon lens in place. The Spira-Shield gaskets are positioned by channels similar to O-ring grooves.
2.2.5 Optical Quality

Strehl ratios, $S$, can be used to quantify the focal quality of CCAM’s lens system on ACT. The Strehl ratio is the ratio of the intensity at the Gaussian image point in the presence of aberration, divided by the intensity that would be obtained if no aberration were present.

Thus, $S$ describes how insidious aberrations are in the optical system, relative to an aberration-free diffraction limited system. A Strehl ratio of 1 describes a system where no aberrations are present. Strehl ratios $S$ greater than 0.1 can be expressed as,

$$
\ln S \approx (2\pi \sigma)^2, \quad (2.7)
$$

where $\sigma$ is the rms optical path variation over a large bundle of rays. Using output from J. Fowler’s Code V file, the Strehl ratios across the CCAM focal plane were calculated. In CCAM we aimed for Strehl ratio’s of 0.95 and above. Figure 2.16 depicts the calculated Strehl ratios across the 8×32 detector array in CCAM. As expected, the Strehl ratios are worse on the outer edges of the array with the lowest being 0.95. However, these ratios are adequate for CCAM to be the first light engineering receiver on ACT.

![Strehl Ratio of the 8x32 Array on ACT](image)

Figure 2.16: Calculated Strehl ratios for the 8x32 detector array in CCAM on ACT. The row select number sequentially denotes the 32 detectors in each 1×32 column.
2.3 Cryogenics

2.3.1 Dewar Constraints

CCAM is a custom built cryostat initially designed to mate to the WMAP [98] prototype telescope for testing on the roof of the Princeton physics department. This proved challenging because the cryostat had to have enough real estate to accommodate two pulse tubes, three sorption refrigerators, cold optics, detector array, and read-out electronics, yet fit into a small receiver area (∼60 cm wide) between the spare WMAP telescope mirrors. The final cryostat design uses a modular approach to fit the necessary cryogenic, optical, and detector elements in the small allotted space. The design has four basic components:

1. **Refrigerator box 1 (FB 1)**. FB1 holds a pulse tube cryocooler and a two-stage $^3$He/$^4$He sorption refrigerator system.
2. **Refrigerator box 2 (FB 2)**. FB2 holds a pulse tube cryocooler and a $^4$He sorption refrigerator system.
3. **Optics tube (OT)**. The optics tube houses the cold filters and optics.
4. **Detector box (DB)**. The detector box (DB) contains the detectors and cold read-out electronics.

This modular design, allowed multiple components to be designed and tested simultaneously. Figure 2.17 is a rendered drawing of the CCAM cryostat.

2.3.2 “Fridge Boxes”

The two refrigerator boxes on either side of the detector box depicted in Figure 2.17 provide cooling power for the entire cryostat. The arrangement, construction, and dimensions of FB1 and FB2 are detailed in [1] but highlighted below are the key components for operation.

The isolated location in Chile compels us to avoid using expendable liquid cryogens for cooling power. Instead, we utilize two pulse tube cryorefrigerators, one in FB1 and a second in FB2 to get the cryostat cold enough to operate the sorption refrigerators. Both pulse tubes are PT 407’s manufactured by Cryomech, Inc. ¹⁶ Pulse tubes are a reliable way of providing low vibration pre-cooling power using a closed cycle of compressed helium instead of liquid cryogens. In tandem, the two PT 407’s cool the cryostat’s first stage to ∼50 K

¹⁶Cryomech Inc., http://www.cryomech.com/ Telephone: (315) 455-2555
Figure 2.17: The CCAM cryostat. The optics tube is at a 22.5° angle to the horizontal. Light enters from the front of the optics tube and is focused on the detector array in the detector box. The two refrigerator boxes on either side of the detector box house the refrigeration system. Cold fingers feed through the fridge boxes to the detector box to provide cooling power.
and the second stage to $\sim 3.5$ K. Schematics of FB 1 and FB 2 are shown in Figure 2.18 and Figure 2.19. Photographs of the completed fridge boxes are shown in Figure 2.20.

2.3.3 Sorption Refrigerators

Three closed cycle sorption refrigerators are used to cool the detectors and optics below the pulse tube’s base temperature. Our refrigerators were originally designed by Mark Devlin’s group at the University of Pennsylvania [26]. At Princeton they were constructed, characterized, and optimized. FB 2 houses a single $^4$He sorption refrigerator that cools the baffling and optics adjacent to the detectors to 800 mK. FB 1 contains a two-stage $^3$He/$^4$He sorption system that cool the detector package in the detector box to $\sim 270$ mK.

Sorption refrigerators work by lowering the pressure above a liquid allowing the molecules with more kinetic energy to escape and cool the liquid until the vapor pressure equals the pressure above the liquid [26, 102, 18]. The absorber used in our refrigerators is coconut-based activated charcoal. When heated to $\sim 45$ K, the charcoal releases (desorbs) helium. If the condensation point of the refrigerator is held below the condensation temperature of the gas, the gas will condense and collect in the pot. When the absorber is cooled, the remaining uncondensed gas is re-absorbed reducing the vapor pressure above the liquid.

After the helium has condensed into the pot, the pumps need to be cooled to re-absorb the remaining gas. We utilize gas-gap heat switches mounted on the $4$ K baseplate and heat strapped to the pumps to thermally connect the pumps to the cold reservoir. Each heat switch, manufactured by Chase Research Cryogenics\(^{17}\) consists of a stainless steel cylinder containing helium gas, two concentric copper cylinders, charcoal as an absorber, and a $10$ kΩ heater resistor. The heat switch works in a similar fashion as the sorption refrigerators. When the heater in the charcoal is turned on, helium gas is released and thermally shorts the two concentric cylinders. When the heater is turned off, the charcoal absorbs the gas that connects the switch, and the heat switch will cool to the off state in approximately ten minutes. A schematic of the two-stage $^3$He/$^4$He sorption system is shown in Figure 2.21.

The refrigeration cycle starts by heating all three pumps to drive out the helium gas. The three gas-gap heat switches which heat sink the three pumps to the baseplate are disconnected while both $^4$He refrigerators are heated to $45$ K and the $^3$He refrigerator is

\(^{17}\)Chase Research Cryogenics LTD. http://www.chasecryogenics.com/
Figure 2.18: Schematic of FB1. The color code shows the distinct temperature stages. The pulse tube is on the left and encased in superinsulation (superinsulation is discussed in Section 2.3.7). The $^4$He refrigerator is in the middle while the $^3$He refrigerator is on the far right. Both pumps are supported with G-10 cylinders to support the pot and pumps on their thin walled stainless tubes. In addition, both pumps are superinsulated to reduce radiation loading on the 4K stage when the pumps are heated to release helium gas.
Figure 2.19: Schematic of FB 2. The color codes show the distinct temperature stages. The pulse tube is on the right and the $^4$He refrigerator is on the left. Similar to Figure 2.18, the $^4$He refrigerator is supported with G-10 cylinders and are superinsulated.
Figure 2.20: Photographs of FB 1 and FB 2. The photographs of FB 1 and FB 2 are of their respective 4 K baseplates. The shiny crinkly material surrounding the sorption refrigerators is superinsulation which will be discussed in Section 2.3.7.
Figure 2.21: Schematic of the $^3$He and $^4$He refrigerators used in FB 1 to cool the detectors to 300 mK. The $^4$He refrigerator in FB 2 is identical but is not thermally connected to a $^3$He refrigerator.

heated to 35 K. Approximately an hour later, the $^4$He gas is fully condensed in the $^4$He pots. At this point, the temperature of the $^4$He pots should be approximately the temperature of the condensation point (CP), 3.5 K. When enough liquid has condensed both $^4$He pumps are cooled via the gas-gap heat switches to the 4 K baseplate, effectively “pumping” on the liquid in the pots. The $^4$He pot in FB 2 cools to $\sim 800$ mK, cooling our optics and baffles near our detectors to 800 mK. Meanwhile, the $^4$He pot in FB 1 which is heat strapped to the $^3$He condensation point cools, additionally cooling the $^3$He CP. When the temperature of the $^4$He pot/$^3$He CP is below 1 K, the $^3$He gas in the $^3$He refrigerator will be almost entirely condensed into the $^3$He pot. The $^3$He pump can then be thermally connected to the 4 K baseplate through the gas-gap heat switch, pumping on the $^3$He liquid in the pot. This causes the $^3$He pot to cool to $< 300$ mK at which point the cycle is completed. A plot of the temperatures of the various fridge elements during the cycle is shown in Figure 2.22.
Figure 2.22: Temperatures of the sorption refrigerator components during a cycle while installed in the cryogenic test bed. In this particular cycle, the Helium 4 pump was already slightly warm, $\sim 11\,\text{K}$, at the start of the cycle. A typical cycle takes approximately 2 hours.

### 2.3.4 Optimization of the $^4\text{He}$ Refrigerator

For the $^4\text{He}$ refrigerator, the superfluid film that forms at the lambda transition, $T_\lambda = 2.18\,\text{K}$, presents technical design challenges that are insufficiently addressed in the literature. In this section we present the modeling, design, and testing of a pumping orifice that allows one to optimize the ultimate cooling temperature and hold time. The following work in this subsection comes from a paper by J. Lau, M. Benna, M. Devlin, S. Dicker, L. Page.

The presence of a superfluid film limits the hold time of many $^4\text{He}$ refrigerators. Its primary effect is to drain liquid $^4\text{He}$ from the evaporation pot (shown in Fig.2.23) and allow it to evaporate in a region of the apparatus where it gives no useful cooling power. The thermal conductivity of the film is negligible [23, 24, 25] and does not in itself limit the performance.

To minimize the effects of the superfluid film, a smooth orifice [2, 106] is introduced into the pump tube, just above the evaporation pot. This limits the amount of helium...
<table>
<thead>
<tr>
<th>Symbol(s)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_c$</td>
<td>Length of pump tube from orifice to pump.</td>
</tr>
<tr>
<td>$L_p$</td>
<td>Length of pump tube from orifice to condensation plate.</td>
</tr>
<tr>
<td>$l$</td>
<td>Position of evaporator pot from the condensation plate.</td>
</tr>
<tr>
<td>$b$</td>
<td>Radius of pump tube.</td>
</tr>
<tr>
<td>$a$</td>
<td>Radius of orifice.</td>
</tr>
<tr>
<td>$t_p$</td>
<td>Thickness of pump tube wall.</td>
</tr>
<tr>
<td>$n_0$</td>
<td>Number of moles of $^4$He in refrigerator.</td>
</tr>
<tr>
<td>$T_c$</td>
<td>Temperature of the condensation point.</td>
</tr>
<tr>
<td>$T_0$</td>
<td>Steady-state temperature of liquid He in evaporator pot.</td>
</tr>
<tr>
<td>$P_0$</td>
<td>Steady-state pressure of gas above the liquid He in evaporator pot.</td>
</tr>
<tr>
<td>$P_1$</td>
<td>Pressure just above the orifice.</td>
</tr>
<tr>
<td>$P_2$</td>
<td>Pressure at the top of the film at a distance $l$ below the condensation plate.</td>
</tr>
<tr>
<td>$m$</td>
<td>Atomic mass of helium.</td>
</tr>
<tr>
<td>$c_s$</td>
<td>Velocity of sound in helium.</td>
</tr>
<tr>
<td>$\eta$</td>
<td>Viscosity of gas.</td>
</tr>
<tr>
<td>$\rho_g$</td>
<td>Density of Helium gas.</td>
</tr>
<tr>
<td>$\gamma = 5/3$</td>
<td>Ratio of heat capacities for helium as an ideal gas.</td>
</tr>
<tr>
<td>$L$</td>
<td>Latent heat per mole for helium.</td>
</tr>
<tr>
<td>$t_0$</td>
<td>Thickness of superfluid film.</td>
</tr>
<tr>
<td>$u_c$</td>
<td>Maximum of the superfluid film flow velocity.</td>
</tr>
</tbody>
</table>

Table 2.5: Selected Notation

that will be lost by bulk transport since the flow velocity of the film is bounded above by a superfluid critical velocity and the finite film thickness which is determined by the surface properties [137]. This orifice can dramatically increase the hold time, $t_{hold}$, of the refrigerator. However, if the radius $a$ of the constriction is too small, the steady-state temperature, $T_0$, of the evaporation pot will suffer because the pumping speed is reduced. We present below a model that describes the dependance of $t_{hold}$ and $T_0$ on $a$. To describe the system with just a simple set of equations, we make a number of approximations which are outlined. Rather than describing the details of the gas and fluid flow, the goal of the model is to provide guidelines for building and optimizing related systems. In particular, we determine the value of $a$ that gives the best performance, that is, the longest hold time $t_{hold}$ without the pot temperature $T_0$ exceeding the desired design temperature.
Figure 2.23: Sorption refrigerator. The unit is held by the CP. At the start of the cycle the charcoal pump is held at 45 K and gaseous $^4$He is condensed by the CP, held at $T_c$, and drips down to fill the pot. After the pot is full, which takes $\sim 1$ hour, the pump is cooled to 4 K and pumps on the liquid $^4$He. The orifice, shown as an insert, is welded to the pump tube.

Model of the Refrigerator

The model of the gas and film flow through the apparatus breaks down into three parts: the flow of gas through the constriction, of gas along the pump tube, and of the film through the constriction (and up the wall of the pump tube), see Figure 2.23. By necessity the treatment of the rarefied gas is approximate, since the gas is highly compressible fluid and in the transition regime between continuous behavior and free molecular flow. In addition, the gas-superfluid interface is incompletely understood at a fundamental level. However, though the physical processes involved in the refrigerator are in general complex, we find that with a number of simplifying assumptions, we can model the gross characteristics of the system.

The mass transport from the pot through the constriction is divided between the gas and the film. Let us denote the corresponding rates by $\frac{dM_1}{dt}$ and $\frac{dM_2}{dt}$. The film then
creeps up the inner wall of the pump tube, and evaporates before it reaches the condensation plate, since the latter is kept at a constant temperature $T_c > T_\lambda$. We shall assume that the evaporation takes place at a distance $l$ from the condensation plate (rather than spread out over a certain area) and that the film evaporates at a temperature $T_\lambda$.

Given these assumptions, the gas and film flow can be described by four mass transport rates: the flow of the gas through the orifice, $\frac{dM_1}{dt}$, the flow of film through the orifice, $\frac{dM_2}{dt}$, the flow of gas through the lower part of the pump tube, $\frac{dM_3}{dt}$, and the gas flow in the upper part of the pump tube (above the point where the film evaporates) $\frac{dM_4}{dt}$. These flow rates must satisfy:

$$\frac{dM_3}{dt} = \frac{dM_1}{dt}, \quad (2.8)$$
$$\frac{dM_4}{dt} = \frac{dM_1}{dt} + \frac{dM_2}{dt}. \quad (2.9)$$

**Relevant Properties of $^4$He Gas**

At temperatures above its boiling point the stable phase of helium is a monatomic and very weakly interacting gas, which over a wide range of temperatures can be described as an ideal gas with a ratio of heat capacities of $\gamma = 5/3$.

The viscosity of an ideal gas is given by the kinetic theory expression, $\eta = \frac{5}{16} \frac{d^2}{\pi} \sqrt{\frac{k_BTm}{\pi}}$, where $d$ is the effective diameter of a gas molecule, $k_B$ is Boltzmann’s constant, $T$ is the temperature of the gas, and $m$ is the atomic mass of the gas, which is based on the assumption of elastic collisions between gas molecules of effective diameter $d$ without long range interactions. This formula does not apply exactly to real gases, and at temperatures close to its boiling point even the weak Van der Waals interactions of $^4$He must become significant. Various empirical formulas with modified temperature dependence have been proposed [31]. In the absence of comprehensive data on the viscosity of $^4$He gas below its condensation temperature, we nevertheless use the ideal gas formula, and choose $d$ such that the viscosity at $T = 1.64$K agrees with the value of $\eta = 5.47 \times 10^{-7}$kg m$^{-1}$s$^{-1}$ measured by Van Itterbeek and Keesom [57]. This implies $d = 3.54 \times 10^{-10}$m.

The mean free path $\lambda$ is related to the viscosity through an equation of the form $\eta \propto \rho_g c_s \lambda$, where the density of the gas $\rho_g$ is given by $\rho_g = \frac{Pm}{k_BT}$ and the velocity of sound by $c_s = \sqrt{\frac{\gamma k_BT}{m}}$. Purely geometrical considerations allow us to express $\lambda$ in terms of the effective diameter $d$: $\lambda = \frac{m}{\sqrt{2} \pi \rho_g d^2}$. 
For a realistic base temperature of $T_0 = 0.6 \text{ K}$ and assuming saturated vapor pressure this implies $\lambda = 4 \times 10^{-4} \text{ m}$, which is of the same order of magnitude as the radius $a$ of the constriction. Thus we are right in the transition regime between continuous fluid flow and free molecular flow.

**Gas flow through the orifice**

Since we shall not be dealing with temperatures much below $T_0 = 0.6 \text{ K}$ or constrictions of radius much less than $a = 10^{-4} \text{ m}$ we shall use fluid dynamics to describe the flow through the orifice. We shall show that assuming free molecular flow leads to a similar expression for the flow rate.

To determine the gas flow through the constriction, $dM_1/dt$, we use the fact that energy is conserved for an ideal gas in steady adiabatic flow [34],

$$\frac{\gamma}{\gamma - 1} \frac{P}{\rho_g} + gz + \frac{1}{2} u^2 = c_p T + gz + \frac{1}{2} u^2 = \text{constant}, \tag{2.10}$$

where $g$ is the gravitational acceleration, $z$ is the height, and $u$ is the flow velocity of the gas. Given the temperature $T_0$ and the vapor pressure $P_0 = P_{vap}(T_0)$ of the gas in the evaporation pot away from the constriction where $u \approx 0$, the constant in Equation 2.10 is found to be $(\gamma/(\gamma - 1))P_0/\rho_g(T_0, P_0)$.

The gravitational potential term is negligible, and using the adiabaticity constraint $\rho_g \propto P^{1/\gamma}$ [34, pg. 82] we find that $u$ at the orifice reaches the local velocity of sound, when the pressure at the orifice takes the critical value $P_c = P_0 (2/(\gamma + 1))^{\gamma/(\gamma - 1)}$. At this point the mass flow rate takes its maximum value, and reducing the pressure $P_1$ just downstream of the constriction below the critical pressure will not increase it any further.

If $P_1 \leq P_c$ the flow is said to be choked. The physics of choked flow involves finite pressure steps across shock fronts and is relevant to the design of nozzles and rockets. Defining $P_1^* = \text{Max}(P_1, P_c)$ we can write the resulting mass flow rate [34] as:

$$\frac{dM_1}{dt} = \pi a^2 \rho_g(T_0, P_0) c_s(T_0) \left( \frac{2}{\gamma - 1} \right)^{\frac{1}{2}} \left( \frac{P_1^*}{P_0} \right)^{\frac{1}{2}} \left[ 1 - \left( \frac{P_1^*}{P_0} \right)^{-\frac{\gamma - 1}{\gamma}} \right]^{\frac{1}{2}}. \tag{2.11}$$

If we had done the same calculation of the mass flow rate through a small orifice assuming free molecular flow and furthermore negligibly small $P_1$, we would have obtained the expression

$$\frac{dM_1}{dt} = \pi a^2 \rho_g(T_0, P_0) c_s(T_0) \sqrt{\frac{1}{2\pi \gamma}}. \tag{2.12}$$
Apart from the numerical coefficient, this expression is identical to Equation 2.11 in the regime of choked flow, but its validity is restricted to cases where $\lambda \gg a$ and thus we shall employ Equation 2.11 in what follows.

**Gas flow through the pump tube**

To find an expression for the mass flow rate of gas through the pump tube above the orifice, we postulate that the gas that evaporates in the evaporator pot flows up the tube at constant temperature $T_0$ until it reaches the top of the helium film. Beyond that point all the gas, including the evaporation from the film, flows at a constant temperature $T_\lambda$ towards the pump. While these assumptions are approximate, the details of the temperature distribution of the gas are of secondary importance.

The flow rate in a generic tube of radius $b$, length $L$, and pressures $P_1$ and $P_2$ at the high and low pressure ends can be approximated \[\text{[31]}\] as:

$$\left(\frac{dN}{dt}\right) = \frac{1}{k_B T} \frac{\pi b^4}{8 \eta L} \left(\frac{P_1 - P_2}{2}\right) + \frac{1}{k_B T} \frac{2\pi b^3}{3 \eta L} \frac{8k_B T}{\pi m} \left(\frac{P_1 + P_2}{2}\right)^{\frac{3}{2}} (P_1 - P_2). \quad (2.13)$$

where $\eta$ is the viscosity of the gas and $m$ is the atomic mass. This expression is approximately valid both in the regime of continuous, viscous flow and in the regime of free molecular flow, and interpolates correctly between them. Thus, if $P_1$ is the pressure just downstream of the constriction, and $P_2$ the pressure at the top of the film, a distance $l$ below the condensation plate, and a distance $L_c - l$ above the orifice, the transport rate of the gas that evaporated in the pot is given by:

$$\frac{dM_3}{dt} = \frac{m}{k_B T_0} \frac{\pi b^4}{8\eta(T_0)(L_c - l)} \left(\frac{P_1^2 - P_2^2}{2}\right) + \frac{2\pi b^3}{3 \eta L_c - l} \frac{8k_B T_0}{\pi m} \left(\frac{8k_B T_0}{\pi m}\right)^{\frac{3}{2}} (P_1 - P_2). \quad (2.14)$$

Similarly, taking $P = 0$ at the upper end of the pump tube, which is a distance $L_p$ above the constriction, the mass flow rate of gas between the upper end of the film and the pump is:

$$\frac{dM_4}{dt} = \frac{m}{k_B T_\lambda} \frac{\pi b^4}{8\eta(T_\lambda)(L_p - L_c + l)} \left(\frac{P_2^2}{2}\right) + \frac{2\pi b^3}{3 \eta L_p - L_c + l} \frac{8k_B T_\lambda}{\pi m} \left(\frac{8k_B T_\lambda}{\pi m}\right)^{\frac{3}{2}} P_2. \quad (2.15)$$

**Film flow through the constriction**

The two-fluid model of superfluid $^4$He asserts that He II is composed of a superfluid component of density, $\rho_s$, and a normal fluid of density, $\rho_n$. Any surface in contact with $^4$He
vapor at $T < T_\lambda$ will be covered by a film of liquid helium \cite{111,13,4}. The equilibrium thickness of the film is essentially determined by the Van der Waals forces exerted by the molecules of the wall. The condition that the free surface of the film has to be at the same chemical potential leads to a Bernoulli type equation for the film not unlike Equation 2.10:

$$\frac{1}{2} \rho_s u_s^2 + \frac{P}{\rho_0} - \sigma T + g z - \frac{\alpha}{t m} = \text{constant},$$

where $u_s$ is the superfluid flow velocity, $\sigma$ the specific entropy, $t$ the thickness of the film, $\rho_s$ the superfluid component of the density, $\rho_0 = \rho_s + \rho_n \approx 145 \text{ kg m}^{-3}$ \cite{133} the density of liquid helium at superfluid temperatures, $n_t = 3$ the Van der Waals exponent \cite{127,67,128}, and $\alpha$ a constant quantifying the Van der Waals interaction.

The thickness $t$ of an isothermal and isobaric film measured a height $z$ from the free surface of the bulk liquid is given by $t(z) = \left(\frac{\alpha}{g z}\right)^{1/3}$. We assume that at the upper walls of the evaporator pot, where the film is almost static, and begins to converge radially to the constriction, the film has a thickness $t_0$, which in turn fixes the value of $\alpha$. We take $t_0 = 30 \text{ nm}$, which for $T < T_\lambda$ is a typical value for pure $^4\text{He}$ on a clean, smooth substrate \cite{127,137}.

Consider now the moving film \cite{67,128}. The film attached to the lower surface of the diaphragm moves radially towards the constriction, at a constant temperature and gravitational potential. Far from the orifice, the thickness is $t_0$, and the pressure $P_0$, so applying Equation 2.16

$$t = t_0 \left(1 + \frac{t_0^3}{\alpha \rho_0} \left(1 + \frac{1}{2} \rho_s u_s^2 + P - P_0\right)\right)^{-\frac{1}{3}}.$$ \hspace{1cm} (2.17)

The mass flow rate of the film $dM_2/dt = 2\pi r t u_s(r) \rho_s$ must be independent of $r$. The final ingredient required to calculate its value is the flow velocity. It has been shown there is an upper limit to the velocity of superfluid film flow characterized by the sudden onset of dissipation that destroys superfluidity \cite{127}. We use this maximum velocity $u_c$ as the one fit parameter of our model for comparing to experimental data. Values generally lie in the range $0.1 \text{ m s}^{-1} < u_c < 1 \text{ m s}^{-1}$ \cite{127,137}.

Assuming that evaporation at the top of the film always proceeds sufficiently rapidly to drive the film through the orifice at the maximum rate $u_c$,

$$\frac{dM_2}{dt} = 2\pi at_0 u_c \rho_s(T_0) \left(1 + \frac{t_0^3}{\alpha \rho_0} \left(1 + \frac{1}{2} \rho_s u_c^2 + P_1 - P_0\right)\right)^{-\frac{1}{3}}.$$ \hspace{1cm} (2.18)
With expressions for the four relevant mass flow rates $dM_i/dt$, and given values of $T_0$ and $l$ we can impose Equations 2.8 and 2.9 to calculate the total mass loss rate, and thus the hold time of the refrigerator. We next consider heat transport along the pump tube to find $T_0$.

**Heat flow along pump tube**

The walls of the stainless steel pump tube determine the load on the evaporation pot. Knowing the thermal conductivity $\kappa$ of stainless steel as a function of temperature, the total heat conducted through a distance $l$ from the condensation plate at temperature $T_c$ to the top of the film is

$$W_{\text{tot}} = \frac{2\pi b t_p}{l} \int_{T_\lambda}^{T_c} \kappa(T) dT,$$

(2.19)

where $t_p$ is the wall thickness of the pump tube, $\kappa(T)$ is the thermal conductivity of stainless steel [32] and the top of the film is assumed to be at $T_\lambda$.

The remainder of the heat flow, that is the part that is not used to evaporate the film, is conducted through a distance $L_C - l$ along the lower part of the pump tube and into the liquid helium bath. The power into the evaporation pot, which is at temperature $T_0$, is therefore given by

$$W_{\text{pot}} = \frac{2\pi b t_p}{L_C - l} \int_{T_0}^{T_\lambda} \kappa(T) dT.$$

(2.20)

This is the power that evaporates $^4\text{He}$ from the free surface of the bulk liquid.

