DEVELOPMENT OF A BROADBAND OPTICAL SPECTROPHOTOMETER USING SUPERCONDUCTING TRANSITION-EDGE SENSORS

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Abstract

For many years, particle detectors which exploit the unique properties of materials at low temperatures have been used for the detection of neutrons, alpha particles, beta particles, x-rays, gamma rays, heavy ions, and even exotic “dark matter”. In all energy regimes, these devices far surpass the energy sensitivity of their room-temperature equivalents making them the detectors of choice in high-demand applications.

This thesis describes efforts toward a similar revolutionary detector system designed for the high-sensitivity measurement of near-infrared/optical/near-ultraviolet photons. Extending the superconducting transition-edge sensor (TES) technology developed for the Cryogenic Dark-Matter Search (CDMS) at Stanford University, we have designed and tested the first high-efficiency (∼50% Q.E.) broadband (250 nm–2500 nm, 5 eV–0.5 eV) optical detector capable of determining the energy of the incoming photon to a resolution of 0.15 eV FWHM giving a resolving power of R=20 at 3 eV (equivalently, a resolution of 20 nm at ∼400 nm). These TES devices use the superconducting-to-normal transition of tungsten at around 80 mK as a sensitive thermometer to quantify the heat deposited by the individual light quanta.

The devices are fabricated at the Stanford Nanofabrication Facility by our group using a CMOS-compatible process. The detectors are 20 µm × 20 µm square, 35 nm thick films of high-purity tungsten with the electrical connection provided by a patterned aluminum layer. The sub-microsecond photon event rise-time and ∼5 µs fall-time allow ∼100 ns event timing resolution and per-pixel count rates exceeding 30 kHz. These devices are exciting for many applications, foremost of which is photon-starved astrophysics. During a recent observing campaign, we demonstrated a complete four-pixel photon-counting system. We applied a
four-channel TES array to the single-photon spectroscopy of time-variable compact objects at the 2.7 m diameter telescope at the McDonald Observatory in Texas.

This thesis describes the progress of this program from its recent inception to the present, including the design and testing of the devices, the optical and cryogenic infrastructure, and the significant experimental results to date.
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Somewhat unique to this project was the combination of low-temperature physics and astrophysics. Through this union I was fortunate to have Roger Romani as another mentor. From first working with Roger I was impressed by his complete mastery of any project he chose to undertake. His extensive knowledge of experimental systems dispelled any myths I had about theorists being disconnected from experimental reality. I am continually impressed by his complete thoroughness and his ability to tackle long and difficult problems without flinching. Some successes take a large amount of diligence and effort, both of which Roger gave copiously to this project. His directness and intensity kept me always on my toes and always thinking. I admire his ability to think out of the box for innovative solutions to our most challenging problems.
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Because this project was spun off from the much-larger CDMS work, I drew a great amount of knowledge and time from members of that group. First and foremost I wish to thank Betty Young. Never have I met anyone more generous with their time and wisdom than Betty. She is always willing to go above and beyond to make my work successful while never asking for anything in return. No one has treated me more as a colleague than she. I fear that, with her usual humility, she will dismiss these thanks as unwarranted when she deserves more.

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For the last ten years, I have been graced with another loving family. Larry, Nancy, Laura, Carrie, and Scott have treated me like one of their own from day one, for which I will always feel privileged.

Finally, I thank my best friend and life companion, my wife Holly. The love and support she shows me cannot be expressed in any number of words. Every day I strive to be the pillar of strength to her that she is to me. It is with great affection that I dedicate this work to her.
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Chapter 1

Introduction

Astrophysicists will always place high demands on detector developers to improve the sensitivity of their instruments. Since bright objects are able to be analyzed using conventional detector systems, the faint objects become increasingly important for furthering our understanding of the universe. In studying these faint astronomical sources it is imperative that we extract all possible information from the incoming signal while minimizing optical losses. This requires an efficient detector and accompanying optical system that work effectively together to provide maximal information from each available photon.

Every such photon has a short list of measurable parameters: momentum, energy, time-of-arrival, polarization, and phase. Each of these properties of light has been used to further our understanding of the universe, however no observational system to date is able to record all of these parameters simultaneously. Every system has design trade-offs that allow the measurement of the parameters of highest interest at the expense of the other less-critical parameters. Nevertheless, recent advances in optical photon detector development with devices such as Superconducting Tunnel Junctions (see Section 2.6) and Superconducting Transition-Edge Sensors (the subject of this thesis) allow the development of optical detection systems that are able to simultaneously measure more parameters from each photon than is possible with existing systems.

The photon parameters listed above are each measurable, but with a varying degree of
difficulty. For instance, photon momentum, for all practical purposes, is simply the angle of incidence of the incoming light. This angle may be selected via an imaging system (telescope optics) that is able to transform photon momentum into focal-plane position with low loss. Such a transformation eliminates the requirement that the detector be able to intrinsically measure the incident photon angle and, instead, requires it to measure the photon position in the image plane. Because this mapping is efficient and because focal-plane position is easier to measure than photon momentum, developers have little impetus to design detectors that measure the photon angle intrinsically.

Similar arguments can be made for photon polarization and phase. The measurement of polarization is relatively easy to integrate into a detector system by using two detectors and a broadband polarizing beam-splitter, such as a Wollaston Prism. Again, this polarization-to-position conversion is efficient, thereby obviating the need for an intrinsic polarization measurement by the device. Phase can be measured using an interferometer to interfere the incoming light before it reaches the detector, however it is a quantity that is traditionally less important to optical astronomy and is often not measured.

We have two remaining parameters, photon energy and time-of-arrival. The spectral energy distribution of the incoming radiation is of such high importance to the understanding of the physics behind the light source that it is often measured to high accuracy at the expense of all other parameters. The energy (or, equivalently, wavelength) of the incoming photon can be selected by external mechanisms such as dispersive gratings and filters, however these can reduce the overall detector efficiency significantly. Ideally, therefore, energy determination should happen on an event-by-event basis intrinsically in the detector.

Time-of-arrival is available in photon-counting detectors but is discarded by integrating detectors, often in favor of high focal-plane area coverage and the ability to measure high fluxes. Most astronomical objects are thought to be static on the time-scale of an observation. Thus, long observations of interesting sources with integrating detectors and dispersive gratings has enabled the detailed study of the spectral and spatial content of...
these objects. However, with the discovery of variable-emission compact objects (such as pulsars and accreting black-hole binaries) and highly time-variable sources such as gamma-ray bursts, photon time-of-arrival is becoming a much more interesting quantity to have at our disposal. Although time-to-position mapping systems have been used with integrating detectors in the past for temporal averaging, intrinsic time resolution is a desirable quantity for a detector, especially for the study of aperiodic sources or sources in which the period is unknown.

Therefore, we have arguably determined the most important intrinsic characteristics that an ideal photon detector should have. We desire a high spatial-resolution imaging detector with good energy resolution and time-of-arrival determination. Additionally, we wish the device to work over as large an energy range as possible with high efficiency. Such an instrument is the ultimate goal, the pursuit of which has begun with the work described in this thesis. Though much more must be accomplished before a revolutionary instrument is complete, the progress made so far is extremely encouraging.

1.1 Astronomical Considerations

Since high-efficiency optical photon counters with energy resolution have not existed until recently, there is excitement in the immediate application of our devices to observational astronomy—even considering the limitations of the devices to date. Assuming we can build our observational system with a high QE (> 50%), broad energy response (0.5–5 eV), an energy resolution of 0.1 eV FWHM or better, and sub-microsecond photon timing, we are able to probe a portion of phase-space unavailable using conventional systems. Of particular relevance is the observation of objects which exhibit emission behavior well-matched to our system capabilities. Compact emission sources, such as neutron stars and accreting black holes and white dwarf stars, are able to produce highly time-variable signals with spectral fluctuations on time-scales under a millisecond.

The pulsars (rapidly spinning neutron stars) are particularly intriguing for detailed study since comprehensive models have been developed regarding the light-emission mechanisms
from the low-energy radio band to the high-energy gamma band.\textsuperscript{2–4} These models predict specific temporal and spectral behavior across the IR/optical/UV band. Since the majority of these pulsars are very faint, a high-efficiency photon-counting detector with time and energy resolution is required to extract the physics from the low available flux.

For initial astronomical application of the system we must perform measurements using existing ground-based telescopes. In particular, our first observations require fiber coupling of the device to the focal plane of the telescope. Since the telescopes tend to have long focal lengths, the image size at focus is fairly large. Using the focal lengths of the specific telescopes we can estimate the minimum size for our aperture to ensure adequate collection of light while minimizing the sky background. For example, the 10 m diameter telescope at the Keck Observatory has an $f/15$ port with a focal length of 150 m. The reported median seeing of 0.5 arc seconds gives an image size for a point source of 350 $\mu$m at focus. This sets the target scale for our focal plane aperture and provided the impetus for the design of light-collection optics using large-diameter fibers discussed in Sections 4.3 and 5.2.4.

1.2 Notes about this Thesis

To avoid confusion, I should note that for the sake of brevity and for lack of a more descriptive term I liberally use the term “optical” to define an energy range that spans across the optical bandwidth of our TES devices. This band roughly covers a factor of 10 in energy and wavelength, from $E = 0.5\text{ eV} \ (\lambda = 2.5\ \mu\text{m})$ to $E = 5\text{ eV} \ (\lambda = 250\text{nm})$. It is evident that the term “optical” with its colloquial meaning of $E = 1.75\text{eV}$–3.1 eV ($\lambda = 400$–700 nm) does not do such a broadband device justice in describing its useful operating range.

Confusing, as well, are the multiple conventions for describing the energy of the photon events. For higher-energy regimes such as the far ultraviolet, x-ray, and gamma bands it is conventional to use units of energy (eV, keV, MeV, etc.) however in the infrared and optical it is conventional to use wavelength (nm, $\mu$m, mm, etc.) or even wavenumber (cm$^{-1}$). Since our devices are essentially particle detectors such as x-ray and gamma photon counters,
and have a constant width “energy resolution”, it is more natural for us to use units of energy instead of wavelength. As this convention is particularly uncommon for an “optical” astronomy instrument I have made an effort to specify both energy and wavelength for the photons where appropriate.

In Chapter 2 I present a brief summary of the prevailing methods of detecting optical radiation with emphasis toward cryogenic detectors. I present in Chapter 3 a detailed look at the physics of the Transition-Edge Sensor followed by some of the relevant practical details of these novel devices. I explain the experimental apparatus in Chapter 4 emphasizing the portions unique to the optical TES experiment. Finally, the bulk of this thesis is Chapter 5 in which I present the experimental results in roughly chronological order, ending with a short view of the on-going work and future prospects for the project in Chapter 6.
Chapter 2

Methods of IR/Optical/UV Detection

Keeping the project goals in mind, in this chapter I give a brief overview of the prevailing detector types for the measurement of near infrared (IR), optical, and near ultraviolet (UV) radiation. For comparison, at the end of this chapter is a table which summarizes the salient characteristics of these devices.

2.1 Chemical Devices

The most ubiquitous optical detector with which we are familiar is the human eye, a chemically-based light detector. Interestingly enough the eye is actually quite good at what it does. Since the retina is composed of around $10^8$ rods and over $10^6$ cones the eye is an impressive imaging detector with a large field of view and good spatial resolution. The rods are more sensitive to incoming light requiring as few as one, up to as many as ten photons to trigger, though several rods must fire together in order for a signal to be sent to the brain. The photosensitive chemical in the eye (called rhodopsin, or *visual purple*), upon the absorption of light, undergoes a structural change which culminates in an electrical signal being sent from the cell. Incredibly enough, the structural change of rhodopsin occurs in
only a few picoseconds, with a relaxation time on the order of milliseconds.

The wavelength sensitivity of the eye is determined by the absorption properties of the rods and cones. The rods have a peak in their sensitivity at $\lambda \approx 510\,\text{nm}$ and the cones at $\lambda \approx 550\,\text{nm}$. Together, the combined absorption properties give us the definition of the visible band of around 400 nm to 700 nm, varying a bit by person.\textsuperscript{5,6} The quantum efficiency of a dark-adapted human eye has a maximum at 510 nm of 3%.

Photographic film works using a combination of electronic and chemical principles. Film is essentially a thin gelatin medium permeated with small crystals of silver halide (typically silver bromide or silver chloride) that range in size from 0.1 $\mu\text{m}$–1.5 $\mu\text{m}$. These “grains” absorb light either directly or mediated by a chemical sensitizer that can adjust the spectral characteristics of the absorption. An absorbed photon excites a photoelectron which may be trapped by interstitial silver ions to form a stable silver atom. This silver atom acts to further trap ions and photoelectrons and thus a cluster of silver grows on the crystal. Such silver specks cause discoloration of the gelatin-silver emulsion forming a “latent image” where the emulsion was exposed to light. When film is developed, the grains with large silver deposits rapidly turn into silver and the grains without a significant amount of attached silver are unaffected, transforming the latent image into a visible image.\textsuperscript{5,7}

Since its spatial resolution is determined by the grain size, film has exceedingly high spatial information content. High resolution film can exceed 40,000 pixels/mm\textsuperscript{2} over with an active area 500 mm $\times$ 500 mm allowing an extremely large field of view. The wavelength response of film is adjustable via the sensitizer added to the emulsion and can be selected in the range of 1.1 $\mu\text{m}$ to through UV, though not simultaneously. However, film has a very poor efficiency with a peak quantum efficiency (QE) at around 4%. Additionally, it is highly nonlinear with a developed exposure density typically proportional to the logarithm of the exposure time.\textsuperscript{7} And, of course, there is no intrinsic energy or time-of-arrival information.
2.2 Photoelectric Devices

In a photoelectric device an incoming photon strikes a low work-function material (usually a soft metal or semiconductor) and liberates an electron. This free electron is accelerated by an externally applied electric field until it strikes a similar low work-function plate called the secondary emitter. By the time the first photoelectron impacts the secondary emitter, the applied electric field has increased its energy by typically a hundred times or more. As it strikes the secondary emitter a shower of photoelectrons exits the plate. Each of these electrons can be subsequently accelerated in a similar manner. Cascading such gain stages can produce upwards of $10^6$ electrons at the final anode for each initial photoelectron—a current which is easily amplified and measured. Such photomultiplier tubes (PMTs) can be made with quantum efficiencies exceeding 50% in the high-energy optical/UV, but typically have poor response in the red and IR\(^*\). The time-response of PMTs is quite good (few ps), however they provide no spectral (energy) information from the arriving photons.