The power into the evaporator pot serves to evaporate helium at a rate $dM_1/dt$ and at a temperature $T_0$. Thus,

$$W_{\text{pot}} = \frac{dM_1}{dt} \frac{L(T_0)}{mN_A},$$

(2.21)

where $L$ is the latent heat of helium [104], and $N_A$ is Avagadro’s number. The total power drawn from the condensation plate includes $W_{\text{pot}}$ as well as the power required to provide the latent heat to evaporate the film at temperature $T_\lambda$. Therefore,

$$W_{\text{tot}} = \frac{dM_1}{dt} \frac{L(T_0)}{mN_A} + \frac{dM_2}{dt} \frac{L(T_\lambda)}{mN_A}.$$

(2.22)

Combining the constraints (2.8), (2.9), (2.21) and (2.22) with the relations (2.11), (2.14), (2.15), (2.18), (2.19) and (2.20), the hold times and steady state temperatures as functions of the specifications of the refrigerator can be computed, in particular as functions of $a$. The variables $T_0$, $P_1$, $P_2$ and $l$ are found through the consistency of the equations.
Applying the Model

Three such refrigerators were made with different orifice radii \( a = 508 \text{µm} \), \( 572 \text{µm} \), \( 635 \text{µm} \).

Not all of the \( ^4 \text{He} \) in the refrigerator can condense. Some of the helium remains gaseous and some fraction of the condensed helium is subsequently spent on the initial cool down. The amount of helium usable for steady state refrigeration is a strong function of \( T_c \). Ideally, as much as 0.8\( n_0 \) is available.

Agreement between the model and data is found when \( u_c = 1.2 \text{ m s}^{-1} \). While slightly larger than expected, we believe that in reality the film is thicker than \( t_0 = 30 \text{ nm} \) due to the approximately 0.05\( \text{µm} \) Ra\(^{18} \) surface roughness of the polished stainless orifice, and that the true \( u_c \) value is lower. It has been shown that when HeII flows over a rough surface its thickness is larger than when flowing over a smooth surface [127]. We also find for no external load on the refrigerator, \( a = 635 \text{ µm} \), \( T_0 = 0.612 \text{ K} \), \( P_1 = 0.047 \text{ N/m}^2 \), \( P_2 = 0.046 \text{ N/m}^2 \) and \( l = 2 \text{ mm} \), in agreement with expectations. With a condensation plate temperature of \( T_c = 4.2 \text{ K} \), the hold time is 40 hours. With \( T_0 = 2.9 \text{ K} \) the hold time is 90 hours at \( T_0 = 0.612 \text{ K} \). Since the pressure drop across the stainless steel pump tube is small and the thermal conductivity of stainless is small, the pump tube may likely be made much shorter but we have not investigated these geometries.

From Figure 2.24 it is evident that the optimal orifice size is determined by \( T_0 \), loading, and the desired hold time. As expected, for fixed pot temperature the hold time is a monotonically decreasing function of the constriction radius \( a \), since the matter transport rates through the constriction for the film increase with \( a \). The steady state temperature however, somewhat surprisingly exhibits a shallow minimum.

For small \( a \), \( (a < 570 \text{ µm} \) for no external loading) as \( a \) decreases \( T_0 \) increases since not enough helium can be removed from the evaporator pot to cool it efficiently. The behavior for large orifice radii, on the other hand, is more complicated and leads to the “hooks” on the lines of constant power loading. In increasing \( a \) starting from the minimum at \( a = 570 \text{ µm} \) (for our setup with no external load), the total mass loss rate increases. Thus a larger pressure drop across the pump tube is required to transport the gas to the pump, and \( P_1 \) increases. However, \( P_1 \) can never rise above the saturated vapor pressure \( P_0 \) of the helium in the evaporator pot, or else no gas could be transported through the orifice into the

\(^{18}\text{Ra} \) is an industry standard specification for average surface roughness. For most machining processes, the rms roughness is 1.3 times the Ra value. We give Ra so one can make a direct comparison to standard roughness gauges.
pump tube. Combined with the exponential temperature variation of the vapor pressure of helium, this sets a lower limit on $T_0$ which increases with $a$. However, this limitation could easily be overcome by using a wider pump tube to reduce the pressure drop. Figure 2.24 plots data for the 3 values of $a$ and the subsequent model fit.

Figure 2.24: Hold time vs. $T_0$ for various $a$ (given in $\mu$m), and loading values on the pot. The measured data are shown as symbols. While $T_c$ was not the same for each, we plot the scaled data for $T_c = 4.2$ K. For different values of $T_c$, simply shift the Y-axis to account for the new amount of He condensed. For example, with $T_c = 2.9$ K, 1.27 moles are condensed. With no loading and $a = 508 \mu$m, the hold time is 98 hours and so one would add 50 hours to all values on the Y-axis. The slight discrepancy between the model and data can be attributed to temperature read-out uncertainty.

2.3.5 Refrigerator Performance

Load curves taken in a cryostat test bed for the completed and optimized $^3$He and $^4$He refrigerators are shown in Figure 2.25. However, when installed in the cryostat there is additional loading on the $^3$He and $^4$He refrigerators. This is due to the various thermal joints and suspension systems between the actual $^3$He and $^4$He evaporation pots and the 300 mK and 800 mK stages. The plots in Figure 2.26 take this extra load into account, and plot the loading on the 300 mK detector array and 800 mK baffling stages as a function of the hold time in the refrigerator.
Figure 2.25: Refrigerator load curves for the $^3$He and $^4$He refrigerators in CCAM as measured in a separate cryogenic test bed. The plots show the temperature of the pots as a function of applied electrical power. Power is only applied to one stage at a time via heater resistors. The equations of best fit lines are given for reference. Note that the $^3$He cooler is roughly 1000 times less effective than the $^4$He cooler.
Figure 2.26: These plots of temperature vs. hold time incorporate the conductance $G$ between the refrigerator pots and the cold components of interest. The conductance is defined as $G = \frac{P_{\text{applied}}}{\Delta T}$. For example, the top plot shows the detector temperature vs. the $^3\text{He}$ refrigerator’s hold time. The bottom plot shows the $800 \text{ mK}$ baffle temperature vs. the $^4\text{He}$ refrigerator’s hold time.
<table>
<thead>
<tr>
<th>#</th>
<th>Fridge</th>
<th>Orifice Radius (µm)</th>
<th>Total Fridge Mass (g)</th>
<th>Total Fridge Volume (cc)</th>
<th>Helium Amount (STP Liters)</th>
<th>Charcoal Mass (g)</th>
<th>Measured Cooling Power (J)</th>
<th>No Load Hold Time (hrs)</th>
<th>No Load Base Temp (mK)</th>
<th>Current Placement</th>
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<tbody>
<tr>
<td>1</td>
<td>^4He</td>
<td>635</td>
<td>800</td>
<td>90</td>
<td>41.5</td>
<td>198</td>
<td>93</td>
<td>66</td>
<td>620</td>
<td>cryostat test bed</td>
</tr>
<tr>
<td>2</td>
<td>^4He</td>
<td>572</td>
<td>809</td>
<td>90</td>
<td>41.4</td>
<td>202</td>
<td>90</td>
<td>93</td>
<td>615</td>
<td>CCAM FB 1</td>
</tr>
<tr>
<td>3</td>
<td>^4He</td>
<td>508</td>
<td>804</td>
<td>90</td>
<td>41.5</td>
<td>200</td>
<td>88</td>
<td>98</td>
<td>610</td>
<td>CCAM FB 2</td>
</tr>
<tr>
<td>4</td>
<td>^3He</td>
<td>508</td>
<td>798</td>
<td>90</td>
<td>41.6</td>
<td>198</td>
<td>90</td>
<td>98</td>
<td>610</td>
<td>MBAC</td>
</tr>
<tr>
<td>5</td>
<td>^3He</td>
<td>508</td>
<td>797</td>
<td>90</td>
<td>41.5</td>
<td>198</td>
<td>92</td>
<td>98</td>
<td>610</td>
<td>MBAC</td>
</tr>
<tr>
<td>6</td>
<td>^3He</td>
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<td>246</td>
<td>27</td>
<td>6.15</td>
<td>43</td>
<td>5.3</td>
<td>&gt;240</td>
<td>215</td>
<td>cryostat test bed</td>
</tr>
<tr>
<td>7</td>
<td>^3He</td>
<td>N/A</td>
<td>245</td>
<td>27</td>
<td>6.15</td>
<td>42</td>
<td>5.5</td>
<td>&gt;240</td>
<td>215</td>
<td>CCAM FB 1</td>
</tr>
<tr>
<td>8</td>
<td>^3He</td>
<td>N/A</td>
<td>247</td>
<td>27</td>
<td>6.15</td>
<td>43</td>
<td>5.6</td>
<td>&gt;240</td>
<td>215</td>
<td>MBAC</td>
</tr>
</tbody>
</table>

Table 2.6: Sorption refrigerator properties. The hold time and base temperature measurements were acquired with no external applied load. The total refrigerator volume was calculated by placing the refrigerator under vacuum and measuring the amount of gas necessary to fill the refrigerator to a certain pressure. The ^3He refrigerator was not allowed to completely evaporate and run out since the no external applied load hold time was greater than ten days.
2.3.6 Integration in DB

The copper cold fingers from FB1 and FB2 feedthrough to the detector box (DB) which contains the detector package and read-out electronics. Because of the need to magnetically shield our multiplexing SQUIDS, attaching the cold fingers to the detector package is not trivial. Ideally Cryoperm, a cryogenic magnetic shielding material would surround the detector package with no holes for external magnetic fields to enter. In reality, this is impossible because feedthroughs are needed to allow electronic wiring and cryogenic fingers to enter the detector package.

The literature suggests that holes in the cryoperm shield with diameter $d$ should be additionally shielded with a $3d$ long cryoperm “snout.” This recommendation prompted us to have a Cryoperm cylinder with an “udder,” where the cold posts could be fed through to the detector package, as well as a small feedthrough in the back for focal plane housekeeping wiring. Figure 2.27 is a photograph of the cold fingers entering the detector box.

![Figure 2.27: Photograph of the detector box. The detector package, Cryoperm, and read-out electronics are not shown. The 300 mK cold finger comes in from the left (FB1) and the 800 mK cold finger comes in from the right (FB2).](image)

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The cold posts travel up the cryoperm udder to the detector package. Here they are thermally attached to the 300 mK detector package and 800 mK optics and baffling. Chapter 3 Section 3.30 will go into further detail on the heat sinking and design of the detector package. Figure 2.28 is a schematic of the detector box.

Figure 2.28: Schematic of the detector box. The red components are held at 50 K and the green and orange cryoperm are at 4 K. The detector box mates to the optics tube where cold baffling are attached. The baffles and other parts depicted in cyan are held at 800 mK. The 300 mK components are shown in purple.
2.3.7 Thermal Isolation and Heat Sinking

The limited cooling capacity of the pulse tubes and sorption refrigerators requires us to restrict the thermal loading on the 50 K, 4 K, 800 mK and 300 mK stages. This is not trivial because structural supports, electronic wiring, detector biasing, and detector read-out wiring all create loading. The anticipated heat loads on the different thermal stages can be calculated and minimized to ensure there is adequate cooling power. Heat loads can be computed and reduced by examining the method of thermal power transfer.

Conduction

The power conducted along a cryostat component with cross sectional area $A$, conductive path length $l$, and thermally sunk to two different temperature baths $T_{\text{high}}$ and $T_{\text{low}}$ can be calculated by,

$$P_{\text{con}} = \int_{T_{\text{low}}}^{T_{\text{high}}} A \frac{\kappa(T)}{T} dT,$$

(2.23)

where $\kappa(T)$ is the thermal conductivity of the component. Thus, to thermally isolate different temperature stages, materials that are physically strong but have low thermal conductivity are ideal for structural support. For carrying electric signals, wire materials high in electrical conductance but of low thermal conductance are optimal. In addition, minimizing the cross sectional area and/or increasing the thermal path length will decrease the conductive loading.

Thermal conductivities of different materials vary greatly depending on the method of heat conduction. Heat can be conducted by transport of electrons or lattice vibrations (phonons). If we consider the electrons and phonons diffusing through the material, a simple kinetic gas theory can be used to determine $\kappa$,

$$\kappa = \frac{1}{3} \frac{C(T)}{V_m} v \lambda \propto C(T),$$

(2.24)

where $V_m$ is the volume of the particle, $v$ is the velocity of the particles, $\lambda$ is the mean free path, and $C$ is the specific heat (per unit volume) [5] (pg.22). Qualitatively, the thermal conductivity $\kappa(T)$ is proportional to the element being transported in this case $C(T)$, the velocity of the particles $v$, and the distance traveled before being scattered, $\lambda$. The factor of $\frac{1}{3}$ considers the motion in only one direction instead of three dimensions. From Equation 2.24, it is evident that knowing the temperature dependance on the specific heat will enable us to estimate $\kappa$ as a function of temperature.
At low temperatures, $T \ll \Theta_D$, the specific heat has an electronic component and a photonic component, $C = C_{\text{phonons}} + C_{\text{electrons}}$. In this temperature range the contribution to specific heat from both photons and electrons scale with temperature as $C_{\text{photons}} \propto T^3$ and $C_{\text{electrons}} \propto T$.

Table 2.7 lists various materials we commonly use and their thermal conductivities $\kappa$. Note how the exponent of $T$ varies between more metallic materials and insulators.

Table 2.7: Thermal conductivity of various materials at cryogenic temperatures.

<table>
<thead>
<tr>
<th>Material</th>
<th>$\kappa$ (W/cm-K)</th>
<th>Temperature Range (K)</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>G-10</td>
<td>1.5e4 $T^{1.28}$</td>
<td>0.1 - 4</td>
<td>[134]</td>
</tr>
<tr>
<td>Kevlar,</td>
<td>3.9e-5 $T^{1.71}$</td>
<td>0.1 - 2.5</td>
<td>[10]</td>
</tr>
<tr>
<td>Vespel SP1</td>
<td>1.8e-5 $T^{1.26}$</td>
<td>0.1 - 1</td>
<td>[81]</td>
</tr>
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<td>Manganin</td>
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<td>1 - 4</td>
<td>[22]</td>
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<tr>
<td>NbTi</td>
<td>7.5e-5 $T^{1.85}$</td>
<td>4 - 9</td>
<td>[116]</td>
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<td>1.5e-4 $T^2$</td>
<td>0.1 - 1</td>
<td>[94]</td>
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<td>0.39 $T^{1.9}$</td>
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<td>[94]</td>
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<td>0.93 $T^{1.23}$</td>
<td>0.3 - 4</td>
<td>[35]</td>
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<td>0.64 $T$</td>
<td>0.05 - 3.0</td>
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<td>Al$_2$O$_3$ (Sapphire)</td>
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</tbody>
</table>

To mechanically support the copper posts that enter up the Cryoperm udder to cool the 300 and 800 mK stages, we use a Vespel SP-1 tube, (6 mm O.D. and 0.2 mm thick) and G-10 tube (a 6 mm O.D. and 0.3 mm thick), respectively. To minimize the conduction from the posts to the 4 K plate, the tubes are anchored with Scotch-weld 2216 epoxy to an aluminum plate on the 4 K stage, travel up a bored hole in the copper posts, and are affixed inside near the top of the copper posts by Scotch-weld 2216 epoxy to increase the conduction length along the tubes. Adding this extra length of Vespel Sp-1 and G-10 decreases our thermal loading on the 300 and 800 mK stages by 80%. The aluminum plate is bolted to the 4 K

---

$^{20}$The Debye temperature, $\Theta_D$, is a measure of the temperature below which phonons begin to freeze out.
baseplate and is adjustable to ensure the Vespel SP-1 and G-10 tubes only contact the top of the copper posts keeping the conduction length as long as possible. A taut kevlar\footnote{Kevlar expands when cooled. To ensure that each kevlar “spider web” or rig is held taut, multiple Belleville washers are used.} rig mounted on the 4 K baseplate keeps the posts from moving laterally. Kevlar “spider webs” support the 300 mK detector tube from the 800 mK radiation shield, the pots of the three sorption refrigerators, and the cold fingers as they are fed from the fridge boxes into the detector box.

The housekeeping and detector read-out wires are also a significant source of conductive loading. Thus, low thermal conductivity wires are essential. Longer wires would additionally help, but this fuels other problems such as electrical pickup. In CCAM, the thermometry wires are small manganin wires $5 \times 10^{-3}$ inches, (0.13 mm) in diameter and the electronic read-out wires are superconducting niobium titanium (NbTi). Both materials have high electrical conductivity but low thermal conductivity.

**Radiation**

The power emitted by a radiative component with temperature $T$, emissivity $\epsilon$, and area $A$ can be computed by the Stefan-Boltzmann law,

$$P_{\text{rad}} = A \times \sigma \epsilon T^4,$$

where $\sigma=5.67 \times 10^{-8}$ Js$^{-2}$m$^{-1}$K$^{-4}$ is the Stefan-Boltzmann constant. Notice the power conducted is proportional to $T^4$, $A$, and $\epsilon$. Thus, the largest radiative loadings in CCAM are:

- Emission from the large area, high temperature, but low emissivity vacuum shell.
- Emission from the large area, but low emissivity radiation shields for higher temperature stages on lower temperature stages.
- Radiation incident on the detectors from the high temperature surroundings entering through the vacuum window.

To minimize the radiation loading from the vacuum shell and radiation shields, each shell is covered in 10-20 layers of aluminized mylar or “superinsulation” or “MLI.”\footnote{CCAM’s superinsulation, part number is NRC2-Cryolam Crinkled, was purchased from MPI Technologies (Email: Price@mpirelease.com).} The mylar substrate has low thermal conductivity and is lightweight while the thin layer of aluminum...
has low emissivity which acts as a reflector. Our MLI is composed of 250-300 Å of 99.6% pure aluminum on 25 gauge mylar.

**Joule Power**

Joule heating is a result of a resistance to an electrical current in a conductor. If a current $I$ is applied to a resistor or wire with impedance $R$, the conducted power, $P_{\text{joule}}$, can be calculated by,

$$P_{\text{joule}} = I^2 R. \quad (2.26)$$

At low enough temperatures, superconducting wire such as NbTi is often used to suppress Joule heating. For isothermal wires, copper is used for its low electrical resistivity, $R$.

Using Table 2.7, the power loading associated with specific components can be computed. Tables 2.11, 2.10, 2.8, and 2.9 list the anticipated calculated load on each thermal stage. The measured performance is also given.

<table>
<thead>
<tr>
<th>Component</th>
<th>Load in $\mu W$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermometry wires to He3 pot</td>
<td>0.3</td>
</tr>
<tr>
<td>Kevlar He3 pot spider web</td>
<td>1.1</td>
</tr>
<tr>
<td>Kevlar support for feed to DB</td>
<td>4.1</td>
</tr>
<tr>
<td>Radiation in FB 1</td>
<td>0.8</td>
</tr>
<tr>
<td>Vespel “post” support</td>
<td>4.0</td>
</tr>
<tr>
<td>Lateral kevlar support for “post”</td>
<td>0.3</td>
</tr>
<tr>
<td>Detector bias and read-out wires</td>
<td>2.5</td>
</tr>
<tr>
<td>Thermometry wires at the detector</td>
<td>0.2</td>
</tr>
<tr>
<td>Kevlar supports to 800 mK shell</td>
<td>&lt;0.0</td>
</tr>
<tr>
<td>Radiation in DB</td>
<td>2.7</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>16 $\mu W$</strong></td>
</tr>
<tr>
<td><strong>Measured Total</strong></td>
<td><strong>17 $\mu W$</strong></td>
</tr>
</tbody>
</table>

Table 2.8: Load analysis for the 300 mK components.
Table 2.9: Load analysis for the 800 mK side. *We are still uncertain of the source of extra loading measured on the 800 mK stage. Most likely it is due to a radiation leak. However, for our cryogenic purposes, the extra loading on the 800 mK stage does not pose a problem for our detectors.

<table>
<thead>
<tr>
<th>Component</th>
<th>Load in µW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermometry wires to He4 pot</td>
<td>0.1</td>
</tr>
<tr>
<td>Kevlar He4 pot spider web</td>
<td>1.0</td>
</tr>
<tr>
<td>Kevlar support for feed to DB</td>
<td>4.1</td>
</tr>
<tr>
<td>Radiation in FB 2</td>
<td>34.6</td>
</tr>
<tr>
<td>G-10 “post” support</td>
<td>5.5</td>
</tr>
<tr>
<td>Lateral kevlar support for “post”</td>
<td>0.3</td>
</tr>
<tr>
<td>G-10 supports in optics tube</td>
<td>121.8</td>
</tr>
<tr>
<td>Thermometry wires at the baffle</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>Radiation in DB</td>
<td>13.6</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>180 µW</strong></td>
</tr>
<tr>
<td><strong>Measured Total</strong></td>
<td><strong>500 µW</strong></td>
</tr>
</tbody>
</table>

Table 2.10: Load analysis for the 4 K thermal stage. The radiation loading is computed by determining the surface area exposed to the 50 K thermal stage, taking \( \epsilon = 0.07 \) [140] for ten sheets of superinsulation, and utilizing Equation 2.25 where \( T \) is the temperature of the 50 K thermal stage. For the above, we use an effective area \( A = 0.60 \text{ m}^2 \).

<table>
<thead>
<tr>
<th>Component</th>
<th>Load in mW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiation from 50 K shell</td>
<td>15</td>
</tr>
<tr>
<td>G-10 support tubes</td>
<td>20</td>
</tr>
<tr>
<td>Titanium supports</td>
<td>5</td>
</tr>
<tr>
<td>Cryogenic wiring</td>
<td>5</td>
</tr>
<tr>
<td>Detector wiring</td>
<td>30</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>175 mW</strong></td>
</tr>
<tr>
<td><strong>Measured Total</strong></td>
<td><strong>200 mW</strong></td>
</tr>
<tr>
<td>Component</td>
<td>Load in W</td>
</tr>
<tr>
<td>-------------------------------</td>
<td>-----------</td>
</tr>
<tr>
<td>Radiation from vacuum shell</td>
<td>20</td>
</tr>
<tr>
<td>G-10 support tubes</td>
<td>3</td>
</tr>
<tr>
<td>Titanium supports</td>
<td>0.3</td>
</tr>
<tr>
<td>Cryogenic wiring</td>
<td>0.1</td>
</tr>
<tr>
<td>Detector wiring</td>
<td>0.5</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>24 Watts</strong></td>
</tr>
</tbody>
</table>

Table 2.11: Load analysis for the 50 K thermal stage. The radiation loading is computed by determining the surface area exposed to 300 K, taking $\epsilon = 0.07$ [140] for ten sheets of superinsulation, and utilizing Equation 2.25. The measured performance is determined by observing the base-line temperature of the thermal stage in question, and comparing it to the pulse tube performance chart. Notice the 1 Watt difference between the anticipated calculated load and the measured load. The uncertainty on the calculation is approximately 10-20% and so the agreement is illusory. Other effects are (1) Not fully determining the surface area unable to be superinsulated. This would allow 300 K radiation unshielded and thus straight into the 50 K thermal stage. For the above, we use an effective area $A = 0.66 \text{ m}^2$. (2) The G-10 support tubes have less than ten layers of superinsulation. Placement of this superinsulation was unfortunately an afterthought after the cryostat was assembled, and thus hard to place without full disassembly of the cryostat. (3) Finally, the measured load can substantially depend on how well the two pulse tubes are functioning. For a few months, the pulse tube in FB1 was not performing to spec, causing the first stage (50 K thermal stage) to run warmer than usual.

### 2.4 Thermometry and Housekeeping

CCAM uses two types of thermometers to read-out temperatures in the cryostat. For temperatures between 300 K - 2.5 K, such as the 50 K stage and the sorption refrigerator pumps, we use Lake Shore Cryotronics, Inc.\(^{23}\) DT-470 and DT-670 silicon diodes. The diodes are biased with 10 $\mu$A, and are two lead measurements to decrease the amount of wiring necessary. Current biased, four lead ruthenium oxide (ROX) temperature sensors are used for temperatures under 2.5 K. The heaters used to servo various thermal stages and heat the refrigerator pumps are controlled by a heater break out box (HBOB). The HBOB, built by E. Switzer, consists of a circuit board that sources current to the heaters. A computer interface to this card allows the heaters to be servoed using the read-out of the diodes and ROX’s.

\(^{23}\)Lake Shore Cryotronics, Inc., http://www.lakeshore.com/ Telephone: (614) 891-2244
Read-out is accomplished through three main systems: BLAST DAS (Data Acquisition System), ABOB (Analog Break out Box) and encoders, which all feed into a single housekeeping computer [47]. The BLAST DAS is used for high rate housekeeping data logging and for control of heaters in the cryostat. The ABOB is used to monitor the remaining systems such as inclinometers and ambient temperatures.
Chapter 3

The CCAM Detector Array

3.1 Introduction

A new type of detector array assembly is used in CCAM to observe millimeter-wave radiation at 145 GHz. The array consists of an $8 \times 32$ array of nearly-touching 1.05 mm$^2$ transition-edge sensor (TES) detectors [76, 56] and are read-out by time-domain SQUID (superconducting quantum-interference device) multiplexers [19, 29]. This new generation of close-packed, SQUID multiplexed TES detectors have advantages over traditional bolometer arrays:

1. The low noise, low power, and low impedance time-domain SQUIDs multiplexers enable the integration of TESs into thousand element arrays while maintaining a manageable$^1$ number of read-out channels. For example, the number of electrical connections for a $32 \times 32$ detector array decreases from 4096 wires to 384 by switching from non-multiplexed conventional read-out to SQUID multiplexer technology.

2. Close-packing the detectors enables the focal plane to be populated with considerably more detectors than previous CMB experiments.

3. Electrothermal feedback resulting from voltage biasing the detectors increases the range of the detectors and increases their speed.

4. Close-packing the pixels into an array maximally uses the available focal plane area.

---

$^1$The number of electrical connections to the detectors held at 300 mK are minimized as much as possible to reduce both electrical and thermal power dissipation through the wires from the cold detector stage to the 4 K electronics.
The detectors used in CCAM are pop-up TESs developed by Harvey Moseley, Jay Chervenak, Christine Allen and colleagues at NASA’s Goddard Space Flight Center (GSFC), and are read-out by time-domain SQUID multiplexers fabricated by Kent Irwin, Gene Hilton, and colleagues at NIST. These components are assembled at Princeton to form columns of $1 \times 32$ detectors and accompanying read-out electronics which are then stacked on top of one another to form the $8 \times 32$ multidimensional array. The information gathered from constructing and reading out the CCAM array will be utilized for manufacturing three similar $32 \times 32$ detector arrays for MBAC to observe the CMB at 145 GHz, 220 GHz, and 265 GHz. This chapter introduces close-packed TES detectors and time-domain SQUID read-out systems and then describes the key technologies developed specifically for CCAM’s $8 \times 32$ array.

3.2 TES Detector Basics

Bolometric detectors are commonly used to observe the CMB. Bolometers measure fluctuations in the heat input from the surroundings by converting it into a measurable quantity such as voltage or current. A bolometer typically consists of an absorber and a thermometer of heat capacity $C$, connected by a small thermal conductance $G$, to a heat sink held at a fixed temperature $T_{\text{bath}}$ (see Fig 3.1). Incoming optical power $P_{\text{opt}}$ incident on the bolometer raises the temperature $T$ of the bolometer causing a change in the resistance of the bolometer. By measuring the change in resistance, we can determine the change in incident radiation. Therefore, the ideal bolometer is usually made of a material that has a large change in resistance for a small change in temperature.

CCAM utilizes TESs biased in their steep $R$ vs. $T$ superconducting transition. This transition from normal ($R_n \approx 21 \text{ m}\Omega$) to superconducting happens at the critical temperature, $T_c \approx 0.5 \text{ K}$, over approximately 2 mK. The temperature coefficient of resistance, $\alpha$, quantifies the change of resistance with temperature by:

$$\alpha = \left(\frac{T}{R}\right) \left(\frac{dR}{dT}\right).$$

(3.1)

A fit to the measurements of the CCAM detectors finds $\alpha$ is approximately $100 \pm 20$.\(^2\)

\(^2\)The data used in the fit to find $\alpha$ was taken in the Super Rapid Dip Probe (SRDP) cryostat in Princeton. The SRDP will be described in more detail later in this chapter.
Figure 3.1: Simple thermal (a) and electrical (b) schematic of a single TES circuit. (a) Incident optical power, $P_{\text{opt}}$, on the absorber raises the temperature $T$ of the TES with heat capacity $C$. The detector is heat sunk to the thermal bath, $T_{\text{bath}}$, by a weak thermal link with thermal conductance $G$. (b) The TES is voltage biased by ensuring both, (i) $R_{\text{bias}} \gg R_{\text{TES}}$ and (ii) $R_{\text{shunt}} \ll R_{\text{TES}}$. Optical power incident on $R_{\text{TES}}$ thus causes a change in current that subsequently flows through an inductor, $L_{\text{in}}$. The changing current through the inductor induces a measurable magnetic flux in a nearby SQUID. Thus, calculating the SQUID response allows us to determine the change in incident power. Figure courtesy of [11].

Past CMB experiments have utilized arrays of individually made bolometers [14], but advances in TES microfabrication now allow scientists to develop CCD-like cameras that consist of arrays of nearly touching detectors. By close-packing the pixels, nearly all the photons collected by the telescope are detected by the receiver. CCAM’s 8×32 detector array, based on this new technology was built to test this concept. This is accomplished by fabricating eleven 1×32 flat “columns”, Figure 3.2(b) on a 100mm diameter wafer, Figure 3.2(a).
Figure 3.2: (a) Wafer map of the flat 1×32 TES columns during fabrication. The nomenclature used to distinguish individual 1×32 columns consists of a letter or series of letters to designate particular wafers, then numbers which correspond to where on the wafer the TES column was fabricated. Figure courtesy of Jay Chervenak. (b) A 1×32 TES detector column. This column is actually comprised of 33 pixels. The last pixel on the right, is a pixel with absorber but without a TES. This pixel is leftover from an initial design of using heaters on each pixel but the 33rd. Aluminum traces connect each TES to wire bond pads at the bottom of the column. From these pads, wire bonds connect to the read-out circuitry. The four holes at the corners and dicing lines are for folding the TES chip into its pop-up configuration. The fold procedure will be discussed later in this chapter. (c) A single pixel. (d) A closeup of the MoAu TES. The gold bars and stripes on the TES suppress excess noise by creating non-superconducting regions that guide the direction of current flow through the superconducting region [124]. Photographs courtesy of O. Stryzak.
There are four components to each pixel: (1) the silicon substrate, (2) the implant, (3) the TES, and (4) the legs/wiring. The silicon substrate is implanted so that it absorbs microwave radiation. The TES occupies a small part of the pixel and absorbs the thermal energy in the absorber. The legs are the weak thermal link that carry the signal to the thermal bath and ultimately the read-out electronics.

The absorber for each pixel is made from $1.05 \text{ mm} \times 1.05 \text{ mm} \times 1.4 \mu\text{m}$ thick silicon, implanted with phosphorus ions (n-type) to optimize the impedance for absorption of our frequency radiation, Figure 3.2(c). After the ion implant, the impedance of the silicon absorber is $100 \pm 10 \Omega/\text{sq}$.

The TES, Figure 3.2(d), is a $75 \mu\text{m} \times 80 \mu\text{m}$ MoAu superconductor fabricated on top of the silicon absorber to measure the phonon temperature of the absorber membrane. Together, gold and molybdenum have the benefit that they do not form intermetallics which would degrade the TES over time. The gold additionally provides protection to the MoAu TES because of its resistance to corrosion.

Leads from the TES, which consist of approximately 1.5% of the pixel area, carry the signal to narrow silicon legs, $5 \mu\text{m}$ wide which create and determine the weak thermal link, $G$, to the thermal bath, $T_{\text{bath}}$. To form the close-packed array, each flat $1 \times 32$ column is folded into a pop-up configuration and stacked.

The Super Rapid Dip Probe (SRDP) [84] cryostat designed and constructed by N. Jarosik, is used to cool and quantify individual $1 \times 32$ TES columns. The SRDP can reach $300 \text{ mK}$ in approximately three hours whereas it takes the CCAM cryostat six days to cool to $300 \text{ mK}$. This makes the SRDP a valuable tool for measuring the properties of TES columns with a rapid turn around time. Each TES column is cooled and quantified in the SRDP before being incorporated into the array. The physical device properties of our TES detectors are shown in Table 3.1. Figure 3.3 shows the $T_c$’s and normal resistances of all eight columns in the CCAM detector array as measured in the SRDP.

Molybdenum (Mo) transforms into a superconductor at a critical temperature, $T_c$, of $1.1 \text{ K}$, while gold (Au) is a noble metal and never makes the superconducting transition. The Mo/Au interface results in a $T_c$ of approximately $500 \text{ mK}$ (see Figure 3.3) which is lower than the critical temperature of Mo alone. This decrease in critical temperature, known as
To distinguish individual 1×32 columns once the TES chip is paired with its read-out chips, we devised a naming scheme where column cards are labeled by which array they are intended for (such as: “8×32”) followed by a unique number. RS 31 corresponds to the left hand side of the column in Figure 3.2. The top graph shows the transition temperatures of the eight 1×32 columns in CCAM. The variation in $T_c$ across each column is due to the unavoidable thinner deposition of molybdenum and gold on the edges of the large 100 mm diameter wafer. The direction in which $T_c$ varies as the row select increases is dependant on the orientation of each column during fabrication. The bottom graph plots the normal resistances of each pixel in the 8×32 array in CCAM. The plot shows some variation in normal resistances between individual columns. These columns were from the trial production run and thus less accurate but subsequent column productions have been much closer to the 21 mΩ specification. Plots courtesy of M. Niemack.
<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>TES Critical Temperature, $T_c$</td>
<td>$\approx 520 \text{ mK}$</td>
</tr>
<tr>
<td>Absorber Thickness</td>
<td>1.4 $\mu$m</td>
</tr>
<tr>
<td>Single Pixel Absorber Dimensions</td>
<td>$1.05 \text{ mm} \times 1.05 \text{ mm}$</td>
</tr>
<tr>
<td>Implant Impedance</td>
<td>$100 \pm 10 \Omega/\text{sq}$</td>
</tr>
<tr>
<td>Implant Type</td>
<td>Phosphorus Ions, n-type</td>
</tr>
<tr>
<td>Leg Width</td>
<td>5 $\mu$m</td>
</tr>
<tr>
<td>Number of Normal Bars on TES</td>
<td>4</td>
</tr>
<tr>
<td>TES Dimensions</td>
<td>$75 \mu$m $\times$ 80 $\mu$m</td>
</tr>
<tr>
<td>TES Material</td>
<td>MoAu</td>
</tr>
<tr>
<td>Normal TES Resistance, $R_n$</td>
<td>21 m$\Omega$</td>
</tr>
<tr>
<td>Molybdenum (Mo) $T_c$</td>
<td>915 mK</td>
</tr>
<tr>
<td>Gold (Au) $T_c$</td>
<td>non-superconducting</td>
</tr>
<tr>
<td>TES Temperature Coefficient of Resistance, $\alpha$</td>
<td>$100 \pm 20$</td>
</tr>
</tbody>
</table>

Table 3.1: Physical device properties of the $8 \times 32$ detector array in CCAM.

the Superconducting Proximity Effect (SPE), is a result of the contact between the normal gold and superconducting molybdenum.3

The thicknesses of the molybdenum and gold are determined by the desired normal resistance and critical temperature of the TES. ACT’s low 21 m$\Omega$ target normal resistance constrains the electrically resistive gold thickness. The molybdenum thickness is then tuned to the fixed gold thickness to achieve the desired critical temperature.

To read-out such a large number of detectors in the array, CCAM and MBAC will use SQUID multiplexing technology which provides the capability to read-out many more detectors at a given time.

### 3.2.1 Biasing and Read-out

Most of the biasing and read-out development at Princeton was done by M. Niemack, so a detailed description will be given in M. Niemack’s thesis [90]. A summary is included here for completeness.

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3SPE describes the effect when a superconducting material is placed in contact with a non-superconducting material. The critical temperature $T_c$ often decreases in the superconductor while the non-superconducting material begins to show signs of weak superconductivity. This effect is caused by diffusion between the superconductor and normal material. Electronic excitations diffuse from the non-superconducting material into the superconductor while the Cooper pairs in the superconductor diffuse into the non-superconducting material.
If each TES is roughly voltage biased with $R_{\text{bias}} \gg R_{\text{TES}}$, the TESs will respond to a change in incident radiation by changing its resistance. Then, by measuring the resulting current change, we can deduce the amount of incident power on the detector. The detectors are voltage biased to take advantage of:

- **SQUID read-out.** By voltage biasing the detectors, we can calculate the change in resistance of the TES by measuring the resulting change in current using low-noise cryogenic SQUIDs. When the current from the TES is sent to an inductor, a magnetic field will be produced. A second inductor can be used to couple the induced magnetic flux from the first inductor to the SQUIDs [19].

- **Electrothermal feedback.** Electrothermal feedback widens the operating range of the TES and increases speed [76, 55]. When power incident on the TES increases, the resistance of the TES will increase creating a drop in the bias power ($P = V^2/R_{\text{TES}}$) dissipated in the TES. Thus, the incoming radiation will be compensated by the decrease in Joule power through the TES. In this feedback mode, the TES is usually able to be kept biased near the middle of the superconducting transition where it is most sensitive.

We avoid using low-resistance electrical lines for voltage biasing the detectors to prevent overloading the 300 mK detector stage with the power loading associated with high thermal conductivity wires. Instead, voltage biasing is accomplished using superconducting NbTi wires, with an external current source followed by a small cold bias resistor, $R_{\text{shunt}}$, in parallel with the TES, as shown in Figure 3.1(b). To ensure the TES is voltage biased, $R_{\text{shunt}} \ll R_{\text{TES}}$. For each 1×32 TES column there is an associated shunt chip manufactured at GSFC with thirty-two individual molybdenum nitride, (MoN) resistors with a nominal resistance at 300 mK of 0.7 mΩ, as shown in Figure 3.4.

After the current flows through the TES, it travels through the coupling inductor, $L_{\text{in}}$. The magnetic flux, $\Phi$, generated by the current flowing through $L_{\text{in}}$ changes the flux in a SQUID placed near $L_{\text{in}}$. The SQUID has a voltage response to the current flowing through $L_{\text{in}}$ according to:

$$V = \frac{R}{2} \left( I^2 - [2I_c \cos(\pi \phi / \phi_0)]^2 \right)^{\frac{1}{2}}, \quad (3.2)$$

where $I$ is the SQUID bias current, $R$ is the resistance of each Josephson junction, $I_c$ is the SQUID’s critical current, $\phi$ is the magnetic flux through the SQUID generated by the
Figure 3.4: Shunt chip. Each TES is voltage biased by using an external current source followed by a small cold MoN resistance resistor in parallel with the TES. The resistors are microfabricated in a row of 32, one for each TES in a 1×32 column, to produce a small cold resistance of approximately 0.7 mΩ. Ensuring $R_{\text{shunt}} \ll R_{\text{TES}}$ is not trivial. GSFC has developed a unique geometry of various metals to accomplish this as can be seen in the top blow up photographs of the shunt chip. Photographs courtesy of O. Stryzak.

$\phi_0 \equiv \hbar/2e$ [129]. When $L_{\text{in}}$ generates flux in the SQUID, the SQUID response moves along the $V-\Phi$ curve as illustrated in Figure 3.5(a). As can be seen from Equation 3.2 and Figure 3.5(a), the voltage response to the magnetic flux is periodic. To make accurate measurements with the SQUIDs, the SQUID output must be linearized such that the feedback is proportional to $I_{\text{TES}}$. This is accomplished by running in a flux locked loop (FLL).
Figure 3.5: (a) The relationship between the applied voltage to the SQUID and the resulting magnetic flux. This is given by Equation 3.2. The lowest curve corresponds to the optimal bias current with the maximum V-Φ amplitude. The higher curves correspond to an increase in the bias current. (b) Simplified schematic of the flux locked loop. The FLL takes the change in flux on the SQUID produced by $L_{in}$ and feeds it into the MCE. The MCE uses a digital PID algorithm to calculate the feedback current necessary to keep the SQUID output linear. The FLL keeps the output linearized by placing a second inductor, the feedback inductor, $L_{fb}$, near the SQUID providing the correct feedback current to null the flux and keep the SQUID response in the linear regime.

The FLL takes the change in flux on the SQUID produced by $L_{in}$ and feeds it into room temperature MultiChannel Electronics (MCE) supplied by M. Halpern and colleagues at the University of British Columbia. The MCE uses a digital PID algorithm to calculate the feedback current necessary to keep the SQUID output linear. The FLL keeps the output linearized by placing a second inductor, the feedback inductor, $L_{fb}$, near the SQUID providing the correct feedback current to null the flux and keep the SQUID response in the linear regime. Once locked, the SQUID output goes to zero and the feedback becomes a measurement of our detector signal. Optical fibers transmit the data from the MCE to the data acquisition computer which can be operated remotely. Figure 3.5(b) shows the basic FFL circuit.

\footnote{There are multiple elements between the SQUID and MCE but the basic concept is the same, and thus will not be detailed here.}
3.2.2 Multiplexing

Reading a single flux locked SQUID (and thus one TES) requires four wires: two to supply the bias current and two to supply the current to the feedback inductor. For a $32 \times 32$ array, this results in over 4000 wires heat sunk to the 300 mK detector stage. In addition to being a nightmare to organize, thousands of wires would put a catastrophic thermal load on the $^3$He sorption refrigerator. To circumvent this problem, the detectors are multiplexed with the NIST time-domain multiplexing system. The multiplexing technology biases the detectors row by row and samples each pixel individually thus decreasing the number of wires going between the 4 K and 300 mK stages. With this method we have achieved sampling of $\approx 500 \text{ kHz}$ per row while at the same time reducing the number of wires for a $32 \times 32$ array to a few hundred wires.

To multiplex an array, each TES detector is coupled to a dedicated “stage-1” (S1) or first-stage SQUID amplifier. The first-stage amplifiers are configured in a column format. The signals from all S1 SQUIDs in a given column are summed and routed to a “stage-2” (S2) or second-stage amplifier. Each S1 SQUID is turned on sequentially, so that the signal from the corresponding element is presented to the S2 at a given times. Since the other S1 SQUIDs remain in a superconducting state, they contribute no signal or noise and dissipate no power. Thus, multiplexing the S1 amplifiers decreases the necessary signal output lines to a single output channel per column. In addition, the address lines for a row of S1 SQUIDs can be wired in series, so only one set of address lines is required per row of the array. The room temperature MCE then processes the signals from each column, controls the timing of the row multiplexing, and applies the switched feedback signal to a common feedback line for each column.

An electrical schematic of how the time-domain multiplexing system reads out TESs is shown in Figure 3.6. A $2 \times 2$ array is shown in Figure 3.7 as an example of how an N-row by M-column array is time-domain multiplexed.

Both the S1 SQUIDs and S2 SQUID for each $1 \times 32$ column are contained in the multiplexer (mux) chip, provided by NIST. This chip is thermally sunk to the 300 mK stage. Figure 3.8 highlights the important features of the mux chips installed in CCAM’s $8 \times 32$ detector array. The signal from the S2 SQUIDs are then carried from 300 mK to the 4 K “series array” (SA) SQUIDs which amplify the signal [90]. The series array is affixed to a circuit board that is then mounted to the 4 K baseplate of the detector box.
Figure 3.6: Electrical schematic of the multiplexing scheme. Each column has 32 stage 1 SQUIDs, one for each TES. At the end of each multiplexing chip is a single stage 2 SQUID. The series array for each column, shown at the top of the schematic is held at 4 K. Figure courtesy of D. Benford. Photographs courtesy of O. Stryzak.
Figure 3.7: A $2 \times 2$ array to demonstrate how an N-row by M-column array is time-domain multiplexed. Each TES is constantly biased while rows of stage 1 SQUIDs are turned on and off sequentially. Once transients settle, $I_{TES}$ is sampled and the next row is sampled. The nonlinearity of SQUIDs requires the signals to be read-out in a feedback mode using digital feedback. This is accomplished in the warm multichannel electronics (MCE) provided by Mark Halpern’s group at the University of British Columbia. Figure courtesy of R. Doriese.
Figure 3.8: The multiplexer (mux) chip. The mux chip reduces the number of wires necessary to read-out the TES detectors by biasing the detectors row by row and sampling each pixel individually. For a given 1×32 column, there is an associated microfabricated mux chip that contains 32 stage 1 SQUIDs which read-out each TES signal, and a stage 2 SQUID which combines the 32 individual signals. The signal is then sent to the series array held at 4 K. Photographs courtesy of O. Stryzak.

To band limit the TES output, a Nyquist chip with individual inductors for each TES is utilized. The inductance $L$ necessary can be determined by [90],

$$L \geq \frac{R_{TES} \gamma}{\pi F_{pixel}} N,$$

(3.3)

where, $\gamma=3$ sets the Nyquist filtering to an acceptable level, $F_{pixel}$ is the rate at which the SQUIDs are multiplexed, $N$ is the number of SQUID channels in a column, and $R_{TES}$ is the bias resistance of the detector. From $R_{TES}$ data gathered from the SRDP, we chose an inductance value of 700 nH. A photograph of the Nyquist chip is shown in Figure 3.9.
3.2.3 Optical Optimization of the TES

A novel method for improving the optical efficiency of the detectors combines an antireflection (AR) coupling layer with a partially absorbing backshort. This approach was suggested to us by Harvey Moseley and Ed Wollack at GSFC. The AR coupling layer is placed a calculated distance from the front of the pixel array to minimize reflections. Together, the silicon and vacuum gap act to suppress reflections off of the pixels. In addition, for each column, there is a partially absorbing backshort of silicon with a thinly doped absorber on the back side that is positioned behind the pixels. By utilizing an absorbing backshort behind the pixels, some of the small asymmetries from folding the TES is mitigated. Figure 3.10 depicts the configuration of the optical optimizing components. With reasonable tolerances on mechanical spacings and surface impedances, we have implemented these components resulting in calculated absorptions of $\sim$70% in-band radiation absorbed in the bolometer with $\geq$20% of the remainder absorbed in a backshort. The AR coupling layer consists of a $2.5\,\text{cm} \times 6.3\,\text{cm} \times 50\,\mu\text{m}$ thick silicon placed 110$\mu\text{m}$ in front of the array face. Together, the silicon and vacuum gap are tuned to be the AR coupling layer. The resistivity of the
Figure 3.10: Configuration of optical optimizing components. Incident light first reaches the 50 μm thick silicon + 110 μm vacuum gap AR coupling layer. The radiation that travels through the AR coupling layer is then largely absorbed by the TES pixel. The backshort behind the pixels is in place to absorb as much of the remaining radiation as possible.
silicon was measured by E. Wollack to be 60 Ω·cm at room temperature. Concern about the brittleness of 50 µm thick silicon prompted the window to be strengthened by sandwiching the 50 µm AR coupling silicon with two 300 µm thick silicon frames. To support the AR window exactly 110 µm in front of the detectors, a custom copper mount that bolts to the front of the array holder and fixes the distance of the AR window was designed. Figure 3.11 demonstrates the strong dependance of the vacuum gap between the AR silicon window and the pixel face.

![Figure 3.11: Plot of the optical efficiency as a function of the vacuum gap between the AR silicon window and the array face. The absorption (gold solid line) and reflection (blue solid line) are both plotted along with the total optical efficiency (dashed gold line). In addition, both polarizations are plotted. The figure is courtesy of S. Staggs.](image)

The AR window is placed in the copper mount and beryllium copper springs are installed to ensure the silicon window is thermally sunk and doesn’t move upon cooling to 300 mK. Numerous dunk tests in LN₂ showed if the silicon frame was allowed to rest completely on the copper mount, the difference in thermal contraction and the force from the BeCu springs would cause enough friction between the two different materials to crack the silicon window. To combat this, the copper mount was milled down everywhere except where the springs pushed down on the silicon AR window. This created platforms for the AR window to rest on. The effect was predicted by Harvey Moseley.\(^5\)
Figure 3.12: (a) Top view and side diagrams of the AR coupling window. Note: drawings are not drawn to scale. (b) Photograph of the AR window clamped down in its copper mount by beryllium copper springs. Beryllium copper was used for its “springiness”, its close coefficient of thermal of expansion to copper, and high thermal conductivity. The thick window frame is visible as is the thin 50µm thick AR layer. Once assembled, the copper AR window holder is bolted to the front of the stop blocks of the array holder. The depth of the copper holder determines the spacing between the AR window and the TES pixels.

coupling window to sit on and be held in place by the springs while reducing the amount of silicon in contact with the copper. Further dunk tests in LN$_2$ proved this modification to be successful. The final design is shown in Figure 3.12.

The silicon backshorts wafers, supplied by GSFC, are ground and polished to 140µm, then n-type ion-implanted on the back for a target impedance of 30Ω/sq. Witness samples show this target was met to within 10%. At Princeton, the implanted wafer is laser diced into the configuration shown in Figure 3.13, and placed in designed slots behind each TES column chip during the TES fold procedure. The assembly procedure of the backshort and TES will be discussed in Section 3.3.4. Post-fold, the backshort fills 95% of the absorbing
Figure 3.13: The backshort. The total height of the backshort is 1000 µm and is keyed on one side to indicate the implanted side, as shown in the figure. Radiation hits the non-implanted silicon side first. The steps on either side allow the backshort to be placed in the unfolded TES, glued in position, and then folded. This is discussed in Subsection 3.3.4.

pixel area. Unlike the AR window, the distance between the backshort and array face does not effect the total optical efficiency.

3.3 Array Assembly

3.3.1 Benefits vs. Manufacturing Challenges

We believe that the use of using close-packed, multiplexed TES detectors will result in better control of systematic errors. However, reliably manufacturing folded stackable, 1×32 columns of TES detectors with accompanying multiplexing read-out chips is not trivial. This new technology introduces many practical challenges that need to be solved. Electrically, the electrical connections between components need to have minimal parasitic resistance and a method of sending signals from the individual column cards to the backplane where they are collected and sent to the 4K series array. In addition, each of these electrical connections must be reliable at cryogenic temperatures. If a critical line such as the detector bias opens up, the entire array would be unusable. Mechanically, a robust holder needs to be constructed that will not break the columns from differences in thermal contraction as
the array cooled. At the same time, the holder must not hold the columns so loosely that
the columns shift position as the array cooled. A reliable and repeatable alignment and
gluing procedure needs to be formulated for affixing chips in their proper places.

The following provides an overview of the array and proceeds to describe the fabrication
of the array using methods devised to overcome these issues.

3.3.2 Array Construction and Assembly Overview

The 8×32 array in CCAM is constructed by stacking eight 1×32 silicon “column cards”
to a custom designed copper holder as shown in Figure 3.14. Each column card contains
a 1×32 TES chip, a shunt chip (Fig. 3.4) with 32 resistors for biasing each TES, a Nyquist
inductor chip (Fig. 3.9) to band limit the TES output, and a multiplexer chip (Fig. 3.8) that
contain the S1 and S2 SQUIDs to multiplex the detector. The discrete chips are integrated
on a bi-layer silicon card structure, as depicted in Figure 3.15. A backplane circuit board
then takes the signal from all 8 columns and sends them to the series array.

The “top card” contains aluminum traces and cutouts for the chips which become re-
cesses when the top card is stacked on the “bottom card.” The chips are placed and adhered
in the recesses in their appropriate configuration and are electrically connected with wire
bonds comprised of 99% aluminum and 1% silicon. Aluminum was chosen because it is
easily wire bonded and becomes superconducting below 1.2 K which avoids parasitic resis-
tance through the bonds.\footnote{Our wire bonds are actually aluminum with 1% silicon. This is common in the semiconductor industry because the small amount of silicon increases the strength of the wire bond.} Flexible circuitry is inserted into Zero Insertion Force (ZIF) connectors\footnote{The company that makes the ZIFs is L. Hirose Electric Co., http://www.hiroseusa.com/ Part Number: FH19-30S-0.5SH (51). The ZIFs are purchased from Digi-Key (800) 344-4539, Part number: HFN30CT-ND Connector} to connect each column card to the backplane. The backplane board contains
circuitry which takes each column’s bias and feedback signals and interfaces them with the
4K series array. Figure 3.16 details the key components of each column card. Table 3.2
lists the contents and position of each column in the 8×32 array.