Working on a similar principle on a highly parallel scale is a MicroChannel Plate (MCP). A MCP is, most simply, a large imaging array of small photomultipliers. These devices allow large number of pixels ($4k \times 4k$) but have the major drawbacks of PMTs of low QE in the red and IR, and no color information.

The final detector I wish to mention in this section is the avalanche photodiode (APD). Though it is a semiconductor device similar to those discussed in the next section, its operation is similar to that of the photomultiplier tube. In photon-counting, or “Geiger” mode, the diode is reverse-biased with a voltage slightly exceeding the breakdown voltage. The diode stays in this unstable condition only until an electron is excited (possibly by a photon) in the depletion region of the diode. The electron accelerates rapidly through the high field and breaks electron-hole pairs in the semiconductor. These carriers further cascade and create more electron-hole pairs. The process continues until the external bias is lowered below the breakdown voltage and raised again above the breakdown voltage.

\(^*\)In the extreme, “solar blind” UV-sensitive devices are desirable for applications in which optical radiation would saturate the instrument.
to “reset” the diode for another event. This process is fast and efficient with a spectral sensitivity approaching 80% from 450 nm to 1050 nm for silicon diodes. Again, however, there is no information as to the energy of the photon which initiated the cascade.

### 2.3 Semiconductor Devices

A wide range of photosensitive devices use semiconductors to provide a mechanism for photon-to-electron conversion, including photovoltaic cells, photodiodes, photoconductive cells, and so on. The basic operating method is similar in all semiconductor photon detectors. With the exception of the APD (as mentioned in the last section), semiconductor devices for photons in the optical range measure integrated flux, i.e. they are not sensitive to individual photon events. Photons with energy greater than the gap energy (on order of 1 eV) are able to generate electron-hole pairs. As a consequence of the indirect band gap in the typical semiconductors (Si and Ge) the lifetime of these charge carriers is very long and they can diffuse macroscopic distances to collection electrodes where they are measured.

By far the most ubiquitous and revolutionary semiconductor device used for imaging, and particularly for imaging astronomy, is the Charge-Coupled Device (CCD). Charge generated by incident flux is localized with arrays of electrodes used as variable-depth trapping sites. By sequentially changing the trapping-electrode voltages the “buckets” of charge can be shifted along a row or column of the array and read out serially. As of this writing, imaging arrays with dimensions of 4k × 4k pixels and larger are common in high-end astronomy.

All of these semiconductor devices share a few common characteristics. The low-energy (long-wavelength) sensitivity is limited by the semiconductor gap. Photons with energy below the gap are not able to excite charge carriers in the semiconductor—thus silicon devices are transparent to photons of wavelength longer than 1.1 µm. For photons of shorter wavelength the QE can be quite good, approaching 90% at 700 nm. However, all semiconductor devices have no intrinsic energy resolution requiring the external selection of the band of interest. As mentioned above, the techniques of using filters or gratings to select this band...
significantly reduces the overall optical efficiency.

2.4 Cryogenic Devices

Cryogenic devices have been recently developed for the direct detection of single photon events and are able to yield information which is unavailable using room-temperature detectors. These devices take advantage of the special properties of materials at low temperatures: lowered heat capacities, lowered thermal and electrical noise, and especially the unique electrical and thermal properties of superconductors. All of these factors allow detectors run at low temperatures to significantly out-perform room-temperature devices in specific areas. Since thermal fluctuations are reduced, signal-to-noise is typically improved as the temperature is decreased. In addition, the availability of SQUID (Superconducting QUantum Interference Device) technology allows the measurement of extremely small signals with the signal-to-noise limit imposed by the device and not the amplifier\(^*\).

As discussed in Chapter 1, in addition to a high QE, we are interested in measuring the photon energy. This information is not available using any of the aforementioned photon counting devices, but is a major goal of cryogenic detectors. Additionally, due to the intrinsic material properties at low temperatures, it may be possible to develop nearly unity QE devices with a very wide operating band.

2.5 Bolometers/Calorimeters

One of the simplest particle detectors to be operated at low temperatures is based on the operating principle of room-temperature bolometers. Figure 2.1 on the following page shows the thermal model of a simple bolometer. An absorber with heat capacity \( C \) is connected to a heat sink (i.e. the refrigerator cold stage) through a weak thermal link, \( g \). When the device is unbiased (\( P_{\text{bias}} = 0 \)) and has no incoming photon power (\( P_\gamma = 0 \), the absorber

\(^*\)For a good discussion of superconductivity relevant to superconducting devices the reader is referred to Van Duzer.\(^9\)
CHAPTER 2. METHODS OF IR/OPTICAL/UV DETECTION

Figure 2.1: Thermal model of a simple bolometer showing an absorber with heat capacity \( C \), bias power \( P_{\text{bias}} \), incident photon power \( P_\gamma \), and a weak thermal link \( g \).

will come to equilibrium with the bath and the absorber temperature \( T_{\text{abs}} \) will equal the bath temperature \( T_{\text{bath}} \).

If an external source of power is turned on, for instance \( P_\gamma > 0 \) due to photon heating, the detector will warm up until the power flowing into the bath through \( g \) is equal to \( P_\gamma \). When this injected power is removed the temperature will decay back down to \( T_{\text{bath}} \) with characteristic time \( \tau = C/g \). If the temperature of the absorber is measured during these changes, and \( C \) and \( g \) are known, we are able to determine the injected power. Since the temperature excursions are quite small we require a sensitive thermometer to measure the temperature of the absorber.

The thermometer of choice is often a doped semiconductor near its metal-insulator transition, such as Neutron Transmutation Doped (NTD) Germanium, which is physically affixed to the absorber. An NTD thermometer has a large change in resistance for a small change in temperature which gives significant output signals for small temperature excursions. The typical figure-of-merit for the sensitivity of such a resistive thermometer is \( \alpha = (T/R)(dR/dT) \) and is typically in the range of 1-10 for these thermometers.\(^{10}\) By operating at temperatures below 100 mK the device resolution can be quite good since the absorber heat capacity is low and thermal fluctuations are significantly reduced. However,
since NTD thermistors tend to be macroscopically large (hundreds of \( \mu \text{m} \)) the large heat capacity precludes their use for eV-scale energies and thus they are most commonly used in for detecting high energy particles (keV or greater).

Even the smallest bolometers of the form described above, NTD or otherwise, tend to have a thermal recovery time that is rather long (\( >100 \mu \text{s} \)). However, by the judicious use of an external bias \( P_{\text{bias}} \) the recovery times can be improved. Since the electrothermally-feedback transition-edge sensor (ETF-TES) is just such a bolometer with high \( \alpha \) and special constraints on the bias power, I relegate discussion of biased bolometers to Section 2.7 where TES devices are introduced.

In general, compared with semiconductor detectors, low temperature bolometers tend to have a larger sensitive band since there is a wider selection of materials available as an absorber. In addition, as mentioned above, cryogenic devices have an increased sensitivity due to the lowered thermal noise at the low operating temperature. When the bolometer is run in a photon-counting mode, this increased sensitivity allows the measurement of the energy of an incoming particle on an event-by-event basis. Such a device is no longer simply measuring incident power and is therefore termed a “calorimeter” due to it ability to measure the energy deposition of each photon individually\(^*\). Of course, since we are photon counting with a device with few \( \mu \text{s} \) decay time, we have the restraint of requiring a lower count rate than that attainable with an integrating detector.

\section*{2.6 Superconducting Tunnel Junctions}

A staple of the low-temperature particle detector arena is the Superconducting Tunnel Junction (STJ). An STJ works on a tunneling principle similar to that of a semiconductor junction device. As one might expect, using tunneling between superconductors instead of semiconductors significantly improves the device performance because of the lower energy of excitation of superconductors.

\(^*\)The distinction between “bolometer” and “calorimeter” is determined more by the operating mode of the device than the intrinsic device construction.
When a metal goes into the superconducting state, the conduction electrons pair and condense into a low-energy state. As in a semiconductor there exists an energy gap between this ground state and the excited-state energy levels. However, in contrast to the eV-scale minimum excitation of semiconductors, the gap energy is on order of $10^{-3}$ eV for superconductors. This small excitation energy allows a great number of quasiparticles (unpaired electrons) to be excited out of the ground state by an incoming photon. Since there is a gap between the superconducting state and the allowed quasiparticle states and recombination requires high quasiparticle density and/or quasiparticle trapping sites, with the proper choice of material the excited quasiparticles can be very long-lived ($\sim \mu$s). Additionally, since the initial energy deposition is much larger than the gap energy, the number of excited quasiparticles is proportional to the initial energy deposited in the superconductor. By collecting these quasiparticles a measurement of the initial energy can be made.

To allow the measurement of these quasiparticle excitations, an STJ consists of two superconducting films separated by an insulator. The insulator must be extremely thin ($<1$ nm or so) to allow significant quasiparticle tunneling to occur between the superconductors. When used as a particle detector a bias current is applied to encourage tunneling in one direction through the barrier and allows the collection of the tunneling electrons with a charge amplifier.

The first STJ particle detector was demonstrated as early as 1969 for the detection of alpha particles. Since then, significant resources have been put into the development of STJ detectors for alpha, x-ray, and gamma radiation. In 1993, Perryman et al., in conjunction with the European Space Agency (ESA), proposed using STJs for the detection of optical photons and such devices were realized two years later. These devices showed a resolving power of 5 across the band of 200–500 nm at rates of $\sim 10$ kHz per pixel, adequate for low-flux low-resolution spectroscopy.

Improvements in energy resolution have been made since the development of these first devices. By switching to tantalum electrodes, instead of the original higher-gap niobium, the

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*In practice, a small ($\sim 10$ mT) magnetic field must also be applied parallel to the barrier to suppress the dc Josephson current.*
ESAs group has reported the best resolution to date for an STJ photon counter of $\sim 0.15 \text{ eV FWHM}$ at $0.5 \text{ eV}$. This resolution degrades to about $0.2 \text{ eV}$ at $5 \text{ eV}$. The resolution of an ideal STJ is limited by the statistics of the quasiparticle generation and collection resulting in an energy resolution that, to first order, is proportional to $\sqrt{E_\gamma}$, where $E_\gamma$ is the incoming photon energy.

Work toward a $6 \times 6$ array of STJs for imaging astronomy is ongoing.$^{15,16}$

### 2.7 Transition-Edge Sensors

A relative new-comer to the detector arena is the Transition-Edge Sensor (TES), sometimes called a Superconducting-Phase-Transition (SPT) thermometer. Conceptually, a TES is just a bolometer (or calorimeter) which uses the superconducting transition as a high $dR/dT$ thermometer. Since the resistance of the superconductor changes from zero to a normal-metal resistance as high as a few Ohms with a change in temperature under a millikelvin, a TES provides the highest sensitivity of any available thermometer.

Standard bolometers, as alluded to earlier, may be run with an external bias power applied. If a fixed power is applied, say by a heating resistor on the absorber, the operating temperature of the detector can be elevated above the bath temperature. Even though the thermal recovery time is still $\tau = C/G$, external biasing allows regulation of the device operating temperature which may be useful for optimizing the thermometer characteristics. For instance, a TES may be run this way using a current to read the resistance of the sensor and a heater to allow temperature biasing into the superconducting transition.$^{17,18}$

A major quality which sets the TES apart from typical bolometers is the ability to run in a self-regulating electrothermal feedback (ETF) mode. This technique simplifies the biasing of a TES in addition to reducing the pulse recovery time. ETF is accomplished (in a bolometer with a positive $dR/dT$) by voltage biasing the device and allowing the Joule heating ($V^2/R$) to provide the thermal bias. The details of such devices are covered thoroughly by Kent Irwin and Sae Woo Nam in other sources$^{19–21}$ and will be reviewed in the following chapter. When used as optical photon detectors, ETF-TES devices are
able to handle count rates of $\sim 30$ kHz/pixel with an energy resolution of better than 0.2 eV across the band of 350 nm to 2 μm (0.6 eV–3.5 eV), matching the performance of optical STJ detectors in a relatively short development time. In contrast to the $\sqrt{E_\gamma}$ dependence to STJ energy resolution, ideal TES resolution is proportional to $\sqrt{E_{\text{sat}}}$, where $E_{\text{sat}}$ is the device saturation energy. This $E_{\text{sat}}$ is fixed by the device geometry and operation temperature, a TES device has a constant energy resolution across its operating band.