After the individual columns cards are assembled and tested in the SRDP, flexible
circuitry is inserted into the ZIFs on the columns and each card is carefully placed into the
custom copper array holder (shown in Figure 3.14) to create the array. This is accomplished
by using a specially designed column loading jig. The loading jig holds each column upside
down to protect the delicate chips and wire bonds using a vacuum chuck. Three separate
Figure 3.14: Photographs of 8×32 copper array holder. The TESs and silicon column cards pictured are mechanical models. In the functioning array, flexible circuitry is inserted into the connectors on the back of the column cards which connect to the backplane. Brass screws are used wherever possible on the array holder to avoid inducing parasitic magnetic fields. The array holder was designed by N. Jarosik.
Figure 3.15: (a) Side view of a single column card. Both the top and bottom silicon cards are 300 µm thick. The top and bottom sides of the TES are 450 µm thick and have a 150 µm gap after folding. The TES pixel protrudes from the edge of the bottom card by 3.7 mm. (b) Eight column cards get stacked one on top of another to form the 8×32 array. The cards are placed upside down in the array holder to protect the delicate components on the top of the card. (c) Top view of a single column card.
Figure 3.16: Photograph of a 1×32 silicon column card. Numbered in the picture: 1. A folded 1×32 TES chip (from GSFC). 2. A shunt chip containing 32 microfabricated shunt resistors to bias the TESs (from GSFC). 3. A Nyquist chip with 32 individual Nyquist inductors to band limit the TESs output (from NIST). 4. A multiplexer chip on which the S1 and S2 SQUIDs multiplex the TES signal (from NIST) 5. Three ZIF connectors where flex circuitry is inserted to connect the array to the backplane. 6. Aluminum wire bonds which electrically connect the components on the silicon card. 7. Gold wire bonds add an extra thermal sink for the TES to the silicon card. 8. A Ruthenium Oxide (ROX) chip thermometer (ROX 102A) from Lake Shore Cryotronics, Inc. is used to measure the temperature of the silicon card. The ROX is thermally sunk and affixed to the bottom silicon card using GE Varnish (VGE-7031). Epo-tek H20E conductive epoxy is used to electrically connect the ROX chip to the top silicon card. This is only placed on some cards for diagnostic tests. 9. An indium soldered copper wire for thermal sinking the card to the copper array holder. 10. Flexible circuitry to connect to the backplane.
Table 3.2: The contents and position of each column in the 8×32 array. We have adopted a nomenclature to distinguish individual 1×32 columns once the by a letter or series of letters followed by numbers that correspond to where on the wafer the TES was fabricated. See wafer map in Figure 3.2(a). Columns 0-4 contain TES’s from GSFC’s Trial Production Run (TPR). Post TPR chips were inserted into columns 5-7 to evaluate the TES chips intended for MBAC’s 145 GHz array. All shunt chips are from wafer “MoN1”. All Nyquist chips are from wafer “ACT Production Run 1.” All multiplexer chips are from the “mux05c 00.01.06” batch.

Although copper is much denser than titanium, we chose to use copper for its high thermal conductivity at 300 mK.
Figure 3.17: Schematic of the main components in the detector array and read-out. The main components with descriptions are shown in gold. The physical connectors used are in blue, and the connections are in grey.
Figure 3.18: Illustration of the process of assembling the $8 \times 32$ detector array beginning with the eight column cards. After thoroughly testing each column card in the SRDP, the flexible circuitry is inserted in each column card. One by one, each column card is loaded into the array holder upside-down using the custom designed card loader. After all eight columns are installed, the thermal straps from each column card are heat sunk to the array holder. The $8 \times 32$ array holder is then mounted on a copper slab which also contains the backplane. The flexible circuitry from the individual cards are then inserted into the backplane and the assembly is completed. The NbTi wires extending out the back of the backplane are subsequently attached to the 4K series array.
With so many steps and components involved in producing an array, characterization sheets, documentation binders, and run sheets were produced to ensure a paper trail of each component and column card as well as tracking progress of TES folding, wafer fabrication, chip deliveries from NIST and GSFC, and column production. The characterization sheets and run sheets are shown in Appendix E.

3.3.3 Fabrication of the Top and Bottom Cards

Silicon was chosen for the circuit substrate to integrate all the components because:
1. Silicon can be cooled to 300 mK.
2. There would be no thermal contraction issues between the silicon chips and the substrate.
3. We could easily use microprocessing techniques to pattern aluminum and gold circuits onto silicon.
4. Silicon wafers are readily available from the semiconductor industry.

The silicon wafers used to produce the top cards were purchased from Silicon Quest International Inc. To circumvent having to evaporate metals on the silicon ourselves we opted to have Silicon Quest do the metal deposition. The ordered wafers were 100 mm p-type \(<1-0-0>\), \(\rho > 10 \ \Omega\)-cm \((<1.34 \times 10^{15} \ cm^{-3} \ \text{dopant concentration} [83])\), 300 \(\mu\)m thick double sided polished (DSP) wafers with 5000Å SiOx, 200Å Cr, and 10,000Å Al. Aluminum on \(\rho > 10 \ \Omega\)-cm silicon was chosen for the circuit design to ensure a negligible parasitic resistance, aluminum becomes superconducting below 1.1 K. The chrome functions as an adhesion layer between silicon and metal, in this case aluminum. The \(\rho > 10 \ \Omega\)-cm silicon specification is critical to ensure the electrons freeze out by 77 K and so the silicon becomes an electrical insulator. As an added precaution, a SiOx layer is fabricated to insulate the aluminum from the underlying silicon. This gives us a backup in case the charge carriers do not freeze out and it allows us to make meaningful warm resistance checks.

The silicon wafers for the bottom cards were also purchased from Silicon Quest International Inc and pre-metalized. The bottom card wafers were 100 mm p-type \(<1-0-0>\), \(\rho > 10 \ \Omega\)-cm, 300 micron thick double sided polished (DSP) wafers with 5000Å SiOx, 200Å Cr, and 5000Å Au. Gold was chosen as the metal for the bottom card for multiple reasons. To ensure the cards would get cold, a heat strap is indium soldered to the gold on the bottom.

\(^9\)Silicon Quest International, Email: sales@siliconquest.com Telephone: (800) 959-3556
card and thermally sunk to the copper array holder. In addition, to increase the thermal conductivity along the length of the card, gold was kept everywhere non-conductive chips were placed. Finally, the TES gets gold wire bonds to the gold on the bottom card to increase the thermal sinking between the TES and the bottom card.

The masks to pattern the top and bottom cards were initially made at the PRISM (Princeton Institute for the Science and Technology of Materials) cleanroom facility at Princeton University by exposing a photomask blank to a transparency containing the desired pattern. The soda lime blank photomasks (5”×5”, 0.090” thick) were coated with AZ1518 photoresist and chrome from Nanofilm. After developing and etching the chrome, the mask was completed. As our masks became more complex we began outsourcing our masks to Infinite Graphics Incorporated who could produce masks with a minimum feature size of one micron at low cost and fast turn around time. Currently, both methods are utilized depending on feature size and time constraints.

The photolithography and etching process is described in Appendix D. Both top and bottom wafers fabricated at PRISM produce two cards each as shown in Figure 3.19. After the wafers are etched in the PRISM clean room they are diced with a Laserod MEL 40 Laser Dicer system. A simple program directs the laser to cut the wafer into two cards in approximately an hour. In addition to dicing the outline of the card, the dicer also makes circular cutouts for alignment pins, circular cutouts for gluing the top and bottom cards together, and rounds corners to prevent the silicon from cleaving. Cleaving in the silicon cards created multiple problems early on in the development, but has since been solved by avoiding right angle cuts. Both top and bottom cards go through this dicing process and are subsequently “triple rinsed” to ensure no particulate will contaminate the cards or the chips.

3.3.4 Folding the TES Detector

The “pop-up” nature of our detectors allows for the formation of a close-packed detector array. However, the process of placing the backshort and folding each 1×32 TES column accurately and uniformly without breaking the 5 micron pixel legs is a challenge. A folding

\footnote{Nanofilm, 2641 Townsgate Road Suite 100, Westlake Village, CA, 91361, Telephone: (805) 496-5031}

\footnote{Infinite Graphics, http://www.igi.com/, Telephone: (612) 721-6283}

\footnote{A triple rinse involves rinsing the part to be cleaned three times with DI water, three times with acetone, three times with isopropanol, and blown dry with nitrogen gas.}
Figure 3.19: Top and bottom card wafer before dicing. (a) One top wafer produces two aluminum top cards (b.) One bottom wafer produces two gold bottom cards. Photographs courtesy of O. Stryzak.

Jig was designed by T. Marriage to fold each column with the least amount of risk to the TES column. This folding jig relied on the 1×32 TES columns from GSFC having incredibly uniform alignment holes, dicing lines, and backshort slots from one column to another. Unfortunately, the variations induced during fabrication, (etching, mask alignment, and depositions) of eleven TES columns on a 100 mm diameter wafer (see Fig. 3.2(a)) makes this requirement impossible to meet. The jig was subsequently modified to compensate for slight variations in each TES column by adding a visual microscope alignment step. The final folding procedure protects the TES column. On average, we break less than 2% of the pixels in the folding process. The following highlights the major issues we faced and the main concepts of the folding procedure.

TES columns arriving from GSFC are first inspected visually under the microscope for any tiny features that might make individual pixels or entire columns unusable such as broken legs, shorts or open wiring on lines to and from each pixel, or debris on pixels that might cause breakage on folding. When a TES column passes inspection and can be folded, it is carefully taken out of its protective case and placed into the folding jig using four cylindrical posts to roughly position the TES chip, (see Figure 3.22). Originally, when we relied on very accurate machined of the folding jig and uniformity between TES columns, the four posts completely constrained the TES chip so that no visual alignment was necessary. However, numerous TES chips were found to have alignment holes too small for the pins. For the twenty plus mechanical folds that were completed, visual measurements
Figure 3.20: Pathologies with pixel folding. (a) These photographs are of TES columns from wafer Y. The dicing lines are clearly not etched out on Y 3-2, and Y 3-1, preventing them from being folded. In addition, Y 2-1 has a small chip of silicon in the alignment hole which, in the original folder would not allow the TES chip to fit into the highly constraining alignment pin. (b) These photographs were taken under the microscope showing that the pixels can be skewed post fold. If stacked next to another $1\times32$ TES column, pixels will break.

The original folding jig was subsequently modified to allow for manual visual alignment while additionally correcting existing machining errors in the fabrication of the folding jig. A second aluminum alignment jig was made to ensure the vacuum chucks are in their correct position before every fold. The previously constricting pins were decreased in diameter to help guide the TES into the vacuum chuck, but still allow for some alignment movement. In addition, the alignment pins were scribed with a cross-hair mark, and the TES mask was
modified to add cross-hair features centered around each of the four alignment holes. The TES could then be positioned accurately in the vacuum chuck and the flat detector is ready to be diced to free the pixels and begin the folding process. Two aluminum covers act as backshort insert guides and as an extra protection from the dicing dust. Four short dicing cuts (always cutting away from the TES pixels) cut the flat TES chip such that it can be folded around its pixels. A double check to ensure that the vacuum is still holding the TES chip securely is essential. It has prevented numerous TES chips from breaking. The folder is then extracted from the laser dicer and the cleaned backshort is prepped to be placed.

The backshort is guided into position using the aluminum covers as guides, carefully noting the implanted vs. non-implanted side. The T-shape of the backshort holds the backshort in place and Scotch-Weld 2216 epoxy is carefully placed at the edges to secure the backshort from slipping during the fold. The placement of the backshort is checked for alignment under the microscope and the epoxy is allowed to dry. When the backshort is solidly affixed to the TES chip (≈12 hours), the small aluminum backshort guides are removed and the folding can begin.

To begin the fold, carefully machined and accurately positioned alignment pins are installed. A small amount of Scotch-Weld 2216 epoxy is placed on spots on both sides of the chip. Care is taken not to put epoxy along the entire length of the silicon TES chip otherwise a crack from differences in thermal contraction will result. Once the glue is placed, the folding jig is double checked for any breaks or abnormalities. The TES chip face containing the protruding backshort is then folded 90 degrees and held in place by additional alignment pins. The second TES chip face is subsequently folded 90 degrees to meet the first side. Tapered dowel pins and a screw tighten the folded TES to its proper shape and dimensions. The vacuum chuck assembly is then placed on a mount to protect it while the epoxy cures. During this time, the vacuum chuck assembly is carefully examined using custom made mounts for our microscope for any slight misalignments. Figure 3.21 contains photographs of the folded detectors once the folding procedure was finalized. Figures 3.22 and 3.23 provide a walk-through of the TES folding process.

3.3.5 ZIFs and Flexible Circuitry

The ZIF connectors are used at the silicon card edge to connect the flexible circuitry to the backplane. Unfortunately, it is not possible to aluminum wire bond to the solder coating that
Figure 3.21: Photographs of a folded TES.
1. The TES columns arrive from GSFC unfolded as shown below.

2. Examine and clean the folding jig to ensure debris that might harm the TES chip is removed.

Screw down the folding arms so they do not move unexpectedly. Use the alignment block to place the vacuum chucks in their correct position and tighten the vacuum chuck screws.

3. Place the unfolded TES on the pins of the two vacuum chucks, trace side down.

4. Center the TES on the four corner alignment holes using a microscope to ensure alignment and apply vacuum to hold the TES against the vacuum chucks.

Screw down the two backshort guides which both guide the backshort and protect the pixels. Ensure the vacuum is still on, then position the folding jig into the laser dicer.

5. Using the four dicing lines on the TES chip as guides, free the two sides of the TES using the laser dicer. Be sure to cut away from the pixels to avoid debris and pre-test cuts with the laser off to avoid damaging the TES.

6. Place a backshort into the slot utilizing the backshort guides, making sure the non-implanted side faces the pixels. Glue the corners of the backshort.

The backshort is exposed on both ends and glue is applied here.

Figure 3.22: TES folding process.
7. Remove backshort guides and place epoxy dabs on TES. If the epoxy is placed along the entire length, thermal contraction issues will arise.

8. Assemble U stands and screw down.

9. Remove four black arm screws to release folding arms. Fold up the the side with the backshort installed and slide arm pins into the U stand.

Fold up the lower side and slide arm pins into the U stand.

10. Insert the two tapered dowel pins and press tight. To fasten the vacuum chucks together, screw the chucks together with the single screw in the middle.

11. Remove the two screws fastening the vacuum chuck to the first folder arm, slide out arm pins and lower the folder arm.

12. Do the same for the other side. Examine the pixels under the microscope and adjust sides accordingly. Place folded TES assembly into the holder on the folding jig to cure.

Figure 3.23: TES folding process continued.
Figure 3.24: Adhered ZIFs on a 1×32 column card. These ZIFs have been nickel plated, adhered with Scotch-Weld 2216, and aluminum wire bonded.

comes with the ZIF connectors. To prepare ZIF for wire bonding to the aluminum circuit, the solder plating on the contacts is first mechanically stripped leaving copper contacts on the ZIF. However, this is also not ideal because the growth of Cu/Al intermetallic compound at the copper aluminum interface can induce mechanical failures and increase the electrical resistance at the interface [44]. To circumvent this, electrolytic nickel is deposited on the copper ZIF contacts.

The ZIF sockets are nickel plated by first thoroughly cleaning them and affixing them into a custom made cleaning jig. Using a buffing wheel and jewelers’ rouge, the solder coating is removed down to the copper core on the top of the ZIF contacts. This leaves solder on the inside of the ZIF connector which mates to the flexible circuitry without any worry of mechanical or technical failure while at the same time removing the solder on the top of the pins which prevent aluminum wire bonding. To ensure the sockets are clean enough for nickel plating the extra material on the ZIFs is removed by ultrasonic cleaning. An electroplating pen\textsuperscript{13} is brushed on the copper pins to apply a thin coat of nickel that can then be aluminum wire bonded to. Figure 3.24 shows ZIFs post nickel plating and installed on a column card.

Flexible circuitry was chosen to connect the ZIF’s on the column cards to the backplane because of its thin and mailable properties. The flexible circuits were purchased from Cirexx

\textsuperscript{13}The pens were purchased from: Hunter Products, Inc., 792 Partridge Dr., PO Box 6795, Bridgewater, NJ 08807, Telephone: (908) 526-8440. Part Number PL-1006 Plating Pen, Nickel.
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Table 3.3: Properties of the flexible circuitry. These need to be explicitly specified when ordering the flexible circuitry from Cirexx.

Numerous dunk tests in LN₂ proved the mechanical and robustness of the flexible circuit. The specifications for our specific flexible circuitry is shown in Table 3.3.

### 3.3.6 Combining the Components to Make a Column Card

Once the cards are cut and cleaned, they are scribed with a serial number for documentation. A 0.7 mm diameter copper thermal strap is indium soldered on the bottom gold card to heat sink the assembly to the copper array holder. Using a glue mask, the ZIF connectors are adhered to the bottom silicon card with a combination of Lord AP-138 adhesion promoter and Scotch-Weld 2216 epoxy. The adhesion promoter ensures the thermal contraction between the connectors, epoxy, and silicon are not problematic. To position the ZIFs at the proper height while the epoxy cures, a spacer made from teflon is used. Teflon was chosen because epoxy will not adhere to teflon.

During the assembly of the column cards, there were two main causes of column failure. First, when moving column cards between the gluing rigs and wire bonding rigs, columns were knocked or dropped. Secondly, the original gluing rig utilized alignment pins and matching holes on the column card to fix the position of the cards and TES chip. However, the dicer the laser dicer’s margin of error (± 10 µm) was enough to cause misalignment or

---

14Our contact at Cirexx is Morgan Hite, mhite@cirexxintl.com.
worse, if the diced circle in the silicon was too small, the silicon card would cleave when placed in the gluing rig. These two problems were solved by modifying the alignment procedure in the gluing rig and having the gluing rig serve the dual purpose of supporting the column card during wire bonding.

The final alignment procedure was created with the array holder in mind. The array holder’s springs push the individual column cards forward and toward the shelf side which were machined to be uniform. Thus, we made the gluing rig/wire bonding rig to have alignment pins on the outside of the column cards. The inside circular holes were still used to align the top and bottom card, but when the TES had to be positioned, the column would be pushed up against the top and right (shelf) side of the gluing rig. To ensure the components would not move while the epoxy cured or during wire bonding, a vacuum manifold system was set up that was capable of securing components individually. The gluing rig was also modified to also hold the column during wire bonding so the column did not have to be manually handled as much. This new gluing/wire bonding rig was modular enough to be transported between the gluing station and the wire bonding station. As an extra precaution, covers were machined to protect the TES chip and column card. The last modification improved the alignment of the TES chip to the column card by adding a visual alignment step using cross hairs and a microscope. The final column card fabrication procedure is shown in Figure 3.25 and Figure 3.26.

Multiple cryogenic tests were conducted in G. Kletetschka’s lab at GSFC to ensure the TES pixels, when secured in the array holder, remained stationary. This was achieved in a liquid helium dewar that vapor cooled the array while a window on the cryostat allowed the array to be viewed and photographed. The pixels were shown to both remain stationary, and withstand multiple cryogenic cycles. Figure 3.27 provides photographs of a mechanical array, both at room temperature, and 4K.

The final 8×32 array installed in CCAM is shown in Figure 3.28 before the AR window was screwed into place. Figure 3.29 shows photographs of the entire assembly including the backplane, flexible circuitry, and array holder.
1. Dice the wafers to create two top and two bottom cards. Clean cards with DI water, acetone, ... 

2. The ZIF sockets are nickel plated. A heat strap is indium soldered to the bottom card and adhesion promoter is applied to the bottom card where the ZIF is to be epoxied. 

3. Using a gluing mask to ensure the proper epoxy thickness, Scotch–Weld 2216 is applied and the ZIFs are placed. The top card is placed on the bottom card using the gluing rig, alignment pins, and vacuum to ensure firm contact. The two cards are glued together by placing glue in the four holes as shown below. 

4. If installing an ROX thermometer, the ROX is glued using GE varnish, then electrically connect with Epotek H20 E silver epoxy. The conductive epoxy needs to be oven cured, thus this step must happen before the heat sensitive chips are placed. 

Figure 3.25: Card assembly process.
5. A thin piece of niobium is epoxied (only in one spot to avoid thermal contraction differences) under the mux chip for extra magnetic shielding. Each chip is placed in its appropriate place and the vacuum is turned on to hold the chips while they are epoxied with Scotch-Weld 2216, again only in spots to avoid thermal contraction differences between epoxy and silicon.

![Image showing the assembly process]

The red circles indicate the gluing spots for the chips.

6. The column card is pushed forward and to the right in the gluing rig to replicate how the card will be aligned in the copper array holder. The TES is then placed, visually aligned under the microscope, and glued in place with Scotch-Weld 2216.

![Image showing the alignment pins]

The red circles highlight the alignment pins.

7. The assembly is taken to be aluminum bonded to complete all the electrical connections. In addition, gold wire bonds are added between the TES and bottom card to improve the thermal conductivity and heat sinking between the TES chip and column card assembly. The column is then stored in a copper carrier to be tested in the SRDP.

![Image showing the column card]

This particular column card has two ROXs because the first one broke.

![Completed column card]

Completed column card

Figure 3.26: Card assembly process continued.
Figure 3.27: Photographs of a mechanical array mounted in the array holder as viewed from a transparent window. The top image was taken when the array was at 293 K. The bottom image was shot when the array was cooled to 4 K. Notice the pixels do not shift in position upon cooling.
Figure 3.28: Photograph of the $8 \times 32$. This array is currently installed in CCAM. A few pixels were broken before being installed into the array due to broken legs pre-folding. However, the loading of the columns into the holder went smoothly.
Figure 3.29: Photographs of the detector array and backplane assembly.
3.3.7 Detector Tube

Constructing and designing a “detector tube” for MBAC is nontrivial. Thus, the CCAM detector holder was designed to be a prototype with the appropriate constraints for MBAC. In order to do so, CCAM’s detector tube must meet several criteria. For example, once CCAM’s detector slab is completed, the assembly needs to be positioned with micron accuracy. Then, it must be thermally sunk to the 300 mK stage. Additionally, the pixel face needs to be shielded from the 4 K detector box radiation, which would saturate the TES detectors. Lastly, since the fridges for CCAM and MBAC are identical, the loading on the 300 mK stage must be minimized identically to that of MBAC.

The key design concepts to be addressed were: balancing the requirement for wiring feedthroughs with the need to block any extraneous radiation, while maintaining adequate magnetic shielding. In addition, we required the design to be modular such that the detector array and backplane could be assembled, then transported and placed into a cryostat in a different location if needed. The final design is illustrated in Figure 3.30.

The modularity of this design allows the detector assembly to be constructed and tested at Princeton, then transported to its corresponding cryostat location. However, this modularity also comes at a price. Each individual component needs to be positioned accurately so that the detector array face is in the correction location. In the CCAM detector tube this was accomplished as follows. The 1×32 TES column is aligned to both the silicon bottom card front edge and center using a microscope and the gluing rig described in Section 3.25. These edges, the bottom card’s front and side, are critical when each column card is subsequently abutted to the front stop block and side shelves with the Be/Cu array holder springs. The entire array holder is then fixed to the detector slab by two alignment pins which mate to holes on the bottom of the array holder. Two additional alignment pins accurately position the detector slab to the 300 mK radiation shell. Seven rigid kevlar spider webs designed and tested by T. Marriage and S. Marriage hold the 300 mK radiation shell in the correct position. Finally, the 800 mK shell is affixed to the 800 mK optics tube with additional alignment pins.
Figure 3.30: Photographs of the detector tube. Before the detector tube is assembled, the 300 mK detector slab shown in Figure 3.29 is carefully tested to ensure the delicate detector biasing and read-out connections are intact. The detector and housekeeping wiring are thermally sunk utilizing a concept by N. Jarosik involving serrated copper tape. The tape creates a thermally tight yet safe clamp for the cables. Multiple screws on both sides of the cables ensure the clamp is secure. The assembled detector slab is placed inside a 300 mK radiation shield. Holes on the detector slab mate to alignment pins on the 300 mK detector slab base to ensure proper placement. A front cover which shields the majority of 800 mK radiation is attached, as is the 300 mK back cover. An additional cover is placed on the rear of the 300 mK stage to shield 800 mK radiation from entering through the 1 cm × 3 cm hole required for the MDM connectors to pass through. This cover has the added benefit of creating a second cable strain relief. Seven rigidly positioned aluminum frames anchored on the 800 mK contain taught kevlar spider webs. The centers of the spider webs are clamped to the 300 mK stage securing the 300 mK radiation shell to the 800 mK radiation shell. This concept was designed and tested by T. Marriage and S. Marriage. The entire detector tube assembly can subsequently be bolted to the 800 mK optics tube. Brass screws are used wherever possible to reduce unwanted magnetic fields. Aluminum tape, not shown in the photographs, is placed over each seam to ensure no 4 K radiation is incident on the TES pixels.
Chapter 4

Preliminary Tests

4.1 Introduction

CCAM was constructed as a test camera for the ACT telescope. In particular, it was constructed to demonstrate the feasibility of using antireflection coated silicon lenses to image millimeter waves onto a close-packed array of multiplexed TES detectors. To verify this concept, CCAM was subjected to a series of tests before deployment in the field. Point source observations were conducted on the roof of the Princeton physics building to confirm the ability of antireflection coated silicon lenses to focus signals on to a focal plane, as well as the capacity of an array of 1.05 mm TES bolometers to measure 2 mm radiation. Subsequently, measurements evaluating the 8×32 detector array’s properties and performance were conducted in the CCAM receiver before being deployed in Chile.

This chapter provides a description of preliminary tests in chronological order conducted in Princeton. In the first section we assess the cryogenic performance of the cryostat. The following section describes the integration of a 1×32 TES column with CCAM’s optics. The final section provides an overview of the 8×32 array and its characterization and performance in CCAM, characterization of the assembled 8×32 array in CCAM.

4.2 Cryogenic Performance

CCAM’s cryogenic temperatures are read-out using the BLAST DAS (Data Acquisition System) originally built for the BLAST experiment, and provided to us by C.B. Netterfield
of the University of Toronto. Temperatures during a typical cool-down of the cryostat are given in Figure 4.1.

![Cool-down Curve](image)

Figure 4.1: Measured temperatures of the main thermal stages in the cryostat as a function of cool-down time. The start time begins when the two pulse tubes are switched on. The 800 mK components cool much faster than the 300 mK due to its smaller amount of mass to cool. Additionally, $^4$He gas is more thermally conductive than $^3$He. The 300 mK stage’s temperature profile is only given below 40 K because an ROX thermometer, which is only sensitive below 40 K, is used to monitor that stage. This cool-down curve was measured before installation of the mechanical heat switch.

The optics tube, detector box baseplate, and refrigerator boxes, which are directly cooled by the two pulse tubes, take approximately two days to reach 4 K. Since, the 800 mK and 300 mK stages’ primary source of thermal conduction is through helium gas in sorption refrigerators they take longer to cool. Typically, an additional four days were necessary to cool the detector array to 4 K. This prompted us to design a mechanical heat switch to decrease the cool-down time by providing an additional thermal conduction path between the 300 mK and 800 mK stages and 4 K detector box baseplate. A mechanical heat switch was chosen instead of a gas-gap heat switch from the need to completely break the thermal conductance path to the 300 mK and 800 mK stages when cycling the sorption refrigerators. The mechanical heat switch consists of a 15 cm long, 0.6 cm$^2$ cross-sectional area, copper heat strap thermally sunk to the 4 K detector box and 300 mK and 800 mK stages. By rotating the heat switch with a rotary motion feedthrough outside the cryostat, a 3 cm
O.D., 2.8 cm I.D., G-10 actuator rod rotates to open and close the thermal conductance path between the 300 mK and 800 mK stages to the 4 K detector box. The implementation of the mechanical heat switch decreased the cool-down time of the detector array to 4 K by \(~ 1\) day. The nominal time required to cool respective stages is listed in Table 4.1.

<table>
<thead>
<tr>
<th>Stage</th>
<th>Time to 50 K</th>
<th>Time to 4 K</th>
<th>Time to 800 mK</th>
<th>Time to 300 mK</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 K baseplates</td>
<td>(\approx 25) hrs</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>4 K baseplates</td>
<td>(\approx 27) hrs</td>
<td>(\approx 45) hrs</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>800 mK optics</td>
<td>(\approx 48) hrs</td>
<td>(\approx 65) hrs</td>
<td>(\approx 115) hrs</td>
<td>-</td>
</tr>
<tr>
<td>300 mK detector array</td>
<td>(\approx 70) hrs</td>
<td>(\approx 110) hrs</td>
<td>(\approx 115) hrs</td>
<td>(\approx 120) hrs</td>
</tr>
</tbody>
</table>

Table 4.1: Time required for each cryogenic stage to reach key temperatures after implementation of the mechanical heat switch.

The cryogenic stages of CCAM were modeled to determine if the measured performance could be improved. The model suggested the largest source of thermal conductance loss came from the interfaces between elements. This effect is pictorially shown in Figure 4.2.

![Figure 4.2: Schematic representation of temperature loss at interfaces between components.](image)

Figure 4.2: Schematic representation of temperature loss at interfaces between components.

To improve the conductance between interfaces, [138, 53, 72] were used as a guide. The importance of smooth cryogenic contacts to increase the thermal cross-section was suggested by [138, 72]. Thus, the surfaces at interfaces were machined smooth. The “effective thermal cross-section” can additionally be increased by ensuring the interface is tightly bolted together at room temperature, with Belleville washers to ensure that the tight joint
is maintained at cryogenic temperatures. Figure 4.3 illustrates dependence on applied force between components on the overall thermal conductivity.

In addition, [72] recommends the use of indium or Apiezon N grease between interfaces. However, this use comes with multiple caveats. Apiezon N thermal grease freezes below liquid helium temperatures so care must be taken to apply only a thin layer. In addition, while the malleability of indium allows it to conform between joints increasing the interface’s effective thermal cross-section, it also transitions into a superconductor at 3.4 K and has been shown to decrease thermal conductivity below 200 mK. Figure 4.3 depicts the thermal conductivity increase with the addition of indium and Apiezon N grease between copper joints.

![Figure 4.3: Thermal conductivity of copper to copper interfaces for both indium and Apiezon N grease interfaces at two applied forces, 22 N and 670 N. For reference, a bare copper-copper interface with an applied force of 670 N is overplotted. The data used to produce these plots were taken from [72].](image)

The recommendations listed above were used as a guide to increase the thermal conductivities inside CCAM. After a few iterations, we were pleased with the resulting thermal profiles illustrated in Figure 4.4.
Figure 4.4: Top: Temperature Profile of the 800 mK components. The plot shows the measured increase in temperature between the $^4$He sorption refrigerator in FB2 and the 800 mK baffles in the optics tube. The 800 mK temperature gradient is largely due to the effective cross-sectional area available between the 800 mK radiation shield and cryogenic feed through that travels up a cryoperm udder to magnetically shield the detectors. Bottom: Temperature profile of the 300 mK components between the $^3$He sorption refrigerator in FB1 and the detector tube in the detector box. The two major sources of the gradient between the detector array and $^3$He sorption refrigerator are: (i) the effective cross-sectional area between the 300 mK radiation shield and cryogenic feed through which is constrained by the magnetic shielding and, (ii) the cryogenic feedthrough between FB1 and the detector box which uses two kevlar spider webs to support the 2.5 cm diameter, 15 cm long copper feedthrough. The kevlar spider webs create a computed load of $4\mu W$ on the 300 mK stage which correspond to a temperature increase of $\Delta T=15$ mK. While the 800 mK stage also has two spider web supports, the $^4$He sorption refrigerator can easily support a $4\mu W$ loading, $(\Delta T=15\mu K)$. 
4.3 Calculated Thermal Performance of the Detector Array

The thermal conductivities measured in the last section, and shown in Figure 4.4, are critical for cooling the detector array to 300 mK so the optimal detector sensitivity can be achieved. To ensure the detector array holder can in turn cool the multiplexor, shunt, and Nyquist chips, as well as the TES detectors, tests were conducted in a cryogenic test bed running the same sorption refrigerators as in CCAM. This determined if problematic sources of loading needed to be addressed. Similar to the 300 mK and 800 mK stages, the expected thermal performance was calculated and compared to the values measured.

To determine the predicted thermal performance, the specific heat and thermal conductivity for each element in the detector array needs to be calculated. The rest of this section is devoted to computing and analyzing each individual element.

4.3.1 Specific Heat

In the following we compute the specific heat for materials in the detector array at their operating temperatures.

**Silicon**

The specific heat of silicon is heavily dependant on dopant concentration. From [60], silicon doped with concentrations above \(6 \times 10^{16} \text{cm}^{-3}\) have an extra electric component to its specific heat for temperatures between 0.06 K-1.6 K. The phosphorus doped silicon used in the top and bottom detector cards have a resistance of 10 Ω-cm which corresponds to a concentration of \(1.46 \times 10^{16} \text{cm}^{-3}\). As a result, its specific heat at temperature \(T\), is dominated by phonons and is given by,

\[
c_{\text{phonon}} = \frac{12}{5} \pi^2 N_A k_B \left(\frac{T}{\theta_D}\right)^3 \text{(J/molK)},
\]

where \(\theta_D = 658 \text{K}\) is the Debye temperature of silicon, \(k_B\) is Boltzmann’s constant, and \(N_A\) is Avogadro’s number. However, the silicon which constitutes the absorbing pixels has a dopant concentration of \(4 \times 10^{19} \text{cm}^{-3}\). This dopant concentration is high enough for electrons to contribute to the specific heat [60]. Thus, the specific heat is a sum of both the extrinsic specific heat and lattice specific heat given by,

\[
c_{\text{phonon}} + c_{\text{electron}} = \frac{12}{5} \pi^2 N_A k_B \left(\frac{T}{\theta_D}\right)^3 + \gamma_{si} T \text{(J/molK)}.
\]

\(^1\)The cryogenic test bed is described in Appendix D.
Experimental studies have shown for phosphors doped with concentrations of $4 \times 10^{19}$ cm$^{-3}$, $\gamma_{si} = 6.6 \times 10^{-5}$ (J/molK) [60].

**Superconducting Aluminum**

In the normal state, the specific heat of aluminum can be calculated by a sum of its lattice and electronic contributions,

$$c_{\text{phonon}} + c_{\text{electron}} = \frac{12}{5} \pi^2 N_A k_B (\frac{T}{\theta_D})^3 + \gamma_{al} T \text{(J/molK)}, \quad (4.3)$$

where $\gamma_{al} = 1.35 \times 10^{-3}$ (J/molK) and $\theta_D = 427.7$ K for aluminum. However, at $T_c = 1.165$ K, aluminum transitions into a superconductor. At temperatures below $T_c$, the electronic specific heat dominates the normal aluminum lattice specific heat. Thus, the specific heat for superconducting aluminum is given by [103]:

$$c_{\text{electron}} = \gamma_{al} T_c \exp^{-\frac{1.34 T_c}{T}} \text{(J/molK)}. \quad (4.4)$$

**Gold**

The heat capacity of gold at temperature $T$ can be calculated by its lattice and electronic contributions by,

$$c_{\text{phonon}} + c_{\text{electron}} = \frac{12}{5} \pi^2 N_A k_B (\frac{T}{\theta_D})^3 + \gamma_{au} T \text{(J/molK)}. \quad (4.5)$$

From [104] $\theta_D$ for gold is 162 K and $\gamma_{au} = 6.89 \times 10^{-4}$ J/molK$^2$.

**Plastic**

Because no free electrons exist in a plastic only photons contribute to the specific heat. From [136], a typical plastic at temperature $T$ has specific heat:

$$c_{\text{phonons}} = 1 \times 10^{-5} T^3 \text{(J/gK)}. \quad (4.6)$$

Table 4.2 tabulates the specific heat contributions for each material in the detector array.

**4.3.2 Thermal Conductivity**

The kinetic gas theory can be used to calculate the thermal conductance of each material. The thermal conductivity of the electrons and phonons which transport heat is given by,

$$\kappa = \frac{1}{3} cv_\lambda \lambda,$$

where $c$ is the specific heat, $v$ is the velocity of the particles, and $\lambda$ is the mean free path.
Material | Specific heat (J/gK)
---|---
Silicon ($N_D < 6 \times 10^{16} \text{cm}^{-3}$) | 6.5 × 10$^{-9}$
Silicon ($N_D > 6 \times 10^{16} \text{cm}^{-3}$) | 7.1 × 10$^{-7}$
Superconducting Aluminum | 2.2 × 10$^{-6}$
Gold | 1.1 × 10$^{-6}$
Plastic | 2.7 × 10$^{-4}$

Table 4.2: Calculated specific heats of the materials in the detector array at 300 mK.

**Silicon**

Computing the thermal conductivity of silicon is problematic because of its strong dependence on the dopant concentration, or, equivalently the number of free electrons available to conduct heat.

For lightly doped silicon, (doped concentrations below 6 × 10$^{16}$ cm$^{-3}$), the thermal conductivity is dominated by phonons. The conductivity then depends on the geometry and surface scattering. The mean free path, $\lambda$, of the phonons is greater than the size of the silicon card, so we use the thickness of the card is used to calculate the thermal conductance. The velocity of sound of silicon is $v_s = 5800 \text{m/s}$ [49].

For highly doped silicon, (doped concentrations above 6 × 10$^{16}$ cm$^{-3}$), the thermal conductivity is dominated by electrons. The electronic contribution to the thermal conductivity, $\kappa_{\text{elec}}$, can be calculated at temperature $T$ using the Wiedemann-Franz law [5],

$$\kappa_{\text{elec}} = \frac{\pi^2 k_B^2 T}{3e^2 \rho}, \quad (4.7)$$

where $e$ is the electron charge, $k_B$ is Boltzmann’s constant, and $\rho$ the electrical resistivity. For the TES absorbers, which have a phosphorous concentration of 4 × 10$^{19}$ cm$^{-3}$, $\rho$ is $\approx 2 \times 10^{-3} \Omega\text{-cm}.$

**Superconducting Aluminum**

Below the critical superconducting temperature of aluminum, $T_c = 1.165 \text{K}$, the number of electrons which form Cooper pairs increases rapidly and as a result, the thermal conductivity $\kappa$ can be represented at temperature $T$ by [139],

$$\kappa = \kappa_0 \exp(\alpha[1 - \frac{T_c}{T}]), \quad (4.8)$$

where $\kappa_0$ is the conductivity at $T_c$ and $\alpha$ has been experimentally found to be 1.8. For 99.999% aluminum, $\kappa_0 = 3 \text{W/cmK}$ [16] but this value is heavily dependent on purity [139].
For 99.99% aluminum, $\kappa$ is a factor of ten less than 99.999% aluminum, and for 99% aluminum, $\kappa$ is a factor of a thousand less than 99.999% aluminum [139]. On the column card assembly, the purity of the aluminum traces on the silicon top card is 99.99%, and the aluminum wirebonds are 99% aluminum (1% silicon).\textsuperscript{2}

Gold Wirebonds

For metals, the thermal conductivity $\kappa$ at low temperature is due to heat transport from electrons. Since the specific heat for metals is $\propto T$, $\kappa = aT$ where $a$ is a characteristic of the metal. From [132], $a_{\text{gold}} = 0.57$ (W/cmK$^2$) for 99.99% gold.

Commercial Copper

Like gold, the thermal conductivity of copper at low temperatures is governed by electrons. From [79], $a_{\text{cu}} = 1$ (W/cmK$^2$).

Epoxy

We were not able to obtain thermal conductance values for Scotch-weld 2216. To estimate its thermal conductivity, we used the known conductance of Stycast 1266 epoxy. At a temperatures $T$ between 0.045K to 0.45K, the thermal conductivity of Stycast 1266 is $4.9 \times 10^{-4} T^{1.98}$ (W/cmK) [40].

Summary/Reference Plots

Figures 4.5 and 4.6 show the thermal conductivity for the materials used in the detector array as a function of temperature. Table 4.3 summarizes the thermal conductivities for the different materials used in the detector array. Tables 4.3, 4.4, 4.5, and 4.6 tabulate the heat capacities, thermal time constants, and thermal conductivities of individual elements in the detector array.

\textsuperscript{2}The addition of 1% silicon in the aluminum wire bonds produce stronger bonds [46].
Figure 4.5: Thermal Conductivity vs. T of 99.99% pure Al, copper, and gold.

Figure 4.6: Thermal Conductivity vs. T of 99% pure Al and epoxy.
Table 4.3: Calculated thermal conductivities of the card assembly at 300 mK.

<table>
<thead>
<tr>
<th>Material</th>
<th>Thermal Conductivity (W/cmK)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silicon</td>
<td>$2.2 \times 10^{-4}$</td>
</tr>
<tr>
<td>Highly doped Silicon</td>
<td>$2.3 \times 10^{-4}$</td>
</tr>
<tr>
<td>Superconducting Aluminum Traces</td>
<td>$2.7 \times 10^{-1}$</td>
</tr>
<tr>
<td>Superconducting Aluminum Wirebonds</td>
<td>$2.7 \times 10^{-4}$</td>
</tr>
<tr>
<td>Gold</td>
<td>$1.7 \times 10^{-1}$</td>
</tr>
<tr>
<td>Copper</td>
<td>$3.0 \times 10^{-1}$</td>
</tr>
<tr>
<td>Epoxy</td>
<td>$4.5 \times 10^{-5}$</td>
</tr>
</tbody>
</table>

Table 4.4: Calculated heat capacities of the card assembly at 300 mK.

<table>
<thead>
<tr>
<th>Part</th>
<th>Heat Capacity (J/K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TES chip and frame</td>
<td>$5.8 \times 10^{-9}$</td>
</tr>
<tr>
<td>Silicon in bottom card</td>
<td>$9.6 \times 10^{-9}$</td>
</tr>
<tr>
<td>Silicon in top card</td>
<td>$8.0 \times 10^{-9}$</td>
</tr>
<tr>
<td>Gold on bottom card</td>
<td>$2.2 \times 10^{-8}$</td>
</tr>
<tr>
<td>Aluminum Traces on top card</td>
<td>$5.7 \times 10^{-10}$</td>
</tr>
</tbody>
</table>

Table 4.5: Calculated thermalization time constants, $\tau$, of the card assembly. The thermalization time constant is calculated from the total heat capacity of the part, $c_{\text{tot}}$, and the thermal conductance, $G$, between the part and its “effective temperature bath” where $\tau = c_{\text{tot}}/G$.

<table>
<thead>
<tr>
<th>Part</th>
<th>Thermalization time (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TES chip and frame</td>
<td>1.2</td>
</tr>
<tr>
<td>Bottom card</td>
<td>1.1</td>
</tr>
<tr>
<td>Top card</td>
<td>2.3</td>
</tr>
</tbody>
</table>

Table 4.6: Calculated conductance values of the card assembly.

<table>
<thead>
<tr>
<th>Path</th>
<th>$G_{\text{calculated}}$ (W/K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TES frame to card assembly</td>
<td>$3.5 \times 10^{-9}$</td>
</tr>
<tr>
<td>Card assembly through Cu wire to array holder</td>
<td>$2.0 \times 10^{-9}$</td>
</tr>
</tbody>
</table>
4.3.3 Measured Thermal Conductance Values of the Detector Array

A cryogenic test bed which achieves a base temperature of 220 mK was set up to measure the thermal conductance between the detector array holder, silicon column cards, and TES detectors at 300 mK. The measured values are given in Table 4.7. The measured thermal conductance between the TES frame-card assembly and card assembly-array holder were lower than the calculated vales, but within 20% and 10% respectively.

The measured conductance value between the TES frame card assembly is believed to be lower than the calculated value because of the incapability to accurately compute the thermal conductivity of silicon at cryogenic temperatures. In addition, the discrepancy between the measured conductance value from the card assembly, through the copper wire, to the array holder is likely due to the indium solder joint which connects the copper wire to the detector card. This extra thermal interface, which is hard to quantify, was not included in the calculation.

<table>
<thead>
<tr>
<th>Path</th>
<th>$G_{\text{measured}}$ (W/K)</th>
<th>$G_{\text{calculated}}$ (W/K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TES frame to card assembly</td>
<td>$2.9 \times 10^{-5}$</td>
<td>$3.5 \times 10^{-5}$</td>
</tr>
<tr>
<td>Card assembly through Cu wire to array holder</td>
<td>$1.8 \times 10^{-5}$</td>
<td>$2.0 \times 10^{-5}$</td>
</tr>
</tbody>
</table>

Table 4.7: Measured conductance values of the card assembly. For reference, the calculated values are also provided.

4.4 Sky Data from Princeton

While CCAM’s cryogenics and housekeeping were being optimized, a flat (un-folded) 1×32 TES column and accompanying read-out were designed and assembled by M. Niemack. In November 2005, these components were merged so that CCAM could observe the sky on the roof of the physics department at Princeton University. These observations allowed two critical concepts to be tested and verified, which would remain unresolvable by relying only on lab measurements. The primary questions were, do the AR coated silicon lenses and corresponding optics effectively image the sky onto the focal plane? If so, can 1 mm TES detectors be biased and read-out to produce maps of 2 mm radiation? To answer these questions, CCAM was mounted onto a spare set of WMAP mirrors to conduct sky observations during November and December of 2005.
The Chilean sky emits at a temperature below 10 K, whereas the expected sky temperature at Princeton is approximately 100 K. This extra loading in Princeton would completely saturate the detectors which are optimized for observing in Chile. To conduct observations at Princeton, the sky signal was attenuated by a neutral density filter (NDF). The NDF was constructed from a 1.09 cm thick piece of Eccosorb MF 110 microwave absorber, which has an index of refraction of 1.87 and loss tangent of 0.0315 at 4 K [80]. While the high loss tangent of Eccosorb results in 88.5% attenuation, it also means the NDF will emit radiation corresponding to its physical temperature.\(^3\) The ideal antireflection coating material for a fixed wavelength \(\lambda\) would have an index of refraction of \(n_c = \sqrt{n_{NDF}}\) and thickness \(t_c = \lambda_0/(4n_c)\). This suggested an antireflection coating material with \(n_c = 1.44\) and thickness 300 \(\mu\)m. Teflon is easily obtainable in 300 \(\mu\)m thickness and has an index of refraction of \(n_{teflon} = 1.4\) which made it a good AR coating material for the Eccosorb NDF. The teflon was adhered to the Eccosorb with a thin layer of vacuum grease and thermally clamped down with a copper mount in the 4 K optics.

On November 17, 2005, CCAM saw first light with the Moon utilizing NIST electronics\(^4\) to bias and read-out the TES detectors. Realtime Moon data was examined to verify each detector was biased and read-out properly. Figure 4.8 shows a screen snapshot of the realtime data. This detector’s response to the Moon demonstrated that it was possible to bias, multiplex, and read-out a 1\(\times\)32 TES column.

Subsequent observations of Mars and Saturn were conducted to quantify the quality of CCAM’s optical system. The raw detector and pointing data from these scans were merged to examine point source images and measure the plate scale. The plate scale calculated from the data was compared to the predicted value to evaluate the optical system’s imaging effectiveness. Given the effective focal length of the WMAP mirrors, \(f=3.0\) m, the predicted plate scale was calculated to be 1.13 arcminutes per mm. The centers of the measured beam patterns produced by each pixel were plotted as a function of pixel spacing\(^5\) to determine the plate scale. We measured 1.12 arcminutes per mm in agreement with expectations. Figure 4.9 provides a map, beam patterns, and plate scale calculated from a Mars observation.

\(^3\)To minimize drift of the detector signal, the entire 4 K optics tube was temperature regulated via PID servo loop.

\(^4\)At this time the MCE electronics for CCAM/ACT were not completed.

\(^5\)Each detector pixel is 1.05 mm wide and spaced 0.05 mm apart. This corresponds to a 1.1 mm spacing between the centers of adjoining pixels.
Figure 4.7: Calculated NDF transmission, absorption, and reflection vs. frequency for the NDF used in CCAM for sky observations at Princeton University. The NDF is made of a 1.09 cm thick piece of Eccosorb MF 110 microwave absorber and antireflection coated with 300 $\mu$m of teflon on both sides of the Eccosorb. Loss tangent data used to create this plot are taken from [80].
Figure 4.8: Bolometers responding to azimuthal scanning across the moon. The currents through five TESs that were biased to different points on their transitions are plotted. Since SQUIDs have arbitrary offsets in their read-out, the absolute current (shown here) must be calibrated by analyzing an I-V curve acquired under similar loading conditions without the moon. As the photon loading from the moon increases, the TES resistances increase, causing a decrease in current through the TESs. The minimum current results from saturation of the bolometers when the TESs are driven to their normal resistance ($R_n = 41 \pm 3$ m\(\Omega\) for this test device). The TESs are offset in azimuth from each other due to their position in the column, so that the top, black TES only observed the moon at the edge of the scan, and thus, its response profile is shifted in time with respect to the others because of the azimuthal motion of the moon. Figure courtesy of M. Niemack.
Figure 4.9: Top: Calibrated map of Mars observed by detector RS16 in attowatts. The calibration factor was determined by detector I-V curves acquired under similar loading conditions without Mars. Middle: Measured beam patterns of the 19 working pixels. Bottom: Plate scale analysis from Mars data. The x-axis plots the detector row select number which can be converted into a spacing in the focal plane. The top map was produced using software developed by E. Switzer. The bottom two plots are courtesy of J. Fowler and E. Switzer.
From these point source observations we were able to confirm the ability of antireflection coated silicon lenses to focus signals on to a focal plane, as well as the capacity of an array of 1.05 mm TES bolometers to measure 2 mm radiation.

### 4.5 Detector Array Characterization Before Deployment

Once the detector array concept was verified through observations, a trial production run of TES columns were manufactured at GSFC. With these detector columns a $8 \times 32$ detector array was constructed by the procedure discussed in Chapter 3. Optical and noise measurements on the TES’s were subsequently conducted until the cryostat was deployed to Chile in March 2007.

#### 4.5.1 Detector Failures

Each $1 \times 32$ detector column is cooled and tested in the SRDP before being installed in the detector array. The SRDP measurements quantify each pixel’s properties and find faulty TES’s. Spotting broken pixels is critical for ensuring the maximum number of detectors work in the final array. The multiplexing read-out system requires broken pixels to be electrically shorted or the entire row is destroyed. The main issues found during the SRDP were electrical shorts in the multiplexing chip, open TES loops, and superconducting TES’s.

Once each column card was tested and problematic detectors were electrically shorted via wire-bonds, the array was assembled. The major problem that arose during this process were electrical complications on the backplane. This resulted in four rows, RS0, RS9, and RS17 entirely destroyed by multiplexing shorts. When the detector array was completed and analyzed in CCAM, more detectors showed abnormalities. While these issues did not completely destroy pixels, the signal from these detectors are not always reliable. The relatively large number of failures created in the assembly of the $8 \times 32$ array assembly illustrated the need to check each electrical connection during installation into the array.

When the detector array was installed on the telescope, no major new issues developed. This demonstrates the mobility of the detector assembly which will be critical for MBAC which will hand carry all three of its detector arrays and install them at the telescope site. Figure 4.10 illustrates the sources of failures from each step of the $8 \times 32$ TES array assembly.
Figure 4.10: Pixel failure modes in 8×32 array during construction and deployment. Top: Pixel issues before construction of the array. The SRDP was used to determine which pixels were completely broken or had unpredictable signal responses. Common causes of unpredictable signal responses are, anomalous $T_c$, $R_n$, $P_{sat}$, and significant $1/f$ noise. Middle: Failures created when the columns were assembled to form the 8×32 array. Backplane wiring problems resulted in three rows, RS9, RS11, and RS17 being completely destroyed. After insertion into the cryostat, single pixel failures undetected during SRDP tests destroyed rows RS1, RS19, and RS20. Bottom: Measured good, unpredictable, and broken detectors in Chile.
4.5.2 Detector Time Constant Analysis

The target time constant for CCAM was set by the observation strategy. The telescope is scanned as rapidly as possible to avoid $1/f$ noise in the detectors. The primary experimental goal of ACT is the measurement of the CMB at an angular scale of $\sim 1.7^\circ$. This signal must appear in the detector time frequency well above the $1/f$ knee of the TES, but not at such a high frequency that the detector time constant attenuates the signal. For a typical ACT scan of 5 degrees in Az every 5 seconds, this sets a lower limit of 62 Hz for the detector time constant.

To determine if the detectors met the time constant requirement, the time constants were measured for each working pixel in the $8 \times 32$ array. This was accomplished by modulating a 300 K Eccosorb source via optical chopper placed approximately 20 cm away from the cryostat window. To confine the chopped signal and block external signals, a plate with a 7.7 cm aperture was placed over CCAM’s window and the entire test assembly was shielded from radiation in the room. During the measurement, the 11.5% neutral density filter described in section 4.4 was mounted in the 4 K optics tube to prevent the detectors from saturating. All measurements were multiplexed with the MCE in the feedback + error mode.

The data were analyzed by Fourier transforming the time streams and integrating over points near the chop frequency. The background noise level signal in the chop frequency range was fit in PSD space and subtracted from the peak level. The resulting curve was fit with a single-pole lowpass filter. To determine detector parameters for calibration and confirm system stability, I-V load curves were acquired before and after each measurement. The measured time constants for the $8 \times 32$ array as a function of pixel position in the array are shown in Figure 4.11. Figure 4.12 shows the measured time constants at 3 different bath temperatures for the three types of detectors constituting the $8 \times 32$ array.