### 2.8 Comparison of Detector Types

Note that few of the traits of cryogenic photon counters are exceptional when taken alone. Higher energy resolution can be achieved using gratings, higher count rate and spatial resolution with integrating detectors such as CCDs, and better time determination with photomultipliers and photodiodes. However, when combined with the exceptionally broadband response, even moderate performance in all of the aforementioned categories simultaneously makes these spectrophotometers unique among optical detectors.

Table 2.1 shows a summary of the devices discussed above and their performance in various areas. The “sensitive band” of the devices is defined liberally for the traditional detectors; for instance, film is not sensitive to the entire range of 350–1100 nm simultaneously, though multiple films may be prepared which span this band. Therefore, the actual operating efficiency of traditional devices is much reduced when wavelength sensitivity is introduced via lossy mechanisms such as filters. “Integrated efficiency” is a figure of merit designed to give a measure of the area of wavelength/QE phase-space covered by the device.
which I have defined as

\[
\text{I.E.} = \int \varepsilon(\lambda) d\lambda / 1 \text{ nm}
\]  

(2.1)

where \(\varepsilon(\lambda)\) is the device QE as a function of wavelength. The values listed in the column labeled “Int. Eff.” of Table 2.1 are estimates of this quantity for the various detectors. The column labeled “Pixels” is the actual or effective number of pixels provided by the detector, and \(\lambda/\Delta\lambda\) is a measure of the intrinsic device energy resolution *.

In comparison to the most impressive traditional detector (the CCD), cryogenic devices have fewer pixels and lower peak QE as of yet. However, the integrated efficiency of the CCD is lower than that of cryogenic devices due to the limited sensitive band of the silicon substrate. For photon-starved applications CCDs have the additional limitations of read-noise and dark-current. There are no analogs to these noise sources in single-pixel TES/STJ devices. Finally, the time- and energy-resolution performance of the cryogenic detectors is unmatched by the CCD.

*Detectors in which color information is provided by a lossy mechanism such as filters (color CCD chips) or selective absorption (film, the eye) do not have intrinsic energy resolution.
Chapter 3

Transition-Edge Sensor Details

There is a legacy of success with Transition-Edge Sensors as particle detectors. They have been used to achieve the best energy resolution for a photon-counting spectrometer in the soft x-ray,\textsuperscript{22} improve the discrimination capabilities of detectors for dark matter searches,\textsuperscript{23,24} and give exciting encouragement for their use as high-performance devices for astronomy.\textsuperscript{25} In all cases, the development efforts on TES technology have been met with success rapidly.

At Stanford, in collaboration with Sae Woo Nam and John Martinis at the National Institute for Standards and Technology (NIST), we have developed a TES system optimized for single photon spectroscopy at optical energies. Design began on the first devices in March of 1997 and by October we had successfully detected our first photons using an LED as a light source. By November 1997, after adding a fiber-optic feed into the cryostat, we had achieved a resolution of 0.15 eV FWHM at 1 eV. Such quick success is reassuring when attempting to prove a new technology in a field with a well-established competing technology.\textsuperscript{*}

\textsuperscript{*}For those interested, a detailed time line of accomplishments for this project is given in Appendix C.
3.1 Background on TES Technology

The TES devices we have used for optical detection are composed of a thin film of tungsten (W), nominally 35 nm thick, patterned on a standard silicon substrate. When successfully prepared according to the procedure outlined in Section 3.3, our final W-films have a $T_c$ in the range of 70–100 mK. Electrical connection to the devices is made through (photolithographically defined) aluminum bias traces or “rails” with a typical thickness of 150 nm. Since these rails are superconducting below $\sim 1$ K they are convenient in maintaining a low lead resistance for the TES to SQUID wiring and act to confine heat in the active sensor region. Shown in Figure 3.1 is a photo of a few $\sim 20 \mu$m square pixels with $1 \mu$m wide bias rails, as labeled.

Figure 3.1: Photograph of $20 \mu$m $\times$ $18 \mu$m optical photon detector with W sensor and $1 \mu$m wide Al voltage rails.
3.1.1 Thermal/Electrical Model

![Thermal model of a Transition-Edge Sensor showing a Joule-heating bias power $P_{Joule}$, incident photon power $P_\gamma$, and a weak thermal link $g_{e-\text{ph}}$. At typical transition temperatures $g_{e-\text{ph}} \ll g_{W-Si}$ and $g_{e-\text{ph}} \ll g_{\text{sub}}$ ensuring all elements inside the dotted box are at a temperature of $T_{\text{bath}}$.]

Shown in Figure 3.2, the thermal model of our W-TES is seen to be similar to that of the simple bolometer presented in Section 2.5. In place of the simple absorber, however, is a more complicated set of heat capacities and thermal conductances. As discussed in detail later, the dominant thermal impedance is $g_{e-\text{ph}}$, i.e. the thermal bottleneck for heat deposited in the electron system, is between the electron system and the phonon system of the W itself. Since the transition is only about a millikelvin wide, accurately and stably biasing the device into the transition region is necessary for operation. With such a bias, $T_e$ (the temperature of the electron system) will be at $T_c$ ($\sim 100 \text{mK}$) and the temperature of the W phonon system $T_{ph}$ and the substrate phonon system $T_{Si}$ will be at the temperature of the bath ($< 40 \text{mK}$).

Since we are in an electron-phonon decoupled regime we require the use of a biasing
technique which is able to inject power directly into the electron system of the TES, rather than the phonon system. A heater which is coupled only thermally to the sample would raise $T_{ph}$ in addition to $T_e$, an undesirable arrangement for the proper operation of our devices. For an external heater to be used effectively we must couple the heater resistor electrically to the sample so that the dominant heating term is directly through the electron system. Such independent-heater techniques have been designed and tested for biasing devices used for the detection of x-rays. When compared to the self-stabilizing electrothermal feedback discussed below, independent-heater biasing can provide more control over the biasing parameters for a device but has the drawback of requiring additional heater wires and bias control circuitry for each pixel.

In 1995, Kent Irwin proposed a bias technique which uses resistive heating in the electron system of the TES itself as the bias heater. This technique provides a convenient mechanism for delivering power to the electron system directly and eliminates the requirement for external heaters and heater wires. However, it is arguable that the most significant benefit of using such self-heating in biasing the devices is the self-regulation which each device performs within its own electrothermal system greatly easing the temperature-regulation and film-$T_c$ requirements, as discussed below.

In order to understand qualitatively how this self-regulation works, assume the TES starts in a biased state in its superconducting transition. The TES has a finite resistance $R$ and is being maintained at the transition temperature due to an applied voltage across this resistance. The voltage drop across the device will apply a Joule power $P_{Joule} = V^2/R$ directly to the tungsten electron system, $W_e$. Since $dR/dT$ has positive slope, any increase in temperature will increase the resistance and, due to the constant voltage being applied to the device, the $P_{Joule}$ will drop proportional to $1/R$. This decrease in Joule power acts to cool the sensor back toward the bias point. Correspondingly, a decrease in temperature will decrease the resistance and heat the sensor. This self-regulating “electrothermal feedback” (ETF) obviates the need for precise thermal control via external means and simplifies device operation greatly. The effectiveness of ETF has enabled TES performance to rapidly surpass
CHAPTER 3. TRANSITION-EDGE SENSOR DETAILS

that of existing technologies.

To understand ETF and its consequences to device operation it is illuminating to review the details of TES physics. The standard differential equation is

\[ C_e \frac{dT}{dt} = \frac{V^2}{R(T)} - \kappa (T^n - T_s^n), \]  

(3.1)

where \( C_e \) is the electronic heat capacity, \( T \) is the electron temperature and \( T_s \) the substrate (and bath) temperature. \( V \) is the voltage across the TES, \( R(T) \) is the resistance of the TES, \( \kappa \) is the thermal coupling constant, and \( n \) is the thermal coupling power-law exponent in the range of 4–6 depending on the coupling model. In steady-state the power input provided by the voltage bias balances the flow of power out of the sample into the bath, that is

\[ \frac{V^2}{R_o} = \kappa (T_o^n - T_s^n), \]  

(3.2)

where \( T_o \) and \( R_o \) are the steady-state temperature and resistance, respectively. To first order, this quiescent power dissipation is independent of device bias point since \( T_o \) is nearly \( T_c \) throughout the bias region and \( \kappa, T_s, \) and \( n \) are constant.

An incoming photon with energy \( E_\gamma \) is absorbed by an electron in the tungsten which rapidly (few ps) distributes its energy to the entire electron system\(^{26}\) raising the temperature by \( \Delta T = E_\gamma / C_e \). Equation 3.1 may be expanded to first order in \( \Delta T \) as

\[ C_e \frac{d\Delta T}{dt} = \frac{V^2}{R_o} - \kappa (T_o^n - T_s^n) - \frac{V^2}{R_o^2} \frac{dR}{dT} \Delta T - n \kappa T_o^{n-1} \Delta T. \]  

(3.3)

From Equation 3.2 the first two terms cancel. If we set \( g = n \kappa T_o^{n-1}, \alpha = (T_o/R_o)(dR/dT), \) and \( P_o = V^2/R_o, \) we obtain the following differential equation

\[ \frac{d\Delta T}{dt} = - \left( \frac{P_o}{T_o C_e} \alpha + \frac{g}{C_e} \right) \Delta T \]  

(3.4)
which can be seen to have a simple exponential solution with time constant

\[ \tau_{etf} = C_e \left( \frac{P_o}{T} \alpha + g \right)^{-1}. \]  

(3.5)

By substituting back \( P_o = \kappa(T_o^n - T_s^n) \) and \( g = n\kappa T^{n-1} \) we reach an equivalent expression

\[ \tau_{etf} = \tau_o \left\{ 1 + \frac{\alpha}{n} \left( 1 - \frac{T_s^n}{T_o^n} \right) \right\}^{-1}. \]  

(3.6)

where \( \tau_o = C_e/g \), the intrinsic thermal recovery time in the absence of a bias power. We can further simplify this expression by noting that when biasing in the strong electrothermal feedback regime, \( T_s \ll T_o \) and \( \alpha \) is typically 25 or more\(^*\). This allows the recovery time to be expressed simply as

\[ \tau_{etf} = \frac{n\tau_o}{\alpha}. \]  

(3.7)

The effect of ETF on pulse recovery time is now quite apparent. Assuming \( n = 5 \), as discussed below, pulse shortening by a factor of five is easily accomplished and is further enhanced by high-\( \alpha \) superconducting films.

The full solution for the exponential decay of an small impulse increase in temperature becomes

\[ \Delta T(t) = \frac{E_\gamma \epsilon}{C_e} e^{-t/\tau_{etf}}, \]  

(3.8)

where \( E_\gamma \) is the incoming photon energy, \( \epsilon \) is the fraction of photon energy deposited in the electron system following the photoelectron cascade, and \( C_e \) is the electronic heat capacity. In the approximation that the quiescent power dissipation is constant, all of the heat deposited into the electron system in excess to the bias power is removed by the ETF

\(^*\)Values of \( \alpha \) as high as 1000 have been measured in some of the first tungsten TES devices in the low-current limit.\(^{20}\) With higher currents (required for device biasing) \( \alpha \) is typically \(< 200.^{27}\)
reduction in Joule heating.

Casting Equation 3.8 in terms of sensor power dissipation we get a simple exponential

\[ \Delta P(t) = -\Delta P_0 e^{-t/\tau_{eff}} \] (3.9)

where \( \Delta P_0 = -\frac{V^2}{R^2} \Delta R_o \) is the initial drop in power due to the increase in sensor resistance (and temperature). Since \( \Delta P \) is also equal to \( V \cdot \Delta I \) (ideally with \( V \) constant and known) we integrate our current signal to measure \( E_\gamma \varepsilon^* \). The decay is a simple exponential which integrates to \( E_\gamma \varepsilon = \Delta P_0 \tau_{eff} \). Additionally, since we have control over the input energy we can independently measure \( \varepsilon \). From our tests with “enhanced” electrothermal feedback a value of \( \varepsilon = 0.42 \) was determined.\(^{28}\) The impact of this collection efficiency on energy resolution is discussed later in Section 3.2.

In looking at the W-TES thermal model, I would like to justify our choice of \( n = 5 \). The acoustic mismatch model for heat flow between two materials\(^{29}\) gives a power-law exponent of \( n = 4 \). However, since the temperature of the W is much lower than the Debye temperature (\( \sim 390 \)K) we are in a regime of strong e-ph decoupling. As a consequence we could expect \( n = 5 \) from bulk-metal e-ph scattering calculations.\(^{30}\) Not surprisingly, however, the coupling strength can vary depending on the particular film and temperature range of interest\(^{31}\) so, in practice, the value of \( n \) should be measured for the material and relevant temperature regime.