Manipulation of expressions for $f_{3dB}$ from [54, 91] while assuming an isothermal TES detector model in the low inductance limit, suggests $f_{3dB}$ is proportional to $P_{J0}$, where $P_{J0}$ is the Joule power applied to the TES. The low inductance limit is an acceptable approximation, despite the use of Nyquist inductors in the detector readout, because the $L/R$ electrical time constant is roughly an order of magnitude smaller than the optical time

6 We define the $1/f$ knee as the point where the power spectral density (PSD) is twice its high-frequency value.
7 This method was conceived by M.Niemack.
Figure 4.11: Measured time constants for individual pixels in the 8×32 array. The time constants were acquired by modulating a 300 K Eccosorb source ~ 20 cm away from the cryostat window. The detectors were servoed at $T_{\text{bath}} = 0.37 \text{K}$ between $(0.2 - 0.6)R_{\text{normal}}$. The deviation in $f_{3\text{dB}}$ between detectors is believed to result from varying temperature coefficients of resistance, $\alpha$, and heat capacities, $C$. Figure courtesy of M. Niemack.

Figure 4.12: Measured time constants for the 3 different detector columns, (TPR detectors, X and P, APX, and CVC), in the 8×32 array. The time constants were measured by modulating a 300 K Eccosorb source ~ 20 cm away from the cryostat window at three detector bath temperatures, $T_{\text{bath}} = 0.34 \text{K}, 0.37 \text{K}, \text{and } 0.41 \text{K}$ at $R_{0} \sim R_{n}$. The best fit line yields $f_{3\text{dB}} \approx (6.4 \text{Hz/pW})P_{J0} + 33 \text{Hz}$ demonstrating the correlation between $f_{3\text{dB}}$ and $P_{J0}$. Figure modified from a plot by M. Niemack.
constants [92]. Measurements of time constants for the 8×32 array described above follow this trend. In addition, the bolometers show a roughly constant $f_{3dB}$ between 25%-75% of $R_n$. This demonstrates that $P_{sat}$, the saturation power of the TES detectors results in a lower $f_{3dB}$. For example, if $P_J \approx 2$ pW, $f_{3dB}$ at 0.5$R_n$ is $\sim 3$ ms. For a more complete analysis of the time constant data, see [91]

4.6 Conclusion

The results of the preliminary tests conducted in Princeton provided us with the confidence to send the receiver to the telescope site for observations. In March 2007, CCAM was shipped from Princeton, NJ to the ACT site for installation on the telescope. By June, 2007, CCAM became the first light instrument on the ACT telescope.
Chapter 5

CCAM in the Field

5.1 Cerro Toco Site

The Atacama Cosmology Telescope is located on Cerro Toco in Chile’s Atacama Desert. A map that shows the location of the site in Chile and a photograph of Cerro Toco is given in Figure 5.1. The site is at an elevation of 5200 m approximately 35 km east of San Pedro de Atacama, 67°W longitude, 23° latitude. The high altitude and desert climate result in a dry atmosphere above the site. This minimizes the atmospheric opacity at millimeter wavelengths by water vapor which can create unwanted loading and noise on our detectors.

The location of the telescope is essential for the scientific success and manageability of a large telescope project. The TOCO/MAT and MINT experiments [87, 38] by members of the ACT collaboration on Cerro Toco have established the scientific potential in the region. Observations from Cerro Toco will allow cross-linked maps to be produced from constant elevation scans. This cross-linking strategy was successfully utilized by members of the ACT team with the WMAP satellite.

Other telescopes are taking advantage of the high altitude desert atmosphere. The ACT site overlooks the Atacama Large Millimeter Array (ALMA), and other experiments such as CBI [95], APEX [43], and ASTE [33] have chosen this region for astronomical observations. These experiments have developed a useful infrastructure and scientific community in San Pedro de Atacama. For example, both ALMA and APEX teams have characterized and model the atmospheric opacity in the region between 200 and 1600 GHz [107, 78, 82].
5.2 Operations at the Telescope Site

Even though there are a growing number of telescopes in the area, the remote site presents some logistical challenges. For example, all the equipment needs to be transported 35 km from the base station at 2500 m up mountain roads to the site at 5200 m. In addition, the support systems have to be robust enough so that the telescope can operate with no one at the site.

Two generators supply power to the site. Their tanks hold enough diesel to run continuously under normal daily operations for a little under two days. The diesel needs to be hand pumped on a routine basis to maintain power generation. When the generators are switched, power at the site is disrupted for a few seconds. Power has also been disrupted from contaminated diesel, and the diesel being too cold. These both clog the generator system which causes the generators to turn off unexpectedly. To combat this, in-line filters and a Racor electric in-line diesel heater \(^1\) are installed in the diesel’s path inside the generator compartment. UPS’s are used to protect the critical housekeeping, detector read-out electronics, and computer systems during the these power outages.

\(^1\)Racor heater: 30 Watt, 12 VDC, NOMAD model number 14330.
The two pulse tubes used to cool the cryostat to 4K eliminate the need for liquid cryogens. However, maintenance of the refrigeration system has created challenges in its own right. At the site, temperatures often drop below -20°C. To operate, the pulse tube refrigerators have to be above 7°C. In addition, the electronics has to be maintained at a steady temperature. Thus, the entire receiver cabin that houses CCAM and the support electronics is maintained at 15°C. In addition, each pulse tube compressor nominally requires 7 kW of power during operation. The generators can supply this amount of power, but use a substantial amount of diesel to do so. Approximately 40 liters of diesel are required daily to keep the refrigeration system functional.

Additionally, the heat generated from each compressor needs to be adequately dissipated. This is accomplished by a pair of water chiller systems. To ensure the water does not freeze in the < 0°C, a 40:60 ratio deionized water to ethylene glycol respectively is used as the cooling fluid. The chiller system uses a pump to maintain a 11 liters/min, 10°C flow through the system. Figure 5.2 illustrates the main components of the water chiller system. The pulse tube compressors are housed inside an equipment room to protect them from the harsh environment at the site. To transfer high pressure helium between each pulse tube and compressor, two compressed helium lines are routed ~15 m to the telescope base, and up to the receiver cabin where the pulse tubes and receiver are housed. “Super flexible” helium lines are used to prevent bends from damaging the hoses.

5.3 Jupiter Observations

CCAM was the first receiver to observe with ACT on June 8, 2007. On this date Jupiter was observed over a 60 second time span. The telescope scanned in 2 degree peak-to-peak azimuth at a constant elevation angle of 60°. Figure 5.3 shows a beam map of Jupiter from the first light observation on June 8, 2007. In the following, we present a preliminary analysis of the basic parameters of the instrument: plate scale, beam size, calibration, and noise.
An elevated water reservoir holds \(\sim 8\) gallons of deionized water and ethylene glycol in a 40 : 60 ratio respectively. The water is pumped out of the reservoir by a Leeson pump, Model-M4C17D876A. An in-line valve between the pump and water filter allows the water filter to be changed. The water filter consists of a T-bolt style, bottom-loading, single cartridge container, (McMaster-Carr part number 43905K66), which houses a blanket-wound polypropylene filter cartridge. To monitor the water chiller system a flowmeter (Flowmeter King Model 752013C08) and temperature sensor are positioned between the water filter and compressor. The water exiting the compressor is transferred outside where two radiators dissipate heat using two Marathon Electric cooling fans, (model number DVH-056C11D3202E R120 1/2 HP, 60 Hz single phase), fans mounted to each radiator. A valve between the compressor and radiator allow the flow to be cut off for maintenance purposes. The water from the two radiators is transported back inside to the water reservoir.
Figure 5.3: Beam map from an observation of Jupiter on June 8, 2007. The map was produced by constructing individual maps from 71 working detectors, scaling the maps such that the peak of Jupiter for each map was of unit amplitude, averaging the scaled maps, and smoothing the averaged map by 1 map pixel, (0.4”). Data was acquired over a 60 second time span with the telescope scanning at constant 60° elevation over a 2 degree azimuth range every 4.4 seconds. During observation, a 9 m ladder blocked a portion of the primary mirror and the majority of the 72 primary and 11 secondary mirror panels had yet to be aligned. The rms of the unaligned primary mirror panels during observation was ∼190 µm. Map is courtesy of J. Fowler.
5.3.1 Plate Scale

Raw detector and pointing data from subsequent observations on June 12, 2007 were merged to compute the measured plate scale.\textsuperscript{2} The calculated plate scale from the data was compared to the predicted value to evaluate the optical system’s imaging effectiveness. Given the effective focal length of the telescope, $f = 5.2$ m, the predicted plate scale is calculated to be 6.8′ per cm. To determine the plate scale the centers of the measured beam patterns produced by each pixel were plotted as a function of pixel spacing. In azimuth, the spacing between pixel centers is 1.10 mm and in elevation, the spacing between pixels is 1.22 mm. This corresponds to a measured plate scale of 6.0′ per cm in Az, and 6.4′ per cm in El. Figure 5.4 shows the Jupiter data used to calculate the plate scale.

We believe the measured plate scale differs from the calculated value because during observations, the 72 primary and 11 secondary mirror panels were not yet aligned. At the time of observation the 72 primary mirror panels had an rms of $\sim 190 \mu$m, and the secondary panels were unmeasured. In addition, CCAM’s focal plane was not yet aligned with respect to the telescope. In the future, a Faro laser tracker\textsuperscript{3} will align CCAM to ACT using an aluminum plate mounted on the front of the cryostat window, a known distance from the focal plane.

5.3.2 Beam Sizes

Accurately measuring the beam sizes on the sky is essential for calibrating the instrument. Ideally, this requires a source with angular size less than the beam, but can also be accomplished using a source with a well-characterized extended emission. The source’s brightness distribution can then be deconvolved from the resulting beam map. Additionally, the source should be bright enough to produce an accurate map, but not so bright that the TES detectors saturate. Saturation occurs at a loading of $\approx 8$ pW at 300 mK. The planet Jupiter satisfied these criteria and has angular size of 45.7′ (at the time of observation), and brightness $\approx 172$ K [96].\textsuperscript{4}

Using the known brightness distribution of Jupiter, the FWHM for each pixel can be calculated where the FWHM $\equiv \sqrt{\sigma^2_B \ln 2}$. We model the beam intensity $I(\theta)$ by a Gaussian

\textsuperscript{2}Plate scale is defined in Chapter 2 Section 2.2.1.
\textsuperscript{3}Faro Technologies, Inc. http://www.faro.com/ Telephone: (800) 736-0234
\textsuperscript{4}WMAP measures a Jupiter temperature of 172 K at W-band.
Figure 5.4: Calculated plate scale using data from a Jupiter observation on June 12, 2007. The plate scale is calculated by fitting a 2-D Gaussian to the center of each pixel. The Gaussian centers are plotted over row select number as a function of both Az and El position in arcminutes. CCAM’s center is measured to be off by 3.15 arcminutes in elevation and 7.32 arcminutes in azimuth. The plate scale is within 15% of expectations. The plate scale was calculated by J. Fowler.

plus a constant given by:

\[ I(\theta) = A \exp\left(\frac{-(\theta - \theta_{ij})^2}{2\sigma_B^2}\right) + C, \]  

(5.1)

where, \( \theta_{ij} \) is the detector pointing for detector \((i, j)\), \( A \) is the best fit peak amplitude, and \( \sigma_B^2 \) is the variance of the Gaussian beam. A more detailed discussion of the FWHM calculation can be found in [110]. Calculated FWHMs from two Jupiter observations on June 12, 2007 are shown in Figure 5.5. Figure 5.6 shows the variation in FWHM across the 8×32 detector array.
Figure 5.5: Measured beam sizes from two Jupiter observations on June 12, 2007. Data was acquired for \(\sim 330\) seconds during the first observation, and \(\sim 450\) seconds during the second observation. The angular diameter of Jupiter was 45.7" during the observations, which is smaller (by a factor of \(\sim 20\)) than the measured beams. The FWHM plotted here was calculated assuming a Gaussian beam shape. See [110] for a description of the calculation used to determine the FWHM.
Figure 5.6: FWHM as a function of detector position in the array. The detector position is represented by row select number. The FWHM across the array is correlated with row select of the detectors, but independent of column position. We believe this is due to misalignment of CCAM with respect to the telescope as well as unaligned mirror panels. It is yet unknown why detector C0 RS12 (column 0, row select 12) has an anomalous FWHM. FWHM values courtesy of B. Reid.
5.3.3 Calibrations

To convert point source time stream data from DAC into physically meaningful units, the DAC output is calibrated into Kelvin. Our calibration source is the planet Jupiter, which is well studied at 3 mm [96]. An ephermeris program determines the solid angle of Jupiter at the time of observation. Using 172 K (at 145 GHz) for the typical brightness of Jupiter, and the size acquired from the ephermeris program, the gain in K/DAC is computed by:

\[
\text{Gain in K/DAC} = \frac{T_{\text{Jupiter}} (\pi d_{\text{Jupiter}}^2/4)}{2\pi \sigma_B^2 A_{\text{Jupiter}}},
\]

(5.2)

where, \(T_{\text{Jupiter}}\) is the brightness of Jupiter in Kelvin, \(d_{\text{Jupiter}}\) is the angular diameter of Jupiter at the time of observation, \(A_{\text{Jupiter}}\) is the measured peak amplitude of Jupiter in DAC, and \(2\pi \sigma_B^2\) is the area of the Gaussian beam.

The gain in K/DAC can be converted into pW/K using current vs. voltage (I-V) curves. The I-V curves are measured for each detector before observations by UBC’s MCE software and analyzed by software developed by M. Niemack to calculate responsivities in pW/DAC for each detector. Using the notation listed in Table 5.1, the responsivities can be computed from I-V curves as follows.

<table>
<thead>
<tr>
<th>Notation</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(V_{\text{bias}})</td>
<td>Voltage to bias the TES</td>
<td>...</td>
</tr>
<tr>
<td>(R_{\text{bias}})</td>
<td>Resistance of the biasing lines</td>
<td>(\approx 300, \Omega)</td>
</tr>
<tr>
<td>(I_{\text{bias}})</td>
<td>Current through the biasing lines</td>
<td>(\approx 1, \text{mA})</td>
</tr>
<tr>
<td>(V_{\text{TES}})</td>
<td>Voltage drop across the TES</td>
<td>...</td>
</tr>
<tr>
<td>(R_{\text{TES}})</td>
<td>Resistance of the TES</td>
<td>(\approx 10, \text{m}\Omega)</td>
</tr>
<tr>
<td>(I_{\text{TES}})</td>
<td>Current through the TES</td>
<td>...</td>
</tr>
<tr>
<td>(P_{\text{TES}})</td>
<td>Bias power through the TES</td>
<td>(\approx 8, \text{pW})</td>
</tr>
<tr>
<td>(V_{\text{shunt}})</td>
<td>Voltage drop across the shunt</td>
<td>(\approx V_{\text{TES}})</td>
</tr>
<tr>
<td>(R_{\text{shunt}})</td>
<td>Resistance of the shunt</td>
<td>(\approx 0.7, \text{m}\Omega)</td>
</tr>
<tr>
<td>(V_{\text{fb}})</td>
<td>Measured feedback voltage</td>
<td>(\approx 0 - 1, \text{V})</td>
</tr>
<tr>
<td>(R_{\text{fb}})</td>
<td>Resistance of the feedback lines</td>
<td>(\approx 5300, \Omega)</td>
</tr>
<tr>
<td>(M_{\text{ratio}})</td>
<td>Mutual inductance ratio</td>
<td>(\approx 15)</td>
</tr>
<tr>
<td>(R_{\text{para}})</td>
<td>Parasitic resistance in the TES bias loop</td>
<td>(&lt; 0.02R_{\text{shunt}})</td>
</tr>
<tr>
<td>(R)</td>
<td>Responsivity</td>
<td>...</td>
</tr>
</tbody>
</table>

Table 5.1: Notation used to determine the responsivity.

The responsivity of each detector describes the corresponding change in power incident on the TES from the measured current through the TES. Quantitatively, the responsivity
\( R = \frac{dP_{TES}}{dT_{TES}} \). To determine \( R \) we first compute \( I_{TES} \) and \( V_{TES} \). Figure 5.7 shows an electrical schematic of the TES bias and read-out circuits.

![Schematic of the TES bias and read-out circuits](image)

Figure 5.7: Schematic of the TES bias and read-out circuits. On the left, the TES is voltage biased with voltage \( V_{bias} \) and the bias travels through lines with resistance \( R_{bias} \) with current \( I_{TES} \) to point (1). At point (1), the current is split such that \( I_{TES} \) flows through the TES and \( I_{bias} - I_{TES} \) flows through the shunt resistor. The current through the TES is measured by a FLL circuit described in Chapter 3 Section ?? which has an inductance gain of \( M_{ratio} \approx 15 \). The MCE reads out the feedback voltage \( V_{fb} \) which has traveled through lines with resistance \( R_{fb} \).

From the sub-circuit labeled “A” in Figure 5.7, the current through the TES is simply:

\[
I_{TES} = \frac{V_{fb}}{R_{fb}M_{ratio}}. \tag{5.3}
\]

To determine \( V_{TES} \), the voltage drop between points (1) and (2) in Figure 5.7 is written as both the voltage drop across the shunt resistor and drop through the TES,

\[
V_{shunt} = (I_{bias} - I_{TES})R_{shunt} = I_{TES}(R_{TES} + R_{para}). \tag{5.4}
\]

Since \( V_{TES} = I_{TES}R_{TES} \), Equation 5.4 can be re-written,

\[
V_{TES} = I_{bias}R_{shunt} - I_{TES}(R_{shunt} + R_{para}). \tag{5.5}
\]
Neglecting the parasitic resistance which has a resistance less than 2% of the shunt resistance, the power incident on the TES can be expressed using Equations 5.3 and 5.5 as,

\[
P_{TES} = I_{TES}V_{TES} = \frac{V_{fb}}{R_{fb}M_{ratio}}(I_{bias}R_{shunt} - I_{TES}R_{shunt}).
\]

(5.6)

It follows that the responsivity \( R \) is,

\[
R = \frac{dP_{TES}}{dI_{TES}} = V_{TES}\left(1 - \frac{R_{shunt}}{R_{TES}}\right).
\]

(5.7)

The responsivity for each detector in pW/DAC can then be used to determine the pW/K factor. Figure 5.8 shows the relationship between pW and Kelvin for 46 working detectors. The conversion is found by comparing the power calibration from the I-V curves to the measurement with Jupiter. The best fit line calculates a conversion factor of 3.97e-3 pW/K.

5.3.4 Noise

The nominal instrumental noise dictates numerous aspects of the experiment such as scan strategy and the overall sensitivity achievable. To determine the noise of the instrument, we analyze a section of blank sky time stream data. The time stream data in DAC is converted into Kelvin by the method described in Section 5.3.3. The slope and offset of this calibrated data is removed to clean the signal. The resulting time ordered data is Fourier transformed to generate a noise spectrum. The spectrum for a typical detector is shown in Figure 5.9. We find the nominal instrumental noise to be 1.5 mK/rt[Hz]. In an analysis of all the detectors, B. Reid has found that the best achieved noise performance is about 1 mK/rt[Hz].
Figure 5.8: Conversion factor between Kelvin and pW. All columns demonstrate repeatable pW/K conversions between observations. The gain of the detectors in K/DAC is computed from observations of the planet Jupiter. The detector responsivity is determined from analysis of I-V curves taken immediately before observations. The column 7 detectors, which show the best responsivities are the detectors used in the $32 \times 32$ 145 GHz array in MBAC.

Figure 5.9: Noise power spectrum of a typical detector in the $8 \times 32$ array installed in CCAM. Data was acquired on June 12, 2007 over a $\approx 450$ second time span.
5.4 Conclusion

In the past five years there has been a drive to produce large arrays of millimeter-wave detectors. The Bolocam [42] and AzTEC [6] instruments are equipped with 144-element silicon nitride spider-web bolometer arrays for millimeter-wave observations. However, these experiments do not take advantage of multiplexing read-out or transition edge superconducting detector technology. A number of arrays have been built which utilize this technology, such as SHARC II [30] (12×32 array at 350 µm and 450 µm) and SCUBA2 [50] (four 32×40 arrays at 450 µm and 850 µm) but are optimized for observations at smaller wavelengths. SHARC II is also a free-standing array based on the GSFC detectors and has the most in common with CCAM. CCAM differs primarily in that it operates at a larger wavelength.

At millimeter wavelengths, there is the APEX-SZ experiment [117] (330 element 2 mm and 1.4 mm receiver) and MUSTANG [27] (64 element 3.3 mm receiver) at the Green Bank Telescope. The SPT array [112] is in progress and will contain approximately 1000 TES bolometers. The SPT and APEX receivers were built at U.C. Berkeley and have a larger pixel separation.

We have demonstrated that CCAM successfully images millimeter-wave radiation when mounted on the ACT telescope. It is the first large free-space millimeter array to have done this. From observations of the planet Jupiter, the plate scale was measured to be 6.0’ per cm in azimuth and 6.4’ per cm in elevation while the mean FWHM is 2.0 arcminutes. From analysis of blank sky data, the nominal instrumental noise is measured to be 1.5 mK/rt[Hz]. Further data analysis is in progress to fully characterize the system.
Chapter 6

The CCAM Polarizer

6.1 Introduction

The addition of a low loss, aperture-filling polarizer gives CCAM the capability to analyze polarization. The polarizer constructed to mate to CCAM uses a rotating, antireflection coated, sapphire half wave plate coupled to a fixed wire-grid polarizer and mounts outside the cryostat vacuum, lending itself to easy implementation and modularity. The polarizer is measured to be 96% transmissive with reflections less than 2% at 144 GHz.

The polarizer described here began as a summer project with N. Chang, J. Fulton, C. Kunkel, T. Liu, B. Lyons, D. Sleiter, and J. Woodby. We have built on that work and have made and tested the polarizer described here.

6.2 Polarizer Concept

The polarizer uses a rotating half wave plate and fixed wire-grid to modulate the intensity of linearly polarized light incident on the cryostat window [61]. The differential intensity generated by the polarizer can then be detected by the TES array, which measures total incident power. This strategy is depicted in Figure 6.1.

When monochromatic, linearly polarized light propagates through the half wave plate rotating at a frequency $f_0$ [Hz], the light will emerge with its polarization vector rotating at $2f_0$. When this light passes through the wire-grid polarizer, the transmitted light will be sinusoidally modulated at $4f_0$. The amplitude of this modulation will be a function of the level of polarization of the incident radiation. After traveling through the cryostat’s optics,
Figure 6.1: Polarizer concept. Monochromatic, linearly polarized light passing through a half wave plate rotating with frequency $f_0$ [Hz] will emerge with its polarization vector rotating at $2f_0$. If this light propagates through a fixed wire-grid, the transmitted light will be sinusoidally modulated at $4f_0$.

the TES detector array, which measures differences in power, can be read out to acquire time stream of the modulated polarized signal. If the time stream data is transformed into Fourier space, the polarization data will be seen in the sidebands of the $4f_0$ signal. Systematic signals in the time stream data lying outside the $4f_0$ frequency can be filtered away.

The following two sections detail the design and construction of the half wave plate and wire-grid polarizer. While CMB experiments often describe light by its frequency $\nu$, the analysis and characterization of polarizing optical elements become clearer when light is described by its wavelength $\lambda$. For this reason, in the next two sections, light will be described by its wavelength in free space, $\lambda_0$. At CCAM’s observing frequency, 145 GHz, $\lambda_0 = 2$ mm.

6.2.1 Half Wave Plates

Wave plates change the polarization of an incident wave. This is often accomplished with birefringent materials which inherently have different indices of refraction along the ordinary ($o$-) axis, $n_0$, and along the extraordinary ($e$-) axis, $n_e$. Suppose a monochromatic plate wave is incident on a wave plate of thickness $d$. The difference in index in the wave plate cause the $o$- and $e$- waves to travel at different speeds in the plate. The resulting
transmitted light will be a superposition of the \( o^- \) and \( e^- \) waves, giving rise to a relative phase shift in the outgoing light [15]. For a specific wavelength, \( \lambda_0 \), the phase difference is governed by the thickness of the wave plate. In the specific case of a half wave plate, the thickness of the half wave plate is tuned to generate a \( \pi \) radian phase difference between the transmitted \( o^- \) and \( e^- \) waves. If a plane-polarized wave is normally incident on a half wave plate, and the plane of polarization is at an angle \( \theta \) with respect to the extraordinary axis, the \( \pi \) phase shift through the half wave plate will rotate the original plane wave through a total angle of \( 2\theta \) with respect to the incident direction. The effect of a half wave plate on incident light is illustrated in Figure 6.2.

![Figure 6.2: A Half wave plate. Half wave plates rotate the polarization state of linear polarized radiation. A normally incident plane polarized wave incident on a half wave plate with its plane of polarization oriented at an angle \( \theta \) with respect to the extraordinary axis, will be rotated by \( 2\theta \) with respect to the incident direction.](image)
6.2.2 Wire-grid Polarizers

Linear polarized light incident on a wire-grid polarizer will reflect the E-field component of radiation parallel to the wires, while allowing radiation with E-field's perpendicular to the wires to be transmitted [15]. This effect is depicted in Figure 6.3.

![Figure 6.3: A wire-grid polarizer. A wire-grid polarizer selectively allows linearly polarized light with E-field component perpendicular to the wires to be transmitted. The E-field component parallel to the wires excites electrons along the wires. The accelerating electrons re-emit radiation which destructively interferes with the incident radiation yielding a net zero E-field transmitted in the direction parallel the wires.](image)

6.3 Design and Construction of the Half Wave Plate

The half wave plate was constructed from a 150 mm diameter $\alpha$ cut sapphire purchase from Guild Optical Associates\(^1\). Because the half wave plate's efficiency is strongly dependent on the wavelength ($\lambda_0$) of the incident radiation, the sapphire's thickness was carefully chosen to couple to CCAM's observing frequency. For a half wave plate observing radiation with wavelength $\lambda_0 = 2$ mm, the optimal half wave plate thickness, $t_{HWP}$, is calculated by

$$t_{HWP} = \frac{(2m + 1)\lambda_0}{2(|n_0 - n_e|)}$$  \hspace{1cm} (6.1)

\(^1\)Guild Optical Associates Telephone: (603) 889-6247
where \( m = 0, 1, 2, \ldots \) and \( n_0 \) and \( n_e \) are the ordinary and extraordinary indices of refraction in the half wave plate. To minimize absorptive loss in the sapphire half wave plate, the thinnest sapphire thickness that met Equation 6.1, \((m = 0)\) was chosen. Taking the \( n_0 \) and \( n_e \) indices of refraction for \( \alpha \)-cut sapphire to be 3.07 and 3.40 respectively [73], the minimum half wave plate thickness was calculated to be 3.04 mm.

The absorptive loss through the 3.04 mm thick sapphire half wave plate was calculated from the loss tangent \((\tan \delta)\) of sapphire, where \( \tan \delta = (2.1 - 2.5) \times 10^{-4} \) and \((1.1 - 1.4) \times 10^{-4}\) for the \( o \)- and \( e \)- axes respectively [73]. For 2 mm radiation, the calculated absorptive loss is between 0.75\% and 0.9\%.

The intensity of radiation transmitted through the sapphire half wave plate was additionally maximized by antireflection coating the sapphire. For \( \alpha \)-cut sapphire, the ideal antireflection coating material has index of refraction \( n_c = \sqrt{n_{\text{sapphire}}} = 1.75 \) and thickness \( t_c = 297 \mu m \). Nylon, which has an index of refraction \( n_{\text{nylon}} = 1.73 \), loss tangent, \( \tan \delta_{\text{nylon}} = 0.0008 \), [73], and is readily available in 300 \( \mu m \) thickness, was chosen for the antireflection coating material. Because the half wave plate is external to the cryostat, the thermal contraction difference between nylon and sapphire is not problematic. Figure 6.4 shows the computed loss from both reflections and absorptions in the antireflection coated half wave plate.

### 6.4 Design and Fabrication of the Wire-grid Polarizer

The wire-grid polarizer was constructed by sputtering 3 \( \mu m \pm 0.2 \mu m \) aluminum over a silicon substrate, using photolithography techniques to mask the desired aluminum trace regions, and wet etching the excess aluminum to create a grid of linear aluminum traces on a rigid silicon substrate. A process similar to this is detailed in Appendix B. To minimize absorptive loss in the wire-grid polarizer, high resistivity \((> 10,000 \Omega\text{-cm})\) silicon, which has a low loss tangent, \((\tan \delta = 0.7 \times 10^{-4} \text{[100]})\) at 2 mm, was chosen as the substrate material. The silicon, purchased from Surface Process Group,\(^2\) is a 150 mm diameter, float zone wafer with minimum resistivity of 10,000 \( \Omega\text{-cm} \). The thickness of silicon \( t_{Si} \), was chosen to minimize reflections for \( \lambda_0 = 2 \text{mm} \) radiation. The minimum occurs at thickness:

\[
t_{Si} = \frac{m \lambda_0}{2n_{Si}},
\]

\(^2\)Surface Process Group E-mail: sales@surfaceprocess.com Telephone: (804) 213-3855
Figure 6.4: Calculated performance of the AR coated half wave plate. The half wave plate is made of a 3.04 mm thick piece of α-cut sapphire, antireflection coated with 300 µm of nylon on both sides of the sapphire.

where $n_{Si} = 3.41$ and $m = 0, 1, 2…$. For rigidness, 5.44 mm thick silicon ($m = 18$) was chosen.

The reflections in the wire-grid were additionally minimized by antireflection coating the silicon substrate. The index of refraction and thickness of the optimal antireflection coating was calculated in the same manner as the half wave plate in the previous section. Taking the index of refraction of silicon to be $n_{Si} = 3.41$ [73], the antireflection coating which minimizes reflections in the silicon will have an index of refraction of $n_c = 1.85$ and thickness $t_c = 270$ µm. Cirlex, a polyimide, was chosen as the antireflection coating because of previous success AR coating silicon with Cirlex reducing reflections to less than 1% [74]. The calculated spectrum for 5.44 mm thick high resistivity silicon AR coated with Cirlex ($\tan \delta = 0.007$) is shown in Figure 6.5 [74].

6.4.1 Optimizing the Wire-grid

The dimensions of the evaporated aluminum traces were optimized for 2 mm radiation. To extrapolate the optimum aluminum trace dimensions that producible with microfabrication techniques, we followed the approach of [51]. Houde calculates the currents induced on a
round wire and proceeds to calculate the scattered field generated by those currents. For round wires in free space, the optimal radius $r$, and wire spacing $d$, that will completely reflect incident transverse magnetic (TM) 2 mm radiation while transmitting 2 mm TE radiation is determined by [51]:

$$r \approx \left[ \frac{\lambda_0^3}{(1 - \alpha^2)^4 \pi^7 \sigma Z_0} \right]^{1/6},$$  \hspace{1cm} (6.3)

$$d \approx 2\pi r,$$  \hspace{1cm} (6.4)

where $\sigma$ is the conductivity of the wires, $Z_0$ is the impedance of free space, and $0 \leq \alpha \leq 1$ is a parameter dependant on the angle of incidence and angle of wire-grid rotation. For $\lambda_0 = 2$ mm, $\sigma_{Al} = 3.77 \times 10^7$(mΩ)$^{-1}$, and $\alpha = 0$, which assumes normal incidence and wire-grid orientation which maximizes the transmitted signal, the calculated wire radius, $r$ is 30 $\mu$m, and the spacing between wires, $d$, is 189 $\mu$m. Using Equations (66) and (67) from [51], the parallel and perpendicular reflection coefficients can be approximated. For values of $r$ and $d$ calculated above, $|R_\parallel|^2 \approx 0.9995$ and $|R_\perp|^2 \approx 0.0005$.

Although the aluminum traces producible by microfabrication techniques are not round, Houde’s work is still instructive for optimizing the size and spacing of the traces. His solution suggests the reflection coefficient of a wire-grid polarizer is largely independent of $d$ for the
values of $a$ of interest. We applied this result to a wire-grid polarizer with rectangular traces of dimensions $a, d,$ and $h$ as illustrated in Fig 6.6. Since radial symmetry is broken in rectangular wires, a numerical approach was used to calculate the optimal wire-grid dimensions [70].

The numerical solution suggests the optimum occurs at $a = 75 \mu m$, $d = 225 \mu m$, with $h$ set to $3 \mu m$. However, small variations in $h$ ($\Delta h \approx 1 \mu m$) have a negligible effect. In addition, between $a \in \{50 \mu m-125 \mu m\}$, reflections do not fall below $|R_\parallel|^2 = 0.995$ and, only for wire spacings where $d \geq 10a$ does $|R_\parallel|^2$ fall below 0.9 [70]. The wire-grid was microfabricated with these constraints. The resulting aluminum traces were measured to be $a = 60 \mu m \pm 5 \mu m$, $d = 230 \mu m \pm 5 \mu m$, and $h = 3 \mu m \pm 1 \mu m$.

When combined with the half wave plate, the spectrum of the half wave plate/wire-grid polarizer can be calculated. Figure 6.7 shows the computed reflection, transmission, and absorption for the assembled polarizer.

### 6.5 Polarizer Drivetrain

The half wave plate and wire-grid polarizer are mounted on a 20 cm diameter aluminum frame. Two aluminum clamps, running along the outer diameters of the half wave plate and wire-grid polarizer, fix the half wave plate and wire-grid polarizer positions. Two Kaydon Reli-Slim Bearings, (part number JU065CP0), allow the half wave plate and wire-
grid polarizer to rotate independently with minimal vibration. The half wave plate rotates at $f_0 \sim 1$ Hz via 45 cm timing belt driven by a DC servo motor (Matsushita GMZ-6MP013). At this speed, the rotating half wave plate created no observable vibrations on the receiver.

Figure 6.7: Calculated polarizer performance. The top plot shows the reflection and reflection from particular components of the polarizer. The thick red line depicts the total loss from the polarizer. The bottom plot shows the transmission through each component, and the total calculated transmission.
Figure 6.8: The polarizer drivetrain. Figure courtesy of [61]. The polarizer was designed to be easily mounted in front of the receiver window. The drivetrain was designed to ensure only light that had transversed the half wave plate and wire-grid would enter into the cryostat window. The Slim-line bearings (shown in dark grey) running around the circumference of the drivetrain allow the half wave plate and wire-grid to move independently. The drive shafts (shown in dark grey) are bolted to the slim line bearings and couple to a timing belt (not shown) which is in turn coupled to a timing pulley driven by a DC motor (not shown) The 2 mm spacing between the half wave plate and wire-grid was tuned to maximize in-band transmission through the polarizer.

and wire-grid polarizer. To reduce magnetic fields on the SQUID multiplexors, the DC motor is shielded with a mu-metal cylinder. The wire-grid, which in normal operations remains stationary, can be rotated by hand and fixed in place by two 4-40 set screws. Tick marks outside the wire-grid polarizer indicate the orientation of the wire-grid traces. The rotational speed of the half wave plate is determined by an aluminum finger with one end attached to the rotating half wave plate. A slotted optical switch (Honeywell H0A2001-001) sends a 5 V signal each time the aluminum finger passes through the slot. The entire drivetrain is rigidly mounted to the cryostat window to reduce vibrations on the dewar. Figure 6.8 shows the completed polarizer drivetrain.
6.6 Mathematical Description of the Polarizer

6.6.1 Jones Vectors and Matrices

Jones matrices provide a compact mathematical description of polarization induced by optical elements on incoming radiation [62, 15]. When light traveling in the +z direction passes through a polarization sensitive device, the polarization state lying in the x and y axes is altered. The incident light can be represented by a Jones vector \( \mathbf{J} \) [15],

\[
\mathbf{J} = \begin{bmatrix} E_x \\ E_y \end{bmatrix}
\]  

(6.5)

where \( E_x \) and \( E_y \) are the electric field components decomposed along the \( x \) and \( y \) axes for light traveling along the \( z \) axis. Often, Jones vectors are normalized to unity. This discards the amplitude information needed for absorption calculations, but it simplifies analysis where relative phases and relative amplitudes are the quantities of interest.

The polarization state \( \mathbf{J}' \) resulting from light transmitted through an optical element can be calculated by multiplying the input state, \( \mathbf{J} \), by the 2×2 Jones matrix characterizing the polarization properties of the element, \( \mathbf{M} \), (\( \mathbf{J}' = \mathbf{MJ} \)). If we define the +z axis as the direction of light propagation, and take the polarizing element to lie in the \( xy \)-plane, the polarization states altered by optical elements can be modeled by Jones vectors and Jones matrices such as those depicted in Figure 6.9.

6.6.2 Jones Matrix for the Half Wave Plate

The following procedure was used to determine the Jones matrix for a rotating half wave plate. We started with the Jones matrix for a general wave plate with phase delay \( \phi \). From this Jones matrix, we can determine the Jones matrix for a wave plate at an angle \( \theta \) about the \( z \)-axis in the \( xy \)-plane using the rotation transformation matrix. This Jones matrix which represents a wave plate with retardance \( \phi \) about an angle \( \theta \) about the \( z \)-axis can be further constrained to get the Jones matrix for a rotating half wave plate rotating with frequency \( f_0 \). The full calculation is given below.

If we consider light of wavelength \( \lambda \) incident on a wave-plate of thickness \( d \), the phase delay between the ordinary and extraordinary axes is given by, \( \phi = \frac{2\pi}{\lambda}d\Delta n \), where \( \Delta n = \)
Figure 6.9: Sample Jones vectors and matrices. Right: Jones vectors for common polarization states. Left: Jones matrices for common polarizers.

\[ n_e - n_o. \] A wave plate with its extraordinary axis horizontal can then be described by,

\[
M_{\text{Wave Plate}}(\phi) = \begin{bmatrix}
e^{i\phi/2} & 0 \\
0 & ie^{-i\phi/2}
\end{bmatrix},
\]

where \( \phi = \pi \) for a half wave plate and \( \phi = \pi/2 \) for a quarter wave plate polarizer. For example, if the incident light is linearly polarized in the +45° direction, \( J = \frac{1}{\sqrt{2}}[1,1] \), the transmitted light is given by \( J' = MJ = \frac{1}{\sqrt{2}}[e^{i\phi}, ie^{-i\phi}] \).

The next step is to determine the Jones matrix for a wave plate rotated an arbitrary angle \( \theta \) about the \( z \) axis in the \( xy \)-plane. To do this, the rotation transformation matrix, \( M_{\text{rotate}} \), needs to be defined. For a \( \theta \) rotation in the \( xy \)-plane, the transformation matrix is defined as:
Figure 6.10: A wave plate rotated $\theta$ degrees about the $z$ axis in the $xy$-plane.

\[
M_{\text{rotate}}(\theta) = \begin{bmatrix}
\cos \theta & \sin \theta \\
-\sin \theta & \cos \theta
\end{bmatrix}.
\] (6.7)

The Jones matrix for the rotated wave plate can then be found by:

\[
M_{\text{WavePlate}}(\phi, \theta) = M_{\text{rotate}}(-\theta)M_{\text{WavePlate}}(\phi)M_{\text{rotate}}(\theta),
\] (6.8)

This situation is represented in Figure 6.10.

Using Equations 6.6, 6.7, 6.8, the Jones matrix for a wave plate with retardance $\phi$ and extraordinary axis angled $\theta$ about the $z$-axis in the $xy$-plane is given by,

\[
M_{\text{WavePlate}}(\theta) = \begin{bmatrix}
\cos^2(\theta)e^{i\phi/2} + i\sin^2(\theta)e^{-i\phi/2} & \cos(\theta)\sin(\theta)(e^{i\phi/2} + ie^{-i\phi/2}) \\
\cos(\theta)\sin(\theta)(e^{i\phi/2} - ie^{-i\phi/2}) & \sin^2(\theta)e^{i\phi/2} - i\cos^2(\theta)e^{-i\phi/2}
\end{bmatrix}.
\] (6.9)

In our specific case of a half wave plate, $\phi = \pi$, and the Jones matrix reduces to:

\[
M_{\text{HW P}}(\theta) = \begin{bmatrix}
i\cos^2(\theta) + \sin^2(\theta) & \cos(\theta)\sin(\theta)[1 + i] \\
\cos(\theta)\sin(\theta)[i - 1] & i\sin^2(\theta) - \cos^2(\theta)
\end{bmatrix}.
\] (6.10)

To include the $f_0$ rotation of the half wave plate in the equation above, we can replace $\theta$ by $2\pi f_0 t$ where $f_0$ and $t$ is in seconds. The final Jones matrix for a rotating half wave plate rotating at frequency $f_0$ [Hz] is given by:

\[
M_{\text{HW P}}(2\pi f_0 t) = \begin{bmatrix}
i\cos^2(2\pi f_0 t) + \sin^2(2\pi f_0 t) & \cos(2\pi f_0 t)\sin(2\pi f_0 t)[1 + i] \\
\cos(2\pi f_0 t)\sin(2\pi f_0 t)[i - 1] & i\sin^2(2\pi f_0 t) - \cos^2(2\pi f_0 t)
\end{bmatrix}.
\] (6.11)
6.6.3 Jones Matrix for the Wire-grid Polarizer

The Jones matrix for a wire grid polarizer can easily be determined by manipulating a known Jones matrix, such as those shown in Figure 6.9. Recall, only light perpendicular to the wire grid traces will be transmitted (Section 6.2.2). Arbitrarily picking the traces to lie along the y axis, the Jones matrix for a horizontal linear polarizer would provide the simplest calculation. Similar to the rotation of the half wave plate above, the rotation transformation matrix can be used to determine the Jones matrix for a wire grid with traces oriented with angle $\theta$ to the y-axis.

\[
M_{\text{WGP}}(\theta) = M_{\text{rotate}}(-\theta)M_{\text{WGP}}M_{\text{rotate}}(\theta),
\]

(6.12)

where $M_{\text{rotate}}$ is the rotation transformation matrix given in Equation 6.7, and $M_{\text{WGP}}$ is taken to be, $M_{\text{HLP}}$, the Jones matrix for a horizontal linear polarizer.

\[
M_{\text{HLP}} = \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix}.
\]

(6.13)

Using Equations 6.8, 6.12 and 6.13, the Jones Matrix for a wire-grid lying in the xy-plane and oriented at angle $\theta$ with respect to the y-axis is given by:

\[
M_{\text{WGP}}(\theta) = \begin{bmatrix} \cos^2(\theta) & \cos(\theta)\sin(\theta) \\ \cos(\theta)\sin(\theta) & \sin^2(\theta) \end{bmatrix}.
\]

(6.14)

6.6.4 Jones Matrix for the Half Wave Plate/Wire-grid Polarizer

The Jones matrices characterizing a rotating half wave plate, $M_{\text{HWP}}(f_0, t)$, and wire-grid polarizer, $M_{\text{WGP}}(\theta)$, are multiplied to describe the effect of the polarizer on incoming radiation having Jones vector $\mathbf{J}$:

\[
\mathbf{J}' = M_{\text{WGP}}(\theta)M_{\text{HWP}}(f_0, t)\mathbf{J} = M_{\text{polarizer}}(f_0, \theta, t)\mathbf{J}
\]

\[
= \begin{bmatrix} \cos^2(\theta) & \cos(\theta)\sin(\theta) \\ \cos(\theta)\sin(\theta) & \sin^2(\theta) \end{bmatrix} \begin{bmatrix} \cos^2(2\pi f_0 t) - \sin^2(2\pi f_0 t) & 2i\cos(2\pi f_0 t)\sin(2\pi f_0 t) \\ 2i\cos(2\pi f_0 t)\sin(2\pi f_0 t) & -\cos^2(2\pi f_0 t) + \sin^2(2\pi f_0 t) \end{bmatrix} \mathbf{J}.
\]

(6.15)
The Jones matrix $M_{\text{polarizer}}(f_0, \theta, t)$ quantitatively expresses the effect of the half wave plate/wire-grid polarizer on incoming radiation. From Equation 6.11, the intensity of light transmitted through the half wave plate rotating with frequency $f_0$ will be modulated at $2f_0$. When the radiation transmitted through the half wave plate passes through the wire-grid polarizer, Equation 6.15 shows the transmitted radiation will be sinusoidally modulated at a frequency of $4f_0$. The amplitude of the signal is a function of the polarization of the incident light.

6.7 Experimental Performance

To verify the predicted performance of the polarizer, the polarizer was subjected to the tests described in the following section.

6.7.1 Performance Before Installation on CCAM

The predicted transmission signal over one rotation of the half wave plate was determined using a Jones vector representing linearly polarized light, $J = [1, 0]$, to match the polarization state of the source. The transmitted light will then be described by the product of $J$ and $M_{\text{polarizer}}(f_0, \theta, t)$. To account for the losses in the polarizer discussed in Sections 6.4 and 6.3, the transmission at 144 GHz was acquired from the calculated transmission spectra shown in Figure 6.7 which shows a transmission of 98.4% at 144 GHz. The calculated transmission of the polarizer over one rotation of the half wave plate is given in Figure 6.12.

The measured transmission through the polarizer was compared to the calculated transmission using a diode detector and a temperature-compensated 144.00 GHz local oscillator (L.O.) source mounted at normal incidence on opposite sides of the polarizer. This setup is shown in Figure 6.11. The wire-grid was oriented with its transmission axis parallel to the linearly polarized source to maximize the transmitted signal. The feed horns for the source and receiver were aligned such that the electric field was oriented normal to the plane of incidence (TE mode). The half wave plate was rotated at $f_0 \approx 1$ Hz by the DC motor described in Section 6.5. The time stream data from the detector was synchronously binned and averaged over $\approx 500$ rotations of the half wave plate. The data were normalized by keeping the source and receiver fixed and removing the polarizer. The power measured without the polarizer we took to have perfect transmission and scaled the data acquired
with the polarizer in between the source and receiver using that maximum value. Figure 6.12 plots the measured transmission as a function of the half wave plate rotation angle. Overplotted is the calculated transmission vs half wave plate rotation angle.

From Figure 6.12, transmission through the polarizer was measured to be 97% which is in close agreement with the calculated transmission 98.5%. In addition, both the measured and calculated signals exhibit a sinusoidal $4f_0$ modulation where $f_0$ [Hz] is the rotational speed of the half wave plate. However, this measurement was conducted at a single frequency, (144 GHz), whereas observations in CCAM are measured at $\nu = 145$ GHz over $\Delta \nu \simeq 21$ GHz. To predict the performance of the polarizer over CCAM’s band, the transmission, reflection, and absorption spectra, generated in Section 6.4.1, were integrated over the entire band. Figure 6.13 shows the resulting calculated polarizer performance at $\nu=145$ GHz with $\Delta \nu \simeq 21$ GHz.

### 6.7.2 Detector Response to Polarized Radiation

The polarizer was mounted to CCAM to evaluate the its performance at 145 GHz ($\Delta \nu \sim 21$ GHz) when coupled to a TES detector array.
Figure 6.12: Measured (dashed curve) and calculated transmission (solid curve) vs. rotation angle of the half wave plate at 144 GHz. Both curves display a $4f_0$ modulation. The solid curve is calculated for TE mode radiation and peaks at 0.985. A best fit to the measured transmission yields a peak transmission of 0.970.

Setup and Expectations

The 144.00 GHz linearly polarized source$^3$ and feed horn were aligned such that the electric field was normally incident on the half wave plate (TE mode). The L.O.’s power was attenuated by a fixed 10 dB attenuator and an adjustable attenuator. The adjustable attenuator was tuned to provide the maximum signal during measurements without saturating the detectors (1/4 turn from fully off). This assembly was mounted so that the LO’s feed horn was $\sim 20$ cm away from the wire-grid polarizer. The wire-grid polarizer was positioned between the linearly polarized source and rotating half wave plate. This mitigated the amount of unpolarized light incident on the half wave plate. The half wave plate rotated at $f_0 \sim 1$ Hz and its rotational speed was recorded throughout the data acquisition with an auxiliary input sampled at 100 Hz with the BLAST DAS housekeeping system. The wire-grid polarizer was aligned to maximize transmission at 145 GHz and remained fixed over the 80 seconds. An 11.5% neutral density filter (discussed in Section 4.4) was in the optical path between the polarizer and TES array to prevent the detectors from saturating. This setup

$^3$ZAX Millimeter Wave Corporation http://www.millimeterwave.com/ Telephone:(909) 599-6159
Figure 6.13: Calculated transmission and reflection vs. half wave plate rotation angle over the CCAM band ($\nu = 145\,\text{GHz}$, $\Delta\nu \cong 21\,\text{GHz}$). The bottom plot illustrates signals generated by reflections through the polarizer modulated at $2f_0$, where $f_0$ is the rotational speed of the half wave plate. This is because the wire grid polarizer will not modulate reflections. This is for the geometry shown in Figure 6.11.
Figure 6.14: Polarizer setup to determine the detector response to polarized radiation. The ZAX varactor tuned Gunn oscillator is attenuated by a 10 dB attenuator and a variable attenuator. The feed horn directed light into the polarizer setup. For these measurements, the wire-grid polarizer was placed in front of the rotating half wave plate such that the radiation from the source was incident on the wire-grid polarizer and subsequently transmitted through the half wave plate.

is depicted in Figure 6.14. The detectors were sampled at 400 Hz and temperature servoed at $T_{bath} = 380 \text{ mK}$. I-V curves were taken before and after the data acquisition to calibrate the detector signal and ensure detector stability.

Data Taking and Time Stream Plot

Eighty seconds of time ordered data were acquired with the TES array with the linearly polarized source modulated on and off at 10-30 second intervals. The time stream data for a typical detector is shown in Figure 6.15.

With this setup, the plane of polarization rotates on the detector. If the detectors were unpolarized, we would expect to see the signal on the detectors unmodulated. However, if the detectors had some intrinsic polarization the signal would be modulated at $4f_0$. The resulting four maximum amplitudes should be constant over one rotation of the half wave plate.
Figure 6.15: Time stream data for detector C4 RS2. The linearly polarized source was turned on and off and the resulting detector response was converted into fW from analysis of its IV curve. The offset is arbitrary.

**Fitting and Subtraction**

To compare the measured signal with the expected signal, the two time ordered data streams corresponding to the polarized source being on and off were synchronously averaged over one rotation of the half wave plate after removal of offsets gain. The averaged source on and source off signals were fit by the method of least squares to a sum of sines and cosines with variable amplitudes and phases. The fit for the source off was subtracted from the source on fit to remove the half wave plate synchronous signal.\(^4\) The synchronous subtracted signal was fitted in the same manner as the raw data, and was repeated for each detector.

**Results**

From Table 6.2, the first harmonic is present when the source is both on and off. We believe this signal is dominated by the magnetic field generated by the DC motor, steel timing pulleys, and slim-line bearings which is present in both situations. When the source is on, there seems to be an additional first harmonic source. We have not yet identified the cause of this term. However, the subtraction of the first harmonic synchronous signal

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\(^4\)This could also have been done by coadding the data.
Figure 6.16: Detector response to polarized radiation. The measurement setup is described in Section 6.7.2 and depicted in Figure 6.14. For each detector response, both the source on and source off signal were fit by the method of least squares to a sum of sines and cosines. The source on and source off errors were then estimated from the least square fit covariance matrix. Top: The source off fit was subtracted from the source on fit for each detector. The detector response in DAC was converted to fW from analysis of I-V curves. Middle: The signal resulting from the subtraction of the synchronous signal was fit by the method of least squares to a sum of sines and cosines. The magnitude of the fit’s fourth harmonic is plotted for each operational detector. Bottom: The magnitude of the second harmonic for the working detectors. The magnitudes and errors were computed using the same procedure as the middle plot, but here the fit’s second harmonic is plotted.
from the source-off data removes enough of the first harmonic signal of the source-on data to clearly reveal the fourth harmonic source-on signal.

We believe the second harmonic is dominated by internal reflections for the following reasons. First off, when the source is on the amplitude of the second harmonic signal increases significantly and so is likely not due to magnetic fields. Also, we know that to the extent the detector is polarized the signal will show up at the fourth harmonic. The reflections inside the cryostat are complicated and have not yet been modeled. From Table 6.2 we measure an $\sim 130\%$ increase in the second harmonic signal when the source is turned on.

We model the fourth harmonic source as the polarized response of the detector and or optics to the half wave plate rotation. This signal is present at the fourth harmonic as shown in Figure 6.13. Additionally, if the majority of the fourth harmonic signal is from radiation incident on the rotating half wave plate, we expect the fourth harmonic to increase when the source is on. From Table 6.2, the fourth harmonic signal increases $\sim 250\%$ when the source is turned on vs. when the source is off. From Table 6.2 we conclude the detector and lens system has an intrinsic level of polarization of $\sim 25\%$. It is interesting to note that from Figure 6.16 Column 7 shows a different response to the polarized source. These detectors will be the detectors used in the first MBAC array have an intrinsic level of polarization of $\sim 17\%$.
Chapter 7

Conclusions

We have presented the design, construction, and testing of a new type of camera. It is the first free-standing close-packed array to observe the sky at 145 GHz. By successfully integrating and implementing the new detector, optics, and read-out elements into a single receiver, the work done in this thesis paves the way for other experiments to follow suit. The most significant achievements presented in this thesis are as follows:

We have developed and tested a millimeter-wave antireflection coating for silicon lenses at cryogenic temperatures. This antireflection coating reduces reflections to <1.5% per lens at the designed wavelength while maintaining >90% transmission at $\nu < 300$ GHz. Astronomical observations both in Princeton, New Jersey, and on the ACT telescope in Chile, have verified the imaging capabilities of this new method.