\*The subtleties of this integration when \( V \) is not constant are discussed more fully in Section 3.1.4.
So, an experiment was performed in which the sensor power dissipation was measured while varying the substrate temperature, the results of which are shown in Figure 3.3 on the previous page. The data were fit to a curve of the form \( P = \kappa (T_c^n - T_s^n) \) where \( \kappa, T_c, \) and \( n \) were free parameters. As noted in the figure inset, the resulting least-squares fit parameters are \( \kappa = (2.26 \pm 0.01) \times 10^{-8} \text{W/K}, T_c = 70.4 \pm 0.1 \text{mK}, \) and \( n = 4.986 \pm 0.003. \) These error limits are stated based on the statistics of the least-squares minimization. In reality the systematic errors on the base temperature and sensor-power measurements dominate the uncertainties. Nevertheless, the obtained value for \( n \) validates our assumption of electron-phonon limited heat conduction. The transition temperature of the film was measured independently to be within a few mK of 68 mK and the obtained value of \( \kappa \) agrees with our thermal conductance measurements of related devices.

Since the measured value for \( n \) is that expected for electron-phonon limited thermal conductivity, we expect estimates of the W- Si phonon conduction \( g_{W-Si} \) to be much larger than \( g_{e-ph} \). The expected thermal conduction from the W phonon system to the Si phonon system can be estimated using the acoustic mismatch model.\(^{29}\) A quick calculation gives \( g_{W-Si} \approx 60 \text{pW/K}. \) This conductivity is significantly larger than \( g_{e-ph} = 2.8 \text{pW/K} \) calculated from the measured \( \kappa \) above, as anticipated.

The above estimate is valid for the low-temperature steady-state biasing conditions of our TES devices. During the photon thermalization process, however, the W electron system cascades down through much higher temperatures\(^*\). Because of the differing power-law exponent to the thermal conduction, there exists a crossover temperature, \( T_x \), at which the two thermal conductivities are comparable. Setting \( g_{W-Si} = g_{e-ph} \),

\[
60 \, \text{pW/K} \left( \frac{T}{70 \text{mK}} \right)^3 = 2.8 \, \text{pW/K} \left( \frac{T}{70 \text{mK}} \right)^4
\]

and solving for \( T \) gives \( T_x \approx 1.5 \text{K}. \) The conclusion is that phonons with energy greater than \( \sim 1.5 \text{K} \) are not confined to the W electron system and can escape into the substrate unmeasured, thereby degrading the energy resolution of the sensor.

\(^*\)The “temperature” of the initial 1 eV photoelectron is \( \sim 10^4 \text{K}. \)
3.1.2 Biasing and Readout

![TES Bias Circuit with SQUID Readout](image)

Figure 3.4: TES bias circuit with SQUID readout. $I_{bias}$ is applied from room-temperature and is shunted through a small $R_{bias}$ to voltage bias the TES. The signal ($I_{sensor}$) is read out using an array of 100 dc SQUID amplifiers run in flux-locked feedback mode through feedback resistor $R_{fb}$.

To avoid the challenges of using low-resistance bias lines to the detectors, voltage biasing is accomplished using a room-temperature current source followed by a small cold bias resistor in parallel with the TES, as shown in Figure 3.4. By design, $R_{bias}$ should be much smaller than $R_{sensor}$ to create a stiff voltage bias across the series combination of the SQUID input coil and the sensor. Since the input coil is superconducting it has no dc voltage drop. By running in flux-locked mode the SQUID output is linearized such that the feedback signal is proportional to $I_{sensor}$.

Figure 3.5 on the next page shows a typical current-voltage curve for an optical TES device. Shown are two regimes for the device—superconducting and biased. When the TES is superconducting the sensor current changes rapidly with applied bias current since it is limited only by the parasitic lead resistance ($\sim 5\, \text{m}\Omega$ for this device). Eventually, as $I_{bias}$ is increased, the sensor critical-current ($\sim 19.7\, \mu\text{A}$) is exceeded and the sensor quickly “snaps” into a resistive state. If $I_{bias}$ is further increased the sensor may be driven completely normal.
Once the sensor is resistive it dissipates power. When the sensor is normal, the power dissipation is quadratic in $V$ since $R$ is constant, $P_o = V^2/R = \text{const}$. When the bias voltage is reduced and the sensor begins self-heating in the superconducting-to-normal transition, the power dissipation becomes independent of $I_{bias}$ and is constant, as discussed in Section 3.1.1. In this mode the sensor resistance is quadratic in $V$, $R = V^2/P_o$. When the bias is reduced further, eventually the sensor resistance becomes comparable in value to $R_{bias}$. This prevents the bias resistor from providing adequate stiffness to the voltage bias (effectively moving toward current biasing) and the sensor snaps into the superconducting state, seen in Figure 3.5 near the point $I_{bias} = 8 \mu A, I_{sensor} = 1.8 \mu A$

### 3.1.3 Device Saturation

From the description of TES behavior given in Section 3.1.1 we should expect that, in the small-signal limit, the trailing edge of our pulses should be able to be characterized by a decaying exponential. In the analyses to this point I have made approximations appropriate to a device operating in this small-signal limit. These approximations are valid for small temperature excursions in which the change in sensor resistance is small compared with the normal-metal resistance, $R_n$. Since $R_n$ is a hard upper bound on the TES resistance, there is a well-defined saturation regime where the power “removed” by ETF is a maximum.
and is constant. Figure 3.6 shows the variation in signal pulse shape as the input energy is increased until the temperature excursions are a good fraction of the transition width and the sensor is driven completely into the normal state. The onset of saturation is labeled with the equivalent photon energy ($E_{\text{sat}}$) which is the minimum input energy which saturates the sensor. For our $\sim 20 \mu m$ sensors at 70mK, $E_{\text{sat}} \approx 5 \text{eV}$. The TES remains saturated until the temperature of the sensor drops into the transition region, ETF kicks in, and the sensor signal resumes its exponential decay. The ETF time constant for this device was under 10 $\mu \text{s}$ as evidenced by the smallest pulses.

Interestingly enough, the heat being removed from the TES during saturation is still being monitored by the sensor current and, as long as the pulses are relatively short compared to the intrinsic thermal recovery time $\tau_o$ (Section 3.1.1), the integral of the ETF power is still the initial energy deposited in the W electron system. Consequently, though the pulse height reaches a maximum, the pulse width increases with energy above $E_{\text{sat}}$ to preserve the integral. This effect is illustrated in the inset of Figure 3.6, where the heights and integrals of the saturated pulses are used to estimate the input energy. The pulse height alone is insufficient to determine the input energy, as indicated by the severe non-linearity above a relative input energy of $\sim 0.5$. The integrated pulses show a much better linearity well into saturation.
3.1.4 Consequences of a Finite Input Coil Inductance

To this point, no mention has been made of the limits to the pulse rise-time. A finite-element model of a 20 µm square TES using conservative values for heat conduction across the device indicates that a photon event will be fully thermalized in under 300 ns. This time is sufficiently short to allow the pulse rise-time to be limited by the $L_\circ/R_{loop}$ time constant arising from the SQUID input coil inductance in series with the TES. Considering the circuit model shown in Figure 3.4 on page 25, we can see that the appropriate value of $R_{loop}$ to use in the rise-time calculation is the sum of all of the resistances in the bias loop. This cumulative loop-resistance will vary depending on the TES bias point, but will, in general, be dominated by the TES resistance. For typical values of $L_\circ \approx 250$ nH and $R_{loop} \approx 100$ mΩ, the calculated pulse rise-time $\tau_{calc}$ is 2.5 µs. We find, however, that measured rise-times are always much smaller than expected. For instance, even reducing the loop resistance to $R_{loop} = 30$ mΩ, the expected rise-time $\tau_{calc}$ should be greater than 8 µs. Nevertheless, the measured rise-time is $\sim 1$ µs. A empirical non-ohmic model of the sensor resistance has been used to reproduce such behavior, however this effect must be investigated further.

In addition to affecting the pulse rise-time, the SQUID inductance can couple (through the device current) to the TES thermal system. In the analysis of Section 3.1.1 the inductance of the SQUID input coil was neglected. A more complete treatment must provide for the effect of the finite input-coil inductance in the electrothermal model. Recalling Equation 3.1 on page 21,

$$C_e \frac{dT}{dt} = \frac{V^2}{R(T)} - \kappa(T^n - T^n_s), \quad (3.11)$$

I made the assumption that the sensor voltage bias was constant throughout the pulse event. However, the proper quantity to preserve as constant is the voltage drop across the series combination of the SQUID input coil and the TES. Now, instead of remaining constant,
the voltage drop across the TES assumes the form

\[ V = L \frac{di}{dt} + iR. \] (3.12)

Equations 3.11 and 3.12 are two coupled differential equations which describe the interaction between the SQUID inductance and the TES heat capacity. The existence of both an inductance and a (heat) capacitance in this circuit leads to the possibility of oscillatory behavior. By linearizing these two equations about the steady-state operating point Sae Woo Nam, in his thesis, analytically derives the condition for such “electrothermal oscillations”.

Of course, these coupled equations can be solved numerically to model the dynamic response of our devices without making small-signal approximations. These numerical models can give a view of internal parameters of the system not available for measurement independent of the device current. Figure 3.7 shows the result of modeling the device response to a impulse input of energy with initial conditions appropriate for a properly biased sensor. The upper trace shows the current through the device during an absorption event at \( t = 5 \mu s \). Since the current through the device is also the current through the SQUID input coil, it is our measurable signal. Typically we invert the signal and define the leading edge as the rise and the trailing edge as the fall of the pulse. The effect of the input-coil inductance can be seen in this current signal as a slow rise-time to the leading edge\(^*\). The

\[^*\text{A non-ohmic model of device behavior has not yet been implemented into this calculation.}\]
device parameters used for this simulation are given in Appendix B.

The middle and lower traces in the figure show the instantaneous resistance and Joule heating of the sensor, respectively. In these two traces the more subtle effects of a finite inductance are made apparent. When the TES absorbs a photon its temperature and resistance increase on a time-scale short with respect to the $L_\alpha/R$. This fast temperature/resistance rise is seen in the middle trace as the instantaneous step in resistance from $\sim 0.18\,\Omega$ to $\sim 0.33\,\Omega$ at $t = 5\,\mu s$. In the absence of a series inductance this rapid change in resistance would decrease the sensor current immediately reducing the Joule heating. The series inductor, however, prevents this from happening on a fast time-scale and instead acts as a high-impedance current source and thus it maintains a steady current flow, even though the sensor resistance is now much higher than the quiescent resistance. The result is that the inductor prevents electrothermal feedback from cooling the device and actually heats the electron system for a short time, as evidenced by the $V^2/R$ heating (lower trace). Since this additional heat must be eventually removed via ETF and measured, it acts as a small increase in our photon energy estimate. In the case shown here the heat injected by the inductor causes an overestimate of the true initial energy deposition by 15%.

This overestimate must be taken into account when we determine the efficiency of heating the electron system during the absorption event and subsequent electron cascade. This efficiency, called $\varepsilon$ in Section 3.1.1, is important for correct theoretical energy resolution estimates. To date the only careful calculation of $\varepsilon$ was done during Sae Woo Nam's development of the EETF technique. It is quite important that further work be done to correctly account for the heat-injection gain in our devices. In order to do this correction properly measurements must be made of the true SQUID inductance, which is currently being estimated at 250 nH. Additionally, there exist relatively significant thermal voltage offsets in the cryostat which skew the determination of the device bias current if not measured and taken into account.

Finally, it is interesting to push the simulated device into other operating regimes. In
the model, as when biasing the actual devices, the detector voltage bias can be lowered sufficiently to allow self-sustaining oscillations. Before the emergence of full-on electrothermal oscillations there appears “ringing” on the pulse tails, as shown in Figure 3.8(a). Notice the slow baseline undershoot in the output current pulse (a baseline overshoot in the true device current). As the device bias is pushed lower, the post-pulse ringing takes longer and longer to decay. Eventually, when the bias is lowered sufficiently, the ringing does not damp out but grows to a stable amplitude or, at even lower bias, grows slightly each cycle until the device snaps superconducting and all action ceases. A modeled situation of stable self-sustaining oscillatory behavior is shown in Figure 3.8(b) with a time-base five times longer than in Figures 3.7 and 3.8(a) to show multiple periods. At such a high oscillation amplitude the sensor nonlinearities can be seen as a peak-like periodic current signal\(^*\). Note that the y-scale of Figure 3.8(b) was also adjusted to allow for the much larger current and

\(^*\)At low oscillation amplitude the oscillations become much closer to sinusoidal.
resistance swings during the electrothermal oscillations than during a typical pulse.

3.2 Energy Resolution Limits

In this section the impact of the controllable parameters on final device resolution is studied. Since we are interested in an estimate of the intrinsic device resolution, I will neglect noise sources arising from pick-up, microphonics, and amplifier noise. We have the ability, in principle, to eliminate these sources of noise from the system. Thus, I will analyze only the noise intrinsic to the thermal and electrical system. Since detailed analyses of the intrinsic resolution of bolometer systems have been thoroughly covered in other sources\textsuperscript{32,33} and have been applied to TES systems in particular\textsuperscript{20,21} I will review the work relevant to our devices in specific.

3.2.1 Phonon Noise

The model of our TES devices is a heat capacity $C_e$ at temperature $T_e$ connected to a thermal bath (substrate) at temperature $T_s$ through a thermal link with conductance $g$, as in Section 3.1.1. The tungsten electron system exhibits temperature fluctuations due to power fluctuations through the thermal conductance to the phonon system. This “phonon noise” can be shown to be the dominant intrinsic noise in a TES with electrothermal feedback due to the suppression of Johnson noise.\textsuperscript{20,32} In the high-$\alpha$ limit ($\alpha/n \gg 1$) and $T_n c \gg T_n s$ the effect of phonon-noise fluctuations on the energy resolution is given as\textsuperscript{19}

$$\Delta E_{\text{rms}} = \sqrt{4k_b C_e T_c^2 \alpha^{-1} \sqrt{n/2}}$$  \hspace{1cm} (3.13)

and, assuming gaussian noise, $\Delta E_{\text{fwhm}} = 2\sqrt{2\ln 2} \Delta E_{\text{rms}}$. This equation is frequency independent and is valid for the frequency band over which ETF operates (i.e. $\omega<1/\tau_{\text{etf}}$).

As seen in Section 3.1.1 the W electronic heat capacity plays a crucial role in determining the device behavior. A heat capacity that is too low will cause the temperature excursion during an event to exceed the width of the superconducting transition, causing device
saturation (discussed in more detail in Section 3.1.3). A heat capacity that is too high will result in a temperature change during an event that is too small to be accurately measured above the thermal fluctuations in the device. Equation 3.13 quantifies these fluctuations for a given heat capacity, transition temperature, and film $\alpha$.

Equation 3.13 may be cast in terms of useful measurable device parameters. We define the maximum energy that ETF can remove with characteristic time $\tau_{etf}$, the saturation energy, as $E_{sat} = P_o \tau_{etf}$. Under the assumption of strong electrothermal feedback (high-$\alpha$, $T_c^n \gg T_s^n$), we find that $E_{sat} = C_e T_c \alpha^{-1}$. Thus, Equation 3.13 is equivalent to

$$\Delta E_{rms} = \sqrt{4k_b T_c E_{sat}\sqrt{n/2}} = \sqrt{4k_b T_c P_o \tau_{etf}\sqrt{n/2}}.$$  

(3.14)

A simple estimate of device resolution can be made using realistic values of $E_{sat} = 10$ eV, $T_c = 80$ mK, and $n = 5$ to obtain $\Delta E_{fwhm} \approx 0.05$ eV. Since our energy collection is not complete, as noted in Section 3.1.1, our effective energy resolution drops proportionally with collection efficiency $\varepsilon$. Our effective resolution for such a device is thus $\Delta E_{eff} = \Delta E_{fwhm}/\varepsilon$. Using the value of $\varepsilon = 0.42$, we obtain an expected resolution of $\Delta E_{eff} \approx 0.12$ eV independent of photon energy. Our measured device resolution is $\sim 0.15$ eV at a photon energy of 1 eV and degrades slightly to $\sim 0.2$ eV at 3 eV.

### 3.2.2 An Improved Noise Model

The above noise description allows an estimate of the intrinsic device-limited resolution of our sensors, however such a model does not consider the noise contribution from other elements in the TES circuit. An improved model of the measured noise of a biased TES, including its bias circuit, was recently developed by Enectali Figueroa-Feliciano working at NASA Goddard Space Flight Center. A detailed discussion of this work is forthcoming.$^{34}$ The following discussion is a summary of what I will call the “Figueroa model” for calculating the resolution of TES systems.

In the Figueroa model, no constraints are imposed on the values of $\alpha$, $T_c$ and $T_s$, nor are any assumptions made regarding the frequency band of interest. This leads to a much
more complicated noise model, but one which can account for noise sources internal to the TES itself, such as phonon noise and Johnson noise, as well external sources such as the Johnson noise from the bias resistor ($R_{bias}$ in Figure 3.4 on page 25). In fact, in its full form the model can handle multiple TES devices coupled to each other and to other thermal loads. Such a noise model may need to be considered when thermal absorbers are used in connection with these single pixels (e.g., Au-black) unless the thermal impedance between the absorber and TES is negligibly small. For now, we are justified in using the model for the simplest ETF-TES—a single pixel with no external absorber coupled only to the thermal bath and biased using a small shunt resistor.

The punch-line of the Figueroa derivation for this situation is the following expression for sensor resolution:

$$
\Delta E_{rms} = \sqrt{\frac{4k_b T_c^2 C_e n}{\alpha}} \sqrt{\frac{n}{\phi} (1 + r) \left[ \frac{1}{2} \left( 1 + \frac{T_s^2}{T_c^2} \right) + \frac{n}{\alpha^2 \phi} \left( 1 + r \left( 1 + \frac{\alpha \phi}{n} \right)^2 \right) \right]} \tag{3.15}
$$

where $\phi = 1 - \frac{T_n}{T_c}$ and $r = (R_{bias} T_{bias})/(R_o T_c)$. $R_{bias}$ and $T_{bias}$ are the resistance and temperature of the bias resistor, respectively, and $R_o$ is quiescent operating resistance of the TES. Imposing the limits of high-$\alpha$, $T_c^n \gg T_s^n$, and zero noise-temperature of the bias resistor ($r \rightarrow 0$), Equation 3.15 can be seen to reduce to Equation 3.13 as expected.

Continuing the example from the previous section we can estimate the effects of the bias resistor on the effective sensor resolution. If we first assume a configuration in which a small bias resistor is placed on the cold stage, $R_{bias} = 5 \text{ m}\Omega$ and $T_{bias} = T_s = 40 \text{ mK}$. Using a typical sensor operating resistance of $\sim 50 \text{ m}\Omega$ and $\alpha = 20$, then Equation 3.15 gives $\Delta E_{eff} \approx 0.13 \text{ eV}$—not a significant modification to the simple estimate of $0.12 \text{ eV}$ made using Equation 3.14.

However, if we assume a configuration in which the bias resistor is doubled to $10 \text{ m}\Omega$ and moved to the 1K pot, the situation changes significantly. With the same values for all of the quantities except now $R_{bias} = 10 \text{ m}\Omega$ and $T_{bias} = 1.4 \text{ K}$, we get a significant degradation in resolution to $\Delta E_{eff} \approx 0.23 \text{ eV}$. We now have evidence that this effect is the source
of our performance degradation since the instrumentation of multiple-pixels, discussed in Section 5.2.2.

Though this model improves our estimate of the electrical and thermal noise sources, in my treatment it does not provide for the additional non-white noise mechanisms which may be significant. These mechanisms include nonuniform flux-flow across the sensor, the low-bias onset of electrothermal oscillations, and position-dependent energy loss within a pixel. Further experiments need to be done to determine the extent to which such noise sources manifest themselves in our devices.

3.3 Device Design and Fabrication

Our TES devices are composed of a 35 nm thick high-purity W active area and 150 nm thick Al bias rails fabricated on standard 4-inch diameter silicon wafers. The devices are created using a standard two-mask CMOS-compatible photolithographic process outlined in Figure 3.9 on the following page. The wafers are cleaned using a standard RCA wafer clean before metalization in a Balzers 400-series planar magnetron sputtering system. A short (2 min) RF etch is performed as a final substrate clean before metalization. The first layer is the 150 nm layer of Al. A 35 nm thick “inactive” layer of W is deposited on the Al immediately following, to ensure good electrical connectivity between the layers.

The wafers are then removed from the sputtering system and spin-coated with 1 µm thick Shipley 3612 positive resist to give the layered structure in Figure 3.9(a). Using the first mask with an UltraSTEP 1000 Ultratech stepping aligner, the photoresist is exposed to define regions which will eventually become the Al bias rails. The W is wet-etched to expose the Al and allow it to be wet-etched as well. The thickness of Al allows the wet etch to undercut the W (Figure 3.9(b)); a final W etch is performed to remove this W overhang. Note that the isotropic wet-etch of the Al leaves sloped side-walls to aid in adequate step-coverage of the final W layer. The wafers are then put back into the Balzers sputtering system. An RF etch is again performed to remove any oxide on the W prior to deposition of the “active” W layer over the existing features (Figure 3.9(c)). The second and final mask
is used to pattern the active-W features and a final W etch is performed leaving completed devices (Figure 3.9(d)). Finally, the wafers are diced into 1 cm chips using a K&S wafer saw.

A word should be said about the parameters under our control in fabricating the devices. It is questionable whether the sputtering system used to make the films can reliably make the active W thinner than its current thickness of \(\sim 35 \text{ nm}\). We also have not studied the effects of using thicker films. This limits the control of device heat capacity, which is linearly proportional to volume and operating temperature, to varying the device area and \(T_c\).

Both the theory and experimental realization of controlling the \(T_c\) of our W films have been quite successful.\(^{35}\) Using the technique of implantation of magnetic impurities (Fe, Ni, Co), the sensor \(T_c\) can be adjusted to within a few millikelvin of a desired operating temperature. This control allows the more restrictive constraints to the device design to come from the desirable device operating parameters. Since we wish to maintain an energy resolution better than \(\Delta E_{\text{eff}} = 0.15 \text{ eV}\) (see Equation 3.14), we must limit the product \(E_{\text{sat}}T_c\) to below \(\sim 1.3 \text{ eV-K}\). Since we also wish to keep our saturation energy safely above our highest energy of interest, we constrain \(T_c\) to be lower than 130 mK. The lower bound for \(T_c\) is constrained by requiring

\[ \text{(a)} \quad \text{Si wafer after first metalization showing 150 nm thick Al covered with 35 nm of W and } \sim 1 \mu\text{m of photoresist.} \quad \text{(b)} \quad \text{After first photoresist exposure and W and Al etches.} \quad \text{(c)} \quad \text{After second W etch to remove overhang followed by “active” W deposition.} \quad \text{(d)} \quad \text{Completed devices after final exposure and W etch.} \]

Figure 3.9: Diagram of two-mask process of W-TES fabrication (not to scale). (a) Si wafer after first metalization showing 150 nm thick Al covered with 35 nm of W and \(\sim 1 \mu\text{m}\) of photoresist. (b) After first photoresist exposure and W and Al etches. (c) After second W etch to remove overhang followed by “active” W deposition. (d) Completed devices after final exposure and W etch.
event rates greater than 10 kHz/pixel. This imposes a restriction on pulse recovery time. For instance, using the same device parameters discussed in Section 3.2 we obtain a pulse recovery time of \( \sim 40 \mu s \) at \( T_c = 80 \text{ mK} \). If we allow \( T_c \) to be 60 mK we start to have pulse decay times approaching 100 \( \mu s \)\(^*\). At these fall times pulse pile-up will significantly degrade the energy resolution of the device.

Using a value for \( T_c \) of 100 mK we can calculate the heat capacity required to give \( E_{sat} \approx 10 \text{ eV} \). Using the factor of 1.43 increase in heat capacity for a metal below \( T_c \), a normal-metal specific heat of 0.13 \( \frac{J}{g \text{ K}} \), and \( \alpha = 25 \) gives a device heat capacity of 0.28 \( \frac{fJ}{K} \). For a sensor with a thickness of 35 nm this heat capacity corresponds to an active area of \( \sim 25 \mu m \times 25 \mu m \). In a perfect device where all of the initial phonon losses are recaptured \((\varepsilon \rightarrow 1)\) the pixel should be scaled up to accommodate the higher required saturation energy.

These estimates give us a target design size for the active W area of our pixels. Since all of the device parameters are constrained by the energy resolution, saturation, and count-rate requirements it is clear that pixels which vary significantly in area from the 25 \( \mu m \times 25 \mu m \) pixels will suffer performance degradation. If larger pixels are desirable, other methods of increasing the collection area must be developed which do not increase the active-area heat capacity.

\(^*\text{From Section 3.1.1 it can be seen that } \tau_{etf} \propto T^{-3}.\)
Chapter 4

Experimental Apparatus

For any successful experiment, the apparatus used is essential to success. I am extremely fortunate to have been given the use of an experimental system which is the result of significant developmental efforts by previous members of the Cabrera group. The dilution refrigerator, SQUID amplifier mounting and room-temperature electronics, and significant experience in TES operation were all provided without reservation upon beginning this project. Without this strong experimental base, the quick progress of this project would have been impossible. In this chapter, I describe the general apparatus with and emphasis on the modifications made for running the optical detectors.

4.1 Getting Cold

4.1.1 Cryostat Details

Since our W films have a transition temperature around 100 mK and we wish to run the devices using strong electrothermal feedback, we require a refrigeration system capable of reaching temperatures under 50 mK. The cryostat used for all of the work in this thesis is a modified Oxford Instruments KelvinOX-15 $^3$He/$^4$He dilution refrigerator with a nominal cooling power at 100 mK of $\sim$ 15 $\mu$W. This cryostat is routinely able to reach a base temperature of under 40 mK. Through the hard work of previous members of the group,
the KO-15 has been repaired of its superfluid leaks, thanks to Kent Irwin, and outfitted with six low-noise bias lines and SQUID amplifiers, thanks to Sae Woo Nam, sufficient for the read-out of six low-impedance TES devices (see Section 4.2.1). A photo of the probe is shown in Figure 4.1.

The KO-15 is a small refrigerator designed to be operated in a liquid-helium storage dewar with 2-inch inner-diameter neck. Because of its small size, the refrigerator can be cooled in less than a day allowing rapid device testing. Additionally, since it has a port to allow helium transfers while a run is in progress, the KO-15 is capable of staying cold for many weeks. These traits made the cryostat appealing for use in a prototype system which could require transporting the apparatus to a remote site for a practical demonstration of a TES spectrophotometer as an astronomical instrument.