We have constructed and optimized a $^3$He/$^4$He sorption refrigeration system coupled to a pulse tube cryocooler. This eliminates the need for liquid cryogens to cool the receiver at the remote ACT site. The $^4$He sorption refrigerator has $\sim 90$ J cooling power and a no-load base temperature of $\sim 615$ mK. The $^3$He sorption refrigerator has $\sim 5$ J cooling power and a no-load base temperature of $\sim 215$ mK.

In addition, a polarizer was constructed to determine the feasibility of the detector array to measure polarization. In doing so, we find the receiver is intrinsically $\sim 25\%$ polarized.

We have assembled a new type of detector array which consists of an 8×32 array of nearly-touching 1.05 mm$^2$ TES detectors. The array is read-out by time-domain SQUID multiplexers. While there are many advantages to using close-packed multiplexed TES detectors, there are also many challenges to reliably constructing these arrays. In this
thesis, we have devised concrete procedures for assembling close-packed detector arrays and read-out circuitry.

The technology pioneered and proven by this thesis will be directly applicable in the construction of MBAC, the receiver dedicated to the ACT telescope.
Appendix A

CCAM Housekeeping and Detector Pinout

Figure A.1: CCAM housekeeping pinout. In the above table, heaters are denoted “H”, ROX thermometers are denoted “R”, and diode thermometers are denoted “D”. Some of the wiring from the 300 K 50 pin sub D connector is not wired to the 4 K CBOB 25 pin MDM connectors. These connections have been left blank, or are not included. All diodes are two leads as opposed to four leads. Continued on the next page.
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<td>148.4</td>
<td></td>
</tr>
<tr>
<td>He 3 HS FB1</td>
<td>H14</td>
<td>33</td>
<td>16</td>
<td>R16</td>
<td>12,13</td>
<td>1006</td>
<td></td>
</tr>
<tr>
<td>He 3 CP</td>
<td>R0</td>
<td>49</td>
<td>50</td>
<td>R12</td>
<td>10,11 : 22,23</td>
<td>2113</td>
<td></td>
</tr>
<tr>
<td>He 3 pot</td>
<td>R1</td>
<td>19</td>
<td>3</td>
<td>R12</td>
<td>12,13 : 24,25</td>
<td>2071</td>
<td></td>
</tr>
<tr>
<td>0.3 array holder</td>
<td>R2</td>
<td>31</td>
<td>15</td>
<td>R13</td>
<td>12,13 : 24,25</td>
<td>2108</td>
<td></td>
</tr>
<tr>
<td>Si card</td>
<td>R3</td>
<td>35</td>
<td>34</td>
<td>R14</td>
<td>4.5 : 16,17</td>
<td>1248</td>
<td></td>
</tr>
<tr>
<td>0.6 baffle</td>
<td>R6</td>
<td>18</td>
<td>2</td>
<td>R14</td>
<td>10,11 : 22,23</td>
<td>2040</td>
<td></td>
</tr>
<tr>
<td>0.6 pot</td>
<td>R9</td>
<td>27</td>
<td>11</td>
<td>R15</td>
<td>2.3 : 14,15</td>
<td>2096</td>
<td></td>
</tr>
<tr>
<td>60 K</td>
<td>D0</td>
<td>20</td>
<td>4</td>
<td>R11</td>
<td>3,15</td>
<td>0.751</td>
<td></td>
</tr>
<tr>
<td>4 K</td>
<td>D1</td>
<td>23</td>
<td>7</td>
<td>R11</td>
<td>5.17</td>
<td>0.79</td>
<td></td>
</tr>
<tr>
<td>He 4 pump FB1</td>
<td>D2</td>
<td>28</td>
<td>10</td>
<td>R11</td>
<td>7.19</td>
<td>0.781</td>
<td></td>
</tr>
<tr>
<td>He 4 CP FB1</td>
<td>D3</td>
<td>29</td>
<td>13</td>
<td>R11</td>
<td>9.21</td>
<td>0.78</td>
<td></td>
</tr>
<tr>
<td>He 3 pump FB1</td>
<td>D4</td>
<td>32</td>
<td>16</td>
<td>R11</td>
<td>11,23</td>
<td>0.749</td>
<td></td>
</tr>
<tr>
<td>He 4 CP FB2</td>
<td>D7</td>
<td>22</td>
<td>6</td>
<td>R13</td>
<td>5.17</td>
<td>0.722</td>
<td></td>
</tr>
<tr>
<td>He 4 pump FB2</td>
<td>D8</td>
<td>25</td>
<td>9</td>
<td>R13</td>
<td>9.21</td>
<td>0.772</td>
<td></td>
</tr>
<tr>
<td>0.6 DB</td>
<td>D9</td>
<td>28</td>
<td>12</td>
<td>R13</td>
<td>11,23</td>
<td>0.86</td>
<td></td>
</tr>
</tbody>
</table>

Figure A.4: Final CCAM Housekeeping Pinout for Chile Observations. In the above table, heaters are denoted “H”, ROX thermometers are denoted “R”, and diode thermometers are denoted “D”.
<table>
<thead>
<tr>
<th>Feature</th>
<th>Connector</th>
<th>Pins (+,-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tc check 2</td>
<td>Microtek (2-pin)</td>
<td>1,2</td>
</tr>
<tr>
<td>Tc check 1</td>
<td>Microtek (2-pin)</td>
<td>1,2</td>
</tr>
<tr>
<td>DH</td>
<td>L-0-7 #6 (37-pin)</td>
<td>4,23</td>
</tr>
<tr>
<td>DB</td>
<td>L-0-7 #6 (37-pin)</td>
<td>5,24</td>
</tr>
<tr>
<td>DS</td>
<td>Microtek (2-pin)</td>
<td>1,2</td>
</tr>
<tr>
<td>S2FB</td>
<td>K-0-7 #6 (51-pin)</td>
<td>22,39</td>
</tr>
<tr>
<td>S2B</td>
<td>K-0-7 #6 (51-pin)</td>
<td>5,23</td>
</tr>
<tr>
<td>S1FB</td>
<td>K-0-7 #6 (51-pin)</td>
<td>4,38</td>
</tr>
<tr>
<td>Rox</td>
<td>Microtek (2-pin)</td>
<td>1,2</td>
</tr>
<tr>
<td>RSDS</td>
<td>Addr 1</td>
<td>18,37</td>
</tr>
<tr>
<td>RS0</td>
<td>Addr 1</td>
<td>17,36</td>
</tr>
<tr>
<td>RS1</td>
<td>Addr 1</td>
<td>16,35</td>
</tr>
<tr>
<td>RS2</td>
<td>Addr 1</td>
<td>15,34</td>
</tr>
<tr>
<td>RS3</td>
<td>Addr 1</td>
<td>14,33</td>
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<tr>
<td>RS4</td>
<td>Addr 1</td>
<td>13,32</td>
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<tr>
<td>RS5</td>
<td>Addr 1</td>
<td>12,31</td>
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<tr>
<td>RS6</td>
<td>Addr 1</td>
<td>11,30</td>
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<td>RS7</td>
<td>Addr 1</td>
<td>10,29</td>
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<tr>
<td>RS8</td>
<td>Addr 1</td>
<td>9,28</td>
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<tr>
<td>RS9</td>
<td>Addr 1</td>
<td>8,27</td>
</tr>
<tr>
<td>RS10</td>
<td>Addr 1</td>
<td>7,26</td>
</tr>
<tr>
<td>RS11</td>
<td>Addr 1</td>
<td>6,25</td>
</tr>
<tr>
<td>RS12</td>
<td>Addr 1</td>
<td>5,24</td>
</tr>
<tr>
<td>RS13</td>
<td>Addr 1</td>
<td>4,23</td>
</tr>
<tr>
<td>RS14</td>
<td>Addr 1</td>
<td>3,22</td>
</tr>
<tr>
<td>RS15</td>
<td>Addr 1</td>
<td>2,21</td>
</tr>
<tr>
<td>RS16</td>
<td>Addr 2</td>
<td>18,37</td>
</tr>
<tr>
<td>RS17</td>
<td>Addr 2</td>
<td>17,36</td>
</tr>
<tr>
<td>RS18</td>
<td>Addr 2</td>
<td>16,35</td>
</tr>
<tr>
<td>RS19</td>
<td>Addr 2</td>
<td>15,34</td>
</tr>
<tr>
<td>RS20</td>
<td>Addr 2</td>
<td>14,33</td>
</tr>
<tr>
<td>RS21</td>
<td>Addr 2</td>
<td>13,32</td>
</tr>
<tr>
<td>RS22</td>
<td>Addr 2</td>
<td>12,31</td>
</tr>
<tr>
<td>RS23</td>
<td>Addr 2</td>
<td>11,30</td>
</tr>
<tr>
<td>RS24</td>
<td>Addr 2</td>
<td>10,29</td>
</tr>
<tr>
<td>RS25</td>
<td>Addr 2</td>
<td>9,28</td>
</tr>
<tr>
<td>RS26</td>
<td>Addr 2</td>
<td>8,27</td>
</tr>
<tr>
<td>RS27</td>
<td>Addr 2</td>
<td>7,26</td>
</tr>
<tr>
<td>RS28</td>
<td>Addr 2</td>
<td>6,25</td>
</tr>
<tr>
<td>RS29</td>
<td>Addr 2</td>
<td>5,24</td>
</tr>
<tr>
<td>RS30</td>
<td>Addr 2</td>
<td>4,23</td>
</tr>
<tr>
<td>RS31</td>
<td>Addr 2</td>
<td>3,22</td>
</tr>
</tbody>
</table>

Figure A.5: Pinout for the detector bias and readout wiring in CCAM. The figure on the right depicts the backplane layout in CCAM for resistance check purposes.
Appendix B

Assembly Protocol for Helium Sorption Refrigerators

1. Solder fins to the copper pump.
2. Weld the pump out tube to the stainless plate.
3. Hard solder the copper insert to the stainless plate.
4. Weld can to the stainless plate.
5. Clean all surfaces.
6. Leak check the assembly so far before construction continues.
7. Apply epoxy to the copper and stainless surfaces up to the limit of the copper fins with Stycast 2850 FT black. Weigh out charcoal and place in pump up to the copper fins.
8. Epoxy a copper mesh to hold the charcoal in the copper fin area of the pump.
9. Weld the top stainless steel lid on the top of the pump. Flow argon to keep the pump clean during welding. Clean out the fill tube as much as possible.
10. Hard solder an 1/8” OD copper fill tube, keeping the fill tube long, ~10”
11. Leak check to ensure the assembly is leak tight so far.
12. Notch a slit in the large G-10 tube along the axis aligned with the fill tube to allow the G-10 tube to slide past the fill tube.
13. Set up spacer blocks with the G-10 slid out of the way such that the thin walled stainless steel tube is exposed. Slide the condensation plate down the tube down onto the blocks. Align.


15. Leak check to ensure the assembly is leak tight so far.


17. Hard solder the stainless steel to the copper evaporator can.

18. Purge system with argon and make final weld with argon flowing.

19. Leak check the assembly.

20. Cut an access hole in G-10 near the heat sinks on the pump and put the G-10 piece on.
Appendix C

Cryogenic Test Bed Reference

C.1 Design description

The main components of the cryogenic testbed are shown in Figure C.1 and detailed in Table C.1. The pulse tube rests on an aluminum vacuum plate (8) and aluminum vacuum tube (2) to which an aluminum vacuum can (3) is bolted. The 1st stage of the pulse tube (1a) cools an aluminum tube support (10) that is attached to an aluminum 1st stage baseplate (7). An aluminum 1st stage radiation shield (4) bolts onto the 1st stage plate. The 2nd stage of the pulse tube (1b) cools the 2nd stage copper baseplate (6). An aluminum 2nd stage shield is bolted to the copper baseplate to block 300K and 40K radiation (5). Two G-10 support rings (9) arrest motion between the vacuum plate, 1st stage baseplate and 2nd stage baseplate. A pump out port (11) and two 26 pin hermetic Amphenol connectors (12) are mounted to the vacuum plate. A pressure relief valve not shown is also affixed to the vacuum plate as a precautionary measure.

Cylindrical G-10 supports arrest movement between the vacuum and first stage baseplate, first and second stage baseplates, and additionally support the weight of a \(^3\)He/\(^4\)He sorption refrigerator system and other test components. The supports were designed to minimize thermal loading while maximizing its mechanical strength. To minimize the power dissipated in the supports the contact surface area was minimized while the length was maximized. Structurally, the diameter of the support ring was constructed as large as possible to arrest torque between the plates. To compensate for thermal contraction differences between the G-10 supports and metal cylinders, the aluminum ring that holds the G-10
Figure C.1: Cross-section view of the test dewar. 1: pulse tube; 1a: pulse tube 1st stage; 1b: pulse tube 2nd stage; 2: vacuum tube 1; 3: vacuum can 2; 4: 1st stage radiation shield; 5: 2nd stage radiation shield; 6: 2nd stage baseplate; 7: 1st stage baseplate; 8: vacuum plate; 9: G-10 supports between stages; 10: 1st stage aluminum tube support; 11: vacuum pump out port; 12: 26-pin electrical connections feedthrough.
### Table C.1: Summary of test dewar’s components.

<table>
<thead>
<tr>
<th>Dewar Part</th>
<th>Material</th>
<th>Dimension</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulse Tube (PT)</td>
<td>Various</td>
<td>See Cryomech PT-407 Manual for Details</td>
</tr>
<tr>
<td>PT 1st Stage</td>
<td>OFHC Copper</td>
<td>12.07 cm D. x 1.27 cm H.</td>
</tr>
<tr>
<td>PT 2nd Stage</td>
<td>OFHC Copper</td>
<td>8.61 cm D. x 0.95 cm H.</td>
</tr>
<tr>
<td>Vacuum Tube</td>
<td>6061-Aluminum</td>
<td>17.78 cm O.D. x 13.02 cm I.D. x 20.57 cm H.</td>
</tr>
<tr>
<td>Vacuum Can</td>
<td>6061-Aluminum</td>
<td>40.64 cm O.D. x 38.10 cm I.D. x 54.29 cm H.</td>
</tr>
<tr>
<td>1st Stage Shield</td>
<td>6061-Aluminum</td>
<td>45.24 cm O.D. x 33.49 cm I.D. x 45.24 cm H.</td>
</tr>
<tr>
<td>2nd Stage Shield</td>
<td>6061-Aluminum</td>
<td>28.42 cm O.D. x 27.94 cm I.D. x 38.10 cm H.</td>
</tr>
<tr>
<td>2nd Stage Plate</td>
<td>OFHC Copper</td>
<td>30.48 cm D. x 0.63 cm H.</td>
</tr>
<tr>
<td>1st Stage Plate</td>
<td>6061-Aluminum</td>
<td>35.56 cm D. x 1.27 cm H.</td>
</tr>
<tr>
<td>Vacuum Plate</td>
<td>6061-Aluminum</td>
<td>40.64 cm D. x 1.27 cm H.</td>
</tr>
<tr>
<td>G-10 Support</td>
<td>G-10</td>
<td>33.68 cm O.D. x 0.051 cm W. x 5.08 cm H.</td>
</tr>
<tr>
<td>1st Stage Tube</td>
<td>6061-Aluminum</td>
<td>12.06 cm O.D. x 9.53 cm I.D. x 12.32 cm H.</td>
</tr>
<tr>
<td>Vacuum Port</td>
<td>Stainless Steel</td>
<td>QF40</td>
</tr>
<tr>
<td>26-Pin Connector</td>
<td>Various</td>
<td>2.5 cm D.</td>
</tr>
</tbody>
</table>

support cylinder was designed to bend if necessary upon cooling. The final support design is depicted in Figure C.2.

![Figure C.2: G-10 support design. The G-10 cylinder is additionally supported by a G-10 support ring affixed at the midpoint between baseplates. To compensate for thermal contraction differences, the aluminum ring that holds the G-10 support cylinder was designed to bend if necessary upon cooling.](image)

**C.2 Measured Performance**

The two-stage pulse tube cooler mounted in the dewar can be operated successfully below 4K. Table C.2 lists the nominal performance for future reference.
<table>
<thead>
<tr>
<th>Location</th>
<th>Temperature (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 K Baseplate</td>
<td>3.5 K</td>
</tr>
<tr>
<td>40 K Baseplate</td>
<td>35 K</td>
</tr>
</tbody>
</table>

Table C.2: Nominal temperatures.

## C.3 Housekeeping Wiring Table

The following table lists the heater and diode channels (2 lead measurements) which are all fed through the vacuum for manipulation outside the cryostat.

<table>
<thead>
<tr>
<th>26-pin Amphenol (1)</th>
<th>25 MDM (1) on 4 K BP</th>
<th>Object</th>
</tr>
</thead>
<tbody>
<tr>
<td>GND</td>
<td>1</td>
<td>GND</td>
</tr>
<tr>
<td>V</td>
<td>2</td>
<td>Heater 1+</td>
</tr>
<tr>
<td>W</td>
<td>14</td>
<td>Heater 1-</td>
</tr>
<tr>
<td>E</td>
<td>3</td>
<td>Diode 1 I+</td>
</tr>
<tr>
<td>D</td>
<td>15</td>
<td>Diode 1 I-</td>
</tr>
<tr>
<td>G</td>
<td>4</td>
<td>Diode 1 V+</td>
</tr>
<tr>
<td>F</td>
<td>16</td>
<td>Diode 1 V-</td>
</tr>
<tr>
<td>T</td>
<td>5</td>
<td>Heater 2+</td>
</tr>
<tr>
<td>R</td>
<td>17</td>
<td>Heater 2-</td>
</tr>
<tr>
<td>U</td>
<td>6</td>
<td>Diode 2 I+</td>
</tr>
<tr>
<td>C</td>
<td>18</td>
<td>Diode 2 I-</td>
</tr>
<tr>
<td>A</td>
<td>7</td>
<td>Diode 2 V+</td>
</tr>
<tr>
<td>B</td>
<td>19</td>
<td>Diode 2 V-</td>
</tr>
<tr>
<td>X</td>
<td>8</td>
<td>Heater 3+</td>
</tr>
<tr>
<td>S</td>
<td>20</td>
<td>Heater 3-</td>
</tr>
<tr>
<td>H</td>
<td>9</td>
<td>Diode 3 I+</td>
</tr>
<tr>
<td>J</td>
<td>21</td>
<td>Diode 3 I-</td>
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<tr>
<td>a</td>
<td>10</td>
<td>Diode 3 V+</td>
</tr>
<tr>
<td>P</td>
<td>22</td>
<td>Diode 3 V-</td>
</tr>
<tr>
<td>Y</td>
<td>11</td>
<td>Heater 4+</td>
</tr>
<tr>
<td>Z</td>
<td>23</td>
<td>Heater 4-</td>
</tr>
<tr>
<td>L</td>
<td>12</td>
<td>Heater 5+</td>
</tr>
<tr>
<td>K</td>
<td>24</td>
<td>Heater 5-</td>
</tr>
<tr>
<td>N</td>
<td>13</td>
<td>Heater 6+</td>
</tr>
<tr>
<td>M</td>
<td>25</td>
<td>Heater 6-</td>
</tr>
</tbody>
</table>

Table C.3: Electrical connections between the 4 K baseplate and outside the cryostat. This table lists the heater and diode channels (2 lead measurements) which are all fed through the vacuum for manipulation outside the cryostat.
<table>
<thead>
<tr>
<th>26-pin Amphenol (2)</th>
<th>25 MDM (2) on 4K BP</th>
<th>ROX</th>
</tr>
</thead>
<tbody>
<tr>
<td>GND</td>
<td>1</td>
<td>GND</td>
</tr>
<tr>
<td>V</td>
<td>2</td>
<td>-</td>
</tr>
<tr>
<td>W</td>
<td>14</td>
<td>-</td>
</tr>
<tr>
<td>E</td>
<td>3</td>
<td>ROX 1 I+</td>
</tr>
<tr>
<td>D</td>
<td>15</td>
<td>ROX 1 I-</td>
</tr>
<tr>
<td>G</td>
<td>4</td>
<td>ROX 1 V+</td>
</tr>
<tr>
<td>F</td>
<td>16</td>
<td>ROX 1 V-</td>
</tr>
<tr>
<td>T</td>
<td>5</td>
<td>-</td>
</tr>
<tr>
<td>R</td>
<td>17</td>
<td>-</td>
</tr>
<tr>
<td>U</td>
<td>6</td>
<td>ROX 1 I+</td>
</tr>
<tr>
<td>C</td>
<td>18</td>
<td>ROX 1 I-</td>
</tr>
<tr>
<td>A</td>
<td>7</td>
<td>ROX 2 V+</td>
</tr>
<tr>
<td>B</td>
<td>19</td>
<td>ROX 2 V-</td>
</tr>
<tr>
<td>X</td>
<td>8</td>
<td>-</td>
</tr>
<tr>
<td>S</td>
<td>20</td>
<td>-</td>
</tr>
<tr>
<td>H</td>
<td>9</td>
<td>ROX 3 I+</td>
</tr>
<tr>
<td>J</td>
<td>21</td>
<td>ROX 3 I-</td>
</tr>
<tr>
<td>a</td>
<td>10</td>
<td>ROX 3 V+</td>
</tr>
<tr>
<td>P</td>
<td>22</td>
<td>ROX 3 V-</td>
</tr>
<tr>
<td>Y</td>
<td>11</td>
<td>-</td>
</tr>
<tr>
<td>Z</td>
<td>23</td>
<td>-</td>
</tr>
<tr>
<td>L</td>
<td>12</td>
<td>ROX 4 I+</td>
</tr>
<tr>
<td>K</td>
<td>24</td>
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</tr>
<tr>
<td>M</td>
<td>25</td>
<td>ROX 4 V-</td>
</tr>
</tbody>
</table>

Table C.4: Electrical connections between the 4K baseplate and outside the cryostat. This table lists the ROX channels which are all fed through the vacuum for manipulation outside the cryostat.
Appendix D

Microfabrication Recipes

1. Aluminum Top Card Fabrication

The pre-metalized wafers are microfabricated at usually stored at the PRISM facility. The process is shown in Figure D.1.

To prepare top card wafers for the photolithography process, the wafers are “prebaked” for 10 minutes at 110°C which helps to adhere the photoresist to the wafer. HMDS adhesion promotor and AZ5214 positive photoresist are then spun on at 4000 RPM for 40 seconds. The wafer is “soft-baked” for one minute at 95°C, which transforms the photoresist from a liquid to a solid. The photolithography exposure is soft contact for 17 seconds using a Karl Suss MA6 6” mask aligner. The wafer is submersed in a mixture of 1:1 AZ312MIF:DI water for approximate 1.5 minutes to dissolve the areas of photoresist hit by the UV light. The photoresist will remain in the remaining regions, leaving an exact copy of the mask image in photoresist.¹ The wafer is visually inspected under the microscope. If all the features are free of defects, the wafer is “hard-baked” for 1 minute at 110°C which strengthens the photoresist before it is wet etched. With the photoresist acting as a mask for the wet etch, the wafer is submersed in Al-11 aluminum etchant for approximately 3.5 minutes at 50°C which removes the aluminum not covered and protected by the photoresist. The exposed chrome is subsequently wet etched using CR-7 etchant for approximately 25°C at room temperature. The photoresist is then removed using an acetone swab rinse followed by isopropanol, and blow dry.

¹This is only true for positive photoresist. Negative photoresist will produce the opposite effect.
Figure D.1: Process for microfabricating the wafers to produce metalized patterns on the silicon.
2. Gold Bottom Card Fabrication

The same process is followed for fabricating the gold bottom cards except for these two exceptions. The photolithography exposure is a soft contact exposure for 16 seconds as opposed to the 17 second aluminum exposure. Secondly, Gold TFA etchant is utilized to wet etch the unprotected gold after the photoresist exposure.

3. Making Masks from Transparencies

Use $\text{N}_2$ to blow off the glass slide located in black box with blank masks. This ensures any dust particles do not produce features in the fabricated mask. Place the glass slide in the Karl Suss MA6 6” mask aligner’s mask holder. Load a blank low reflective chrome 5”×5” blank mask coated with photoresist, photoresist side up. Place the transparency containing the mask pattern on the blank mask. Visually align the transparency’s pattern to ensure the pattern is centered on the blank mask. Expose for 15 seconds with soft contact. Examine the pattern under the microscope to ensure the pattern was transferred correctly, and use a solution of 1:1 AZ312MIF:DI water to etch the photoresist. Etch away the chrome as described above, leaving transparent regions on the mask. Wash off the remaining photoresist using the procedure described above.
Appendix E

TES Wafer and Run Sheets

<table>
<thead>
<tr>
<th>Metal Deposition</th>
<th>Date</th>
<th>Initials</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cr + Al/Au</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Cr dep.**
- Current: __________ mA
- Rate: __________ A/s
- Pressure: __________ uTorr
- Thickness: __________ A

**Al/Au dep.**
- Current: __________ mA
- Rate: __________ A/s
- Pressure: __________ uTorr
- Thickness: __________ A

Notes:

Figure E.1: Documentation sheet during the microfabrication process.
Photolithography  Date _________________ Initials______

Mask Name ___________________________________

__ 10 min. dehydration bake @ 110° C

HMDS + AZ5214 @ _____ rpm for _____ sec.

__ 1 min. soft bake @ 95° C

Expose for _____ sec, exposure type _____,

intensity Cl1 _____

__ sec development in 1:1

DI:312-MIF

__ 1 min. hard bake at 110°C

Visual Inspection:

Notes:

Metal Etch   Date _________________ Initials______

First etch: Etchant ________________ for _____ minutes at _____ ° C

Visual Inspection:

Second etch: Etchant ________________ for _____ minutes at _____ ° C

Visual Inspection:

__ Photoresist Scrub

Visual Inspection:

Notes:

Emulsitone Application  Date _________________ Initials______

Spin: RPM: ________________ Time: __________ sec

Wafer Dice and Clean  Date _________________ Initials______

 Dice: Program ________________ Current _____ A  Freq. ______ 
kHz

Visual Inspection:

__ Clean

__ Scribe Cards with Wafer #

Notes:

Figure E.2: Documentation sheet continued from the previous page.
Figure E.3: TES characterization sheet for recording potential problematic features on TES columns as well as documenting folding events and issues.
Figure E.4: TES characterization sheet continued from previous page.
References