The sample stage of the cryostat is outfitted with a base-temperature radiation baffle to prevent the flux of 4K blackbody photons from providing an unwanted heat load. Additionally, this radiation shield helps prevent thermal shorts between the cold stage and the nearby 4K vacuum can. In its standard configuration, the sample stage is vertical which requires mounting samples vertically as well. To aid the insertion of fibers into the small alignment ferrules, an additional horizontal cold-stage extension is attached to the existing sample mounting plate. This enables fibers to come straight down from the top of the sample area into a ferrule thereby reducing fiber stresses and the resulting strain on the cryogenic optics.
4.1.2 Fiber Feedthroughs

The KO-15 has been used extensively in device testing for the Cryogenic Dark Matter Search (CDMS) project at Stanford. Since W-TES technology was developed for CDMS, and is the same technology used for the optical devices, the cryostat required only a few modifications to allow the testing of our prototype detectors.

The main adaptation to the KO-15 for the optical project was the addition of fiber-optic cables to allow the introduction of light to the sample stage. The existing brass bulkhead plate was originally designed for eight SMA electrical connectors for vacuum feedthrough to the stainless-steel co-axial cables used for the front-end (cold) amplifier readout. A new plate was made with an additional five holes near the center in which were mounted five Amphenol 905-120-5008 SMA fiber-optic adapters. These adapters are marketed as “hermetic” to allow operation in harsh environments. When used with one Amphenol 906-505-5007 SMA connector (with integrated O-rings) on each side of the brass plate, these components make a vacuum seal sufficient to allow fiber-to-fiber coupling through the bulkhead. Maintaining the integrity of this seal is, of course, paramount for preventing a premature end to a run. For instance, I found that it is not wise to insert and remove the accessible connector during a run as the inner connector can work loose and break vacuum.*

This feedthrough technique has the major limitation of requiring the use of SMA connectors for fiber termination. We found that the optical losses inherent in the SMA couplers are prohibitive when trying to design a low-loss system. In creating a high efficiency optical feedthrough, the fiber-to-fiber coupling via SMA adapters was discarded, however the vacuum seal was still provided by the SMA connectors. The details of this improved feedthrough are discussed in Section 4.3.4.

4.1.3 Device Assembly

All of the devices are assembled into a small G-10 fiberglass holder with copper traces for soldering the SQUID input coil to the device. In the first tests the 1 cm square Si substrate

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*The use of thread-locking compound (e.g. removable Lock-Tite) helps considerably.
was tacked down to the G-10 at its corners using GE varnish. The devices were then wire-bonded to the copper traces using 1%Si–99%Al wire of 1.2 mil diameter. A Cu backing plate was screwed to the G-10 holder with a drop of silver paint used to make thermal contact between the Si and the plate. This assembly was then attached to the cold stage of the cryostat using 0-80 brass screws.

This mounting scheme has one overriding flaw—the relatively large amounts of silver paint used tend to crack upon thermal cycling and the heat sinking degrades noticeably. The present method of heat sinking uses four Cu/Be spring clips which press against the back of the Si substrate. The springs and substrate are then coated with a thin layer of silver paint. Since the paint is not pressed between two surfaces, it tends to more gracefully handle the cool-down/warm-up cycles.

An alternative scheme using a thin layer of Dow-Corning High-Vacuum grease and spring-applied pressure is used by NIST. Though the “grease and pressure” technique has the advantage of allowing multiple thermal cycles, the few times I tried the method I found it provides inadequate heat sinking for our devices and the device performance degrades. It may be necessary to use larger contact areas and/or higher pressure.

4.2 Electronics

4.2.1 SQUID Readout

As mentioned numerous times above, we use Superconducting QUantum Interference Device (SQUID) amplifiers as low-noise cryogenic preamplifiers to read our sensor current. Details of SQUID array testing, noise performance, and operation are covered thoroughly in other sources,\textsuperscript{8,21} so only a brief overview will be provided here.

In current-biased operation the voltage across a single SQUID magnetometer will be periodic in applied flux with a period of one flux quantum, $\Phi_o = \hbar/2e$.\textsuperscript{9} When flux is applied to the SQUID using an “input coil” wound around the SQUID loop, the SQUID becomes a very sensitive ammeter. Under ideal conditions the voltage across a series array
of 100 SQUIDs will be 100 times that of a single SQUID. In the present designs, each SQUID has a peak-to-peak voltage swing of $\sim 30-80 \, \mu V$ giving an ideal array output in the range of 3-8 mV—readily amplified by room-temperature electronics. The trade-off for this gain of 100 is an increase in the inductance of the input coil. In the amplifiers used for this project the input coil has inductance of $\sim 250 \, nH$ which is, in principle, large enough to limit the rise-time of our pulses and complicate the determination of the absorbed energy (see Section 3.1.4).

The SQUID amplifier arrays are designed by Martin Huber of the University of Colorado at Denver and fabricated at NIST in Boulder, Colorado. The figure-of-merit for any current amplifier is the RMS current noise referenced to the input. This noise specification at manufacture, measured in a highly magnetically-shielded environment, is often less than $2 \, pA/\sqrt{Hz}$ and better than $10 \, pA/\sqrt{Hz}$ is routinely achieved in our cryostat. The thermal noise of our devices induces current fluctuations often in excess of $100 \, pA/\sqrt{Hz}$ that easily dominate over the amplifier noise, as desired.

The standard method of operating the SQUID array amplifiers is using a closed-loop constant-flux feedback system. Referring back to Figure 3.4 on page 25, the sensor current $I_{\text{sensor}}$ induces a flux through the SQUID via the input coil. The resulting voltage across the array is amplified and feedback, by room-temperature electronics, through a feedback resistor $R_{fb}$ to a feedback coil integrated on the SQUID chip. This allows the linearization of the SQUID signal and an adjustable and calibrated gain (via selection of $R_{fb}$). The present design of the NIST/CU-Denver SQUID arrays has an input-coil to feedback-coil turns-ratio of 10:1, and $R_{fb} \approx 1 \, k\Omega$. This gives a transimpedance gain of $10 \, k\Omega$ for the entire flux-locked SQUID amplifier chain. Additionally, the measurement bandwidth of the SQUID amplifiers system in feedback mode is 1 MHz allowing precise determination of event times using the fast rising-edge of our events.
4.2.2 Data Acquisition

Analog Shaping/Digital PHA

Since we design our devices to be fairly linear throughout the entire optical band, standard pulse-shaping electronics do a reasonable job of conditioning the signal. The pulses are first conditioned by an Ortec 673 spectroscopy amplifier. This amplifier has shaping time constants from under a microsecond to six microseconds rise and fall. Since the ETF time constant for our signals is of this order, the bulk of the signal-to-noise in our pulses is amplified while the low-frequency fluctuations, such as 60 Hz pick-up and SQUID temperature fluctuations, are suppressed. For simple measurements of sensor linearity and energy resolution we discard timing information and histogram only the event pulse-heights using a Tracor-Northern 7200 multichannel analyzer (MCA). Use of this portable MCA allows us to quickly evaluate individual pixels and optimize sensor bias to achieve the best signal-to-noise ratio.

Though convenient, any MCA does not meet the requirements for a full acquisition system. Since we are photon counting we wish to have a system which is able to record all of the available information from the events, which includes arrival time and energy. A prototype system was designed which allowed such energy and time-tagging on an event-by-event basis for a single channel. The gory details are presented in Appendix A, so just a functional overview is presented here.

The signal from the SQUID feedback amplifiers was first amplified further with a low-noise SRS SR-560 amplifier and shaped using the Ortec 673 Spectroscopy Amplifier, as mentioned above. The filtered pulse signal was split and fed into both a threshold detector, to provide the event trigger, and a high-speed analog-to-digital converter (ADC). When the circuitry of the DAQ received a trigger signal from the threshold detector, two parallel processes occurred: the pulse height was sampled using the ADC, and the value in the time counters were latched into a buffer to allow reading on time scales slow with respect to the clock frequency. The clock reference was provided by a Datum BC637PCI Time and Frequency Processor card with GPS conditioning. This card has a temperature-regulated
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Crystal oscillator running at 10MHz which is continually corrected using GPS satellite signals. The timing error of this system is specified by the manufacturer to be less than a microsecond.

Once the pulse amplitude and time were latched, they were clocked into a high-speed digital interface board (National Instruments DIO-32-HS) in the acquisition computer and logged to disk. The dead-time associated with each event was approximately 12 µs limited by the speed of microcontroller used for handshaking between the DAQ and the computer. However, typical event rates are kept under 30 kcts/s to prevent resolution degradation from pulse pile-up. Since this DAQ was able to handle rates of over 80 kcts/s it did not contribute significantly to overall system dead-time.

However, since this was a prototype DAQ system that slowly morphed into its final state, throughout its useful life it was never properly shielded from line noise causing the ADC to operate far below its resolution specification. As a consequence, the pulse-height determination from the ADC limited the energy resolution of the system. Additionally, this DAQ was not easily scaled up to multiple pixels. However, the event time-stamping worked quite well and was verified on the Crab Pulsar (see Section 5.1.2) to provide a cumulative timing error less than \( \sim 100 \mu s \) over a period of a few hours.

Digital SQUID Feedback

The significant effort of developing an appropriately low-noise, scalable, and computer-controlled data acquisition system was undertaken by our collaborators John Martinis and Sae Woo Nam at NIST. They first demonstrated a digital feedback (DFB) system for dc SQUID arrays on their X-ray microanalysis system using TES devices. For use on this project, they significantly augmented the DFB system to allow the shaping and time-stamping of optical photons across multiple channels. There are many notable advances of this DAQ over my prototype system, as discussed below.

The non-linearized output voltage from the SQUID amplifiers is digitized directly from the \( \times 100 \) pre-amp. The resulting digital signal is processed in real-time using a 66 MHz
FPGA*. The FPGA performs two distinct functions. First, the SQUID signal is fed into a digital version of the SQUID feedback circuitry. The feedback parameters (e.g., lock point, feedback integration/differentiation parameters, etc.) are adjusted remotely via a control computer, uploaded to the FPGA through fiber-optic cables to eliminate ground-loops. The FPGA then applies the feedback parameters to the SQUID signal mimicking the traditional analog feedback electronics. The calculated feedback signal is then fed to the SQUID feedback coil as usual.

The second major function of the FPGA is to further process this feedback signal. Pulse shaping parameters (again controlled via computer) are adjusted to adequately match the pulse time constants. This shaping is applied to the digital signal as a Finite Impulse Response (FIR) filter. Since it is a forward-in-time or “causal” filter, it can be applied to the data in real-time with low memory requirements. More complicated filters such as matched filters, optimal filters, convolutions, etc. require significant processing power and are being considered in the future when processor capabilities increase. Such filters take into account changes in pulse shape as the detector saturates and can extend the linearity of the devices to higher energies.36

The FIR filtering provides an energy determination that can be better than standard RC-CR filtering provided by the Ortec pulse-shaping amplifier mentioned above. This improvement is primarily due to the ability to tune the shaping time constants over a wider range using the digital system than is available with the analog system at present. However, the flexibility of the digital system allows more complex processing which would be difficult or impossible with the analog system. Such complex features include the implementation of a fast baseline restore, dc baseline measurement, and a combination of fast and slow triggers to detect pulses and pulse pile-up while helping to reject slow rise-time events such as substrate-hits.

The DFB system is integrated onto a single 3U card. This card includes all the analog and digital circuitry capable of controlling the SQUID feedback and signal processing for a

* A Field-Programmable Gate Array by Alterra Corp.
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single channel. A master clock card provides the synchronous timing signal used by all of
the DFB boards. The clock card derives its 3.125 MHz clock from the 10 MHz GPS signal
mentioned above. This clock drives the DFB circuitry on each card so that each channel
is synchronized to absolute GPS time. This allows absolute time-tagging of events to the
GPS specification of 1 µs with respect to UTC (Coordinated Universal Time).

Once the signals are processed, the extracted parameters are transmitted via fiber-optic
cable to a signal multiplexer board at the host computer. This board is responsible for
collecting the information from each DFB board, assigning the data a channel number, and
clocking it into the National Instruments DIO-32-HS digital I/O board in the host computer.
In the end, each photon has assigned to it a pulse-height, time, channel, and a set of flags
regarding pile-up and pulse shaping, all in the form of a 20-byte packet. Since the peak
throughput of the system in its present form is limited by the National Instruments card
to 66 MB/s the maximum event rate for all channels is over $3 \times 10^6$ cts/s. This cumulative
even rate would allow $\sim 100$ kcts/s/pixel in a 32 channel system, safely above the individual
device count-rate restrictions.

The DFB system was designed with extensibility in mind. For the McDonald Observa-
tory campaign discussed in Section 5.2.4, four TES devices were operated with this system.
This setup included a single clock card driving four DFB boards, one for each sensor. How-
ever, one card per sensor is not necessarily the model for expanding to large sensor arrays.
Since the SQUID feedback is being handled digitally the system has the potential to linearize
multiple SQUID amplifiers with a single DFB card. A similar analog SQUID multiplexing
scheme has been demonstrated successfully by NIST for a prototype 8-channel system.\textsuperscript{37}
The primary concern in applying this idea to our devices is the requirement that the feedback system sample each pixel frequently enough to ensure an accurate reproduction of the pulse shape.

If we assume that the rising-edge of the pulse is too fast to be sampled and the signal
decays with time constant $\tau$, our maximum error in pulse integral estimation, due to ambi-
guity in pulse arrival time, is $1 - e^{-\Delta/\tau}$, where $\Delta$ is the sampling interval. We can see that
this underestimate depends strongly on the pulse decay time. For $\tau = 10 \mu s$ and a sample rate of 3 MHz, the maximum error is $\sim 3\%$. If we maintain a minimum requirement of sampling each device at this 3 MHz, then speed improvements in the feedback system lead to a higher number of pixels that can be supported per feedback channel. For example, a DFB system which is capable of operating at 30 MHz can sample 10 channels, each at 3 MHz.

4.3 Optics

![Diagram of the telescope optics used at the Stanford Student Observatory. The light collected by the telescope is focussed onto a cover-slip-mirror with a hole for the fiber. The light reflected by the cover-slip is re-imaged onto a CCD to monitor the fiber position on the sky.](image)

Figure 4.2: Diagram of the telescope optics used at the Stanford Student Observatory. The light collected by the telescope is focussed onto a cover-slip-mirror with a hole for the fiber. The light reflected by the cover-slip is re-imaged onto a CCD to monitor the fiber position on the sky.

The room-temperature optical system used for the observations at the Student Observatory was designed to allow us to monitor the location of the focussed spot as it is being
positioned over the fiber. Since we only had one small aperture in the telescope focal plane which was feeding light to our TES, the position-monitoring system was essential to ensure that we coupled as much light as possible to the device. In this system, the fiber was placed behind a mirror with a clear hole of diameter equal to the diameter of the fiber core. The optics were such to allow light passing through the hole in the mirror to couple into the core of the cryostat fiber, whereas light reflecting of the mirrored surface around the hole was re-focused onto a CCD and monitored via computer.

The mirrors were made by carefully cleaning 18 mm diameter microscope cover-slip slides to remove any oil and then having Tom Carver in Applied Physics deposit on them a 200 nm film of aluminum. The cover-slips were then brought to CIS where they were coated with photoresist, exposed using a contact aligner, etched using the standard Al wet-etch, and stripped of the remaining photoresist.

The fiber from the cryostat was SMA-terminated and mounted into an SMA receptacle attached to a small (∼20 mm diameter) mount. The mount and receptacle where machined to allow the polished ceramic ferrule and fiber to protrude through the front surface of the mount just slightly. Light was fed into the other end of the fiber and a prepared cover-slip was placed (metal down) over the fiber tip. Under a microscope the cover-slip was positioned to allow only the 50 μm fiber core to be seen through the hole and then epoxied in place. The completed fiber mount was then placed in the focal plane of the telescope.

A schematic diagram of the telescope optics is shown in Figure 4.2 on the preceding page. We placed a 90%/10% pellicle beam-splitter in the incoming f/3.5 beam from the telescope. The purpose was to allow the continuous imaging of the fiber and mirror with a CCD camera with minimal loss of light. This had two functions toward the same goal. First, by sending light up the fiber and out through the mirror, the fiber position and focus could be determined by looking at the CCD image. Second, during an observation the star field is focussed onto the fiber/mirror plane and the CCD image could be used to find objects of interest and move them to the location in the CCD which corresponds to the fiber position. When an object is correctly positioned over the hole in the mirror, and thus the fiber end,
its image in the CCD is seen to disappear as the light is passed into the fiber instead of reflected off the mirror. In this design the fiber location was easily monitored via the CCD, however 10% of the light is thrown away during its first pass through the beam-splitter and possibly an additional ≈5–10% from having to pass through the cover-slip glass before reaching the fiber.

![Diagram of telescope optics](image)

Figure 4.3: Diagram of the telescope optics used at the 2.7 m telescope at the McDonald Observatory. The collected light is focussed through a flip-mirror assembly which can direct the light to a CCD or onto the bare fiber end.

This convenient fiber-monitoring setup was exchanged for a higher-efficiency optical design for our observational work at the McDonald Observatory. This new optical system is diagrammed in Figure 4.3 on the previous page. The cover-slip mirror and pellicle were
replaced by a solenoid-driven flip-mirror. It was necessary for the flip-mirror to be remotely controlled since the assembly could ride far overhead and out of reach depending on the telescope position. The addition of the flip-mirror had two main benefits. First, the 10% loss due to the pellicle beam-splitter and additional loss from the cover-slip surfaces were eliminated. And second, when directing the telescope beam to the CCD, all external light to the fiber end was shielded. This allowed a “dark frame” of sorts to be taken with the TES devices. Such dark frames allowed us to eliminated the sky background and ensure that there were no spurious light-leaks at the cryostat that were being masked by these background events.

The flip-mirror assembly had one major drawback, however. By removing the beam-splitter, we lost the previous ability to monitor the fiber-CCD alignment directly, by either sending light back up the fiber to the telescope, or by watching a bright source disappear into the etched hole in the mirror. Instead, we had to indirectly measure the fiber position and focus. This entailed first measuring the fiber position when the flip-mirror/fiber assembly was not attached to the telescope*. After mounting the assembly on the telescope we guided a bright source onto the previously-estimated fiber position on the CCD. The flip-mirror was changed to allow light to feed the fiber, and we recorded the TES count rate. The bright object was then driven slowly around until the TES count rate was maximized. Then the telescope focus was adjusted and the rate maximized again. This procedure was iterated until we were satisfied that the focus and position were known. A number of times during the night we would repeat this procedure and remeasure the fiber position since it would drift slowly as the differential flexure between the CCD-arm and the fiber-arm changed with the angle of the telescope.

4.3.1 Absolute Efficiency

For a number of reasons, we are interested in determining the absolute optical efficiency of our detector system. This quantity is important to understand for the astronomical goals

*This lengthy calibration was performed by Roger before our trip to Texas.
of the project since we want as high an optical efficiency as possible. By characterizing the entire optical system from end-to-end we are able to find unexpected optical losses and monitor the loss depending on the particular optical system and device configuration used.

Any absolute measurement requires a calibrated reference instrument. The instrument we use is a power meter intended for the measurement of optical losses in communication fibers. It has a calibrated germanium photodiode which determines the absolute power to 2% at wavelengths of 1.55 µm, 1.3 µm, and 850 nm over a power range of 1 µW to 4 mW. In conjunction with this power meter we purchased an adjustable-intensity 850 nm laser source. Since the power meter is calibrated only down to a power of 1 µW and our devices saturate at powers less than 1 pW, we built a calibrated attenuator with a cumulative attenuation of roughly 8 orders of magnitude at 850 nm. Our design uses two “solar filters” made to attenuate individually by a factor of roughly $10^4$. Each filter was measured independently using the laser source and power meter and then placed in series to give the required attenuation of $\sim 10^8$. When this assembly was complete, the attenuation of finished filter-stack was confirmed with an astronomy-grade CCD camera to give an attenuation of $5 \times 10^7$, therefore passing only 2 out of every 100 million photons.

The laser source with the attenuator could now be used to feed a known rate of 1.5 eV (850 nm) photons directly into the cryostat and the count rates in the pixels could be compared to the expected rate given the losses of each piece of the optical system. These lossy components, such as the optical couplers and fiber spool in the cryostat, were measured with the cryostat warm and the results used to estimate the total system efficiency. Specific measurements of the component and cumulative efficiencies are given in Section 5.2.4 when the results from the McDonald Observatory run are discussed.

### 4.3.2 Blackbody Radiation

Since our TES devices are essentially thermal devices, it is important to consider any source of heat which could adversely affect device operation. In our initial trial runs in the DR we mounted the devices vertically on the sample stage which was surrounded by the IVC can at
CHAPTER 4. EXPERIMENTAL APPARATUS

liquid-helium temperature, \( \sim 4.2 \) K. A simple calculation of the total power received by our 1 cm die by the radiation from the can gives about \( 1.8 \) nW \( \text{cm}^{-2} \). This load is not significant to the DR, however since the operating power of our devices is on the order of 10–100 fW, we should be slightly concerned about substrate heating that is on the nW level. Furthermore, a \( 20 \mu \text{m} \times 20 \mu \text{m} \) device, if it were to absorb all of the radiation falling on it from the IVC, would see a constant power of 7 fW—definitely a heat load we wish to avoid\(^*\). Pierre Colling, a post-doctoral researcher in our group at the time of our first optical measurements, added a base-temperature light shield to the cold stage to eliminate the risk of such loading. All but the first few optical TES measurements were made with this heat-shield installed.

The significance of blackbody radiation must again be considered when we envision adding fiber optic light guides to the cold stage of our cryostat. First, assume that the fiber is completely transparent with one end at 300 K and the other at the cold stage. The spectrum of the light incident on the sample then assumes the form of a 300 K blackbody source with the area of the fiber core and an emitting solid angle of \( 2\pi \cos \theta \), where \( \theta \) is the acceptance angle of the fiber\(^†\). Such a 300 K window with a diameter of 200 \( \mu \text{m} \) and an acceptance angle of 12° (N.A. of 0.22) gives a total power delivered to the cold stage of over 2 \( \mu \text{W} \)!

Fortunately, when using fibers, the situation is not nearly as grim. Standard fiber optic cables have strong IR absorption lines due to the level of OH in the glass. Additionally, the reflectivity of W increases in the IR limiting the absorbed power at long wavelengths. Roger Romani’s early estimates of the effects of the fiber absorption and W reflectivity on the blackbody loading gave some hope that a fiber-coupled optical TES would be feasible. Shown in Figure 4.4 on the following page is the transmittance of \( \sim 5 \) m of optical fiber with a high level of OH (termed a “wet” fiber). Note that at energies less than \( \sim 0.6 \) eV (wavelengths greater than \( \sim 2.0 \mu \text{m} \) the transmission becomes negligibly small. Even at 0.7 eV (1.7 \( \mu \text{m} \)) the fraction of the light that is actually absorbed by the W is down to

\(^*\)In actuality the heat loading is much lower since our W films become less absorptive at very long wavelengths. For instance, at a wavelength of 750 \( \mu \text{m} \), the peak of the 4.2 K blackbody, I estimate the absorption to be under 10\% using the skin-depth calculation of Section 4.3.6.

\(^†\)In terms of the fiber “numeric aperture”, or N.A., \( \theta = \arctan (N.A.) \).
20%. When this fiber transmission and IR reflectivity are taken into account, the same 300 K aperture described above delivers only 25 fW to the cold stage and only 3.5 fW would be absorbed if all of the light were incident on a sample of W. The resulting event rate in the W is estimated at roughly 30 kcts/s. This rate is high, though manageable when spread over a few pixels. For the optical system used at the McDonald Observatory we measured our cumulative optical efficiency from the bulkhead to the four devices to be 9% (see Section 5.2.4). The expected blackbody event rate is therefore on the order of 700 cts/s per pixel, and our observed rate was 200–400 cts/s varying from pixel-to-pixel due to the nonuniform illumination pattern.

In all of the experiments to date we have fed light to the devices through optical fibers with at least 3 m of fiber wrapped at 1 K to increase the absorption of the room-temperature blackbody radiation. Such an arrangement allows the fibers to filter enough of this radiation
to prevent undesirable device behavior. However, in the design of an image-plane instrument the problem of finding the proper filter combination is much more difficult, as evidenced by the IR loading problems encountered by the ESA group with their focal-plane array of optical STJ detectors.\textsuperscript{16,38} We are acutely aware of this IR-loading problem and are currently working to solve it.

4.3.3 Fibers and our Cryostat

In standard communications fibers there are two main types of fibers, as described by manufacturers and retailers: single-mode and multi-mode. The distinction comes about from the manner in which light propagates through the fiber at specific wavelengths. Simply, in single-mode propagation the light fills the lowest mode leading to a cross-sectional beam profile that is nearly gaussian. The ratio of the core size to light wavelength determines the criteria for single-mode propagation. It is apparent, therefore, that the classification of a fiber as single-mode must be accompanied by a specification of the single-mode “cut-off” wavelength. This cut-off is the wavelength above which the lowest mode of propagation is the only allowed mode. For wavelengths shorter than the cut-off wavelength the fiber is capable of carrying multiple modes.

We are interested in the broadband operation of fibers. For long wavelengths a specific “single-mode” fiber will, in fact, propagate only the lowest mode, but the same fiber will carry higher modes for shorter wavelengths. In this case, the distinction between single-mode and multi-mode is semantic and is more a convenient distinction of core size. Single-mode fibers typically have core sizes under about 12\,\mu m, whereas multi-mode fibers have cores from 50\,\mu m and up. In the lab we are able to use relatively high-intensity photon sources to inject light into the fibers and thus, a small fiber core does not limit the flux we are able to deliver to the test devices\textsuperscript{*}.

The use of single-mode fibers is advantageous in the lab setting since the small core allows the localization of photons simply due to the small exit aperture of the fiber. Since

\textsuperscript{*}Note that by “high-intensity photon source” I mean a source that can deliver $\sim 10^{-14}$ Watts or so into the fiber—a difficult task for our faint astronomical sources.
commercial fibers are available in sizes smaller than our pixels, the positional confinement of photons allows us to probe some of the position dependent artifacts of the devices as discussed in detail in Chapter 5.

In various tests, we have used fibers with a core diameter as low as 3 µm and as high as 200 µm. All of the fibers were terminated at room-temperature with either an SMA or ST style connector to allow easy coupling to our room-temperature light sources. The un-terminated end of the fiber was drawn through the auxiliary wiring port in our the cryostat into the inner vacuum chamber and down to the 1K pot. The choice to heat sink the fiber to the 1K stage instead of the 4K can was made by matter of convenience. The 1K pot has space available to allow up to 30 m of the tight-jacketed (∼300 µm O.D. with the polyimide buffer) fiber to be spooled snuggly around the copper pot. A bit of Dow-Corning High Vacuum Grease was applied to a section of the fiber to ensure good thermal contact between the fiber and the 1K pot.

From the 1K pot the fibers were drawn down with the SQUID wiring to the heat-exchanger coils where a spare 10–20 cm were looped to give a bit of slack to the fiber at the cold stage. The fibers were then pulled to the sample stage where they were heat sunk and strain-relieved using small coils of stiff copper wire attached to the sample stage. For cases in which we required the fibers to be better strain-relieved, a small-diameter stainless tube about 2 cm long was held by the copper coils and the fiber was passed through the tube and inserted into the alignment ferrules.

Before inserting the fiber into the ferrules, however, the fiber end must be prepared. To ensure the highest possible transmission of the light out of fiber (with minimal scattering and back-reflection), the fiber must be cleaved cleanly or connectorized and polished using fiber polishing tools. For a fiber in a connector the polishing is an easy task not requiring much more than the polishing jig and lapping films. However, for a bare (un-connectorized) fiber the preparation can be much more difficult. I have had considerable success in achieving a clean cleave for fibers with an outer diameter less than ∼125 µm using the standard cleaving procedure published by many fiber-component manufacturers (such as Amphenol).
The procedure involves applying a fair amount of tension to the fiber while lightly touching it with a diamond-tipped cleaving tool. The resulting break in the fiber often results in a smooth fiber tip that requires no further attention.

Unfortunately, the situation is quite different for fibers with an outer diameter of 200 µm or more. These large-diameter fibers tend to fracture or chip during the cleave. Instead of a low-loss fiber end we are left with a highly scattering and lossy termination. The best method for achieving a reasonable polish involves temporarily connectorizing the fiber. Using a melted hard natural pitch (such as Gugolz #73) instead of the standard permanent epoxy, the fiber is terminated with an ST connector and polished with various standard polishing films with a grit size down to 0.3 µm, following the manufacturer recommendations. Once a good polish has been achieved the connector is reheated to melt the pitch and release the fiber. The fiber end is cleaned of the pitch by careful application of kerosene using a soaked cloth. The fiber may be further cleaned using acetone and methanol until it is free of contamination. Though this method is a bit lengthy, the resulting end polish is well worth the effort.

4.3.4 Fiber-to-Fiber Coupling

Though the cryogenic fiber coupling was a particular challenge, a word should be said about the room-temperature fiber-to-fiber coupling used in this experiment as well. We initially used SMA connectors for all of the room-temperature fiber-to-fiber coupling. This style of connector is simple to use as a fiber terminator and the hermetic design allows their use as vacuum feedthroughs. Unfortunately, there are substantial limits to their optical usefulness. SMA connectors, from their original specification, have low standards regarding axial and angular misalignment. Additionally, by design, the absolute rotation angle between two coupled fibers is not preserved when the connectors are disconnected and reconnected. It is very difficult, therefore, to get reproducible low-loss connections between fibers using these connectors. We have measured losses of up to 50% per connector depending on the relative orientation of the two SMA terminators.
For large-core fibers (> 50 μm) a 5 μm axial misalignment does not significantly affect the coupling losses between two fibers. In small-core fibers (10 μm diameter or less), however, the impact of such an axial offset on coupling efficiency is much more significant. The design of the ST connector, with a rotation-key and ceramic collimating ring, reduces coupling losses to less than a few percent. Unfortunately, a source for hermetic ST adapters is not known.

To prevent the optical losses associated with the SMA coupler at the bulkhead all fiber couplers were converted to ST connectors, but the vacuum feedthrough is still provided by an SMA adapter modified as shown in Figure 4.5. A hermetic SMA adapter is bored-out and the ceramic ferrule removed. The polyimide buffer on the fibers is removed down to the bare glass and the fibers are epoxied into the SMA bore using Torr-Seal Low Vapor Pressure epoxy. This feedthrough allows multiple fibers to be inserted through a single vacuum SMA adapter and the whole assembly to be removed easily to change fiber types or replace broken fibers.

4.3.5 Fiber-to-Detector Coupling

Small-core fibers

For device tests using fibers with a core diameter less than the pixel size (< 20 μm), coupling is achieved with a ferrule mounted over the device. The ferrule, typically made of ruby or sapphire 1–3 mm in outer diameter, has a center-drilled hole with a diameter of 127 μm. This hole allows the insertion and precise alignment of 125 μm outer diameter fibers. The
ferrule is positioned using micro-manipulators under a microscope such that the hole is centered over the device. The ferrule is then glued down using Stycast 1266 epoxy and allowed to cure at room temperature for 12 hours. Once the epoxy has cured, the fiber is inserted into the ferrule until it touches the substrate. The final arrangement is shown in Figure 4.6.

This coupling method is advantageous from the standpoint of simplicity, however it has some drawbacks. Certain batches of Stycast 1266 have been seen to etch our tungsten quite effectively. Ensuring that the two parts of the epoxy are measured carefully and mixed very thoroughly reduces the severity of the etching. We also noticed that the W could be damaged by out-gassing volatiles if the epoxy is not fully cured when the assembly is mounted in the cryostat and the cryostat is evacuated. The Stycast can be cured in about 90 minutes if heated, however we found that even moderate heat (~90°C) enhances the degradation of the W by the out-gassing volatiles significantly. It was safest to be patient and allow a minimum of 12 hours from application of the epoxy to evacuation in the cryostat.

Additionally, since the fiber is in direct physical contact with the substrate, the devices and wiring can be damaged by two effects: moisture condensing between the fiber and substrate upon warming the cryostat, and physical motion of the fiber grinding at the surface. Moisture is a problem since the native oxide on the tungsten is water soluble allowing the devices to degrade when exposed to high humidity for an extended time. The condensation was not a problem if the cryostat allowed to sit warm for a few hours before opening the IVC.

The fiber contacting the substrate is obviously a problem where the glass of the fiber
chafes at the metal traces used for the wiring of the devices and breaks connections. Another problem arises from the insertion of the fiber into the ferrule. Often the edges of the fiber will chip slightly causing small glass particles to get in between the fiber tip and the devices. These crumbs of glass scatter light quite well and reduce the optical coupling from the fiber to the sensors.

And finally, for tests at the Stanford Student Observatory (see Section 5.1.4) we required the use of larger core-diameter fibers. The use of a 50 \( \mu \)m fiber is a good match to the optical point-spread function (PSF) of the 0.6 m, \( f/3.5 \) telescope available to us. Since we wished to efficiently couple a single \( \sim 20 \mu \)m pixel to this fiber, a cryogenic focusing solution was developed.

The first such focusing system is shown in Figure 4.7. A 1.8 mm diameter 3.7 mm long quarter-pitch graded-index (GRIN) rod lens* was used to collimate the fiber output. This collimated light is then focussed onto the devices with a 1.0 mm diameter spherical ball-lens†. This lens has a nominal focal length of 0.5 mm allowing high-angle focusing. The

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*Part Number 024-0340, OptoSigma Corp., 2001 Deere Avenue Santa Ana, California 92705.
†Part Number 025-0110, OptoSigma Corp.
focussed spot size from a 50 $\mu$m core fiber was measured to have a diameter of 14 $\mu$m at $\lambda \approx 550$ nm, giving a reduction by a factor of $\sim 3.5$. The combination of these two chromatic elements for focusing meant that the focussed spot size was wavelength dependent. In the red ($\lambda \approx 650$ nm) and blue ($\lambda \approx 400$ nm) the spot diameter was measured to degrade to $\sim 20 $ $\mu$m.

The lens holder itself was machined out of hardened Stycast 1266 in an effort to prevent mismatched thermal contraction between the epoxy and the lens holder. The lens holder was positioned over the devices under a microscope so that an image of the devices was roughly centered on the top surface of the GRIN lens. The lens holder was then epoxied to the Si substrate using a small amount of Stycast 1266. After waiting $\sim 6$ hours for the epoxy to harden sufficiently, a ruby ferrule was positioned under the microscope to select the device over which the fiber would be centered. This ferrule was then tacked down to the top of the GRIN lens with a small amount of Stycast 1266 as well.

This lens system solved many of the problems of the directly coupled fiber mentioned above. The epoxy was moved significantly farther from the devices and, correspondingly, the likelihood of chemical damage from the epoxy volatiles was reduced. Also, the fiber was no longer in contact with the substrate to cause damage, though the optical scattering by dirt and chips of glass between the fiber and GRIN lens was still an issue. In this design the ball-lens was in physical contact with the substrate. This was less of a problem than the sharp edges of the cleaved fiber, but still allowed the devices to be damaged or dirtied by contamination between the lens.

The final optical efficiency could be quite good with the measured losses from the assembly at around 15%—consistent with the expected reflection losses from the air-glass surfaces (see Section 5.2.4). Unfortunately, the thermal contraction of the entire epoxy assembly was too drastic to allow reliable cryogenic cycling. The assembly would typically stay attached during the initial cool-down, but break on warming. In migrating to larger-core fibers an improved design was realized to increase the thermal cycling reliability.
Figure 4.8: (a) Diagram of a machined Al optics mount for coupling a 200 µm fiber to a small (∼50 µm) set of TES pixels (b) Photograph of the assembly mounted on the sample stage of the dilution refrigerator.

Large-core fibers

Since the point-spread function of major telescopes tends to be a better match to 200 µm core fibers than 50 µm, as noted in Section 1.1, we instrumented such large-core fibers in the cryostat. However, since the heat capacity of the devices is constrained by energy resolution requirements (Section 3.2), the device area could not be scaled up to match the fiber core size. To increase our collection area and demonstrate our ability to move to more pixels, we wished to instrument four 20 µm devices simultaneously. This necessitated the implementation of a cryogenic focusing system capable of reducing the output of a 200 µm fiber to the size of approximately 50 µm.

In concept, the focusing system for the 200 µm core fibers is similar to that of the 50 µm core fibers, though the design was changed to that shown in Figure 4.8. The first order of business was to redesign the optics mount to reduce the likelihood of it separating from the substrate due to thermal cycling. Additionally, due to the risk of damage to the W by the Stycast 1266, we wished to further distance the epoxy from the devices. Both objectives were achieved by attaching the base of the optical mount to the substrate using...
long thin stand-off legs. The idea was that during thermal cycling the legs would flex to evenly distribute the strain of the material mismatch between the Al lens holder and the Si substrate. The legs were attached to the substrate with small drops of epoxy well away from any W which it might damage.

A further improvement included affixing the ball lens to the lens holder before mounting it over the devices. By using a thin (15–30 $\mu$m thick) piece of Kapton film to space the ball from a clean flat surface, the ball was epoxied to the inner wall of the mount base. Once cured, the Kapton film was removed, the GRIN lens inserted, and the assembly positioned over the devices under the microscope. Since the ball lens was no longer in contact with the devices directly there was no risk of damaging or dirtying the devices while positioning the optics.

Since we were now dealing with much larger outer diameter fibers ($\sim 250 \mu$m versus 127 $\mu$m) we chose to machine a collimating hole into the top cap of the optics mount instead of using a small ferrule. In this design, the fiber hole is centered on the GRIN lens, so the cap could be repeatedly put onto the GRIN lens and removed without disturbing the fiber alignment. This was a major advantage over having an epoxied ferrule atop the GRIN lens. This removable top-cap allowed us to clean the collimating ferrule when it gets dirty or when a fiber tip breaks off in the hole—a major setback with a permanent ferrule, sometimes necessitating discarding the GRIN lens entirely.

### 4.3.6 Detector Quantum Efficiency

Since high-QE photon-counting spectrometers have been hailed as the next detector revolution for low-flux astronomy\(^{39}\) we are of course interested in creating a system with the highest optical efficiency possible. In present form, the bare W devices are not bad. The QE is determined simply by the absorptivity of the W film. The accepted bulk-tungsten reflectivity is roughly 50% across the optical band, dropping to about 10% in the near IR.\(^{40–42}\) The reflectivity of our films was measured using an optical reflectometer to be in agreement to a few percent with the published data for the band of 400–700 nm.
In addition to the bulk absorptivity, the thin-film nature of the devices can be expected to affect the quantum efficiency. Since we are dealing with an absorptive medium that is nominally only 35 nm thick, we may need to be concerned with the photon penetration depth for long wavelengths. Using an estimate of the electromagnetic skin-depth of a metal given by Jackson,

\[ \delta = \sqrt{\frac{2}{\mu \omega \sigma}} \]  

where \( \mu \) is the material permeability, \( \omega \) is the photon angular frequency, and \( \sigma \) is the W conductivity. Using this skin-depth as a probability of photon absorption, the expected film transparency as a function of wavelength can be estimated. These quantities for a 35 nm thick W film are shown in Figure 4.9. As the skin-depth increases with wavelength, so does the transparency. At wavelengths above \( \sim 3 \mu m \) (energies below \( \sim 0.4 eV \)) the device transparency should aid slightly in reducing long-wavelength photon noise and heat loading, though the transparency is only 60% at 10 \( \mu m \).

There are traditional ways to decrease the reflectivity of a substrate across the optical band, such as dielectric anti-reflection coatings. However, it will probably be difficult to fabricate such a coating that has the proper behavior over the full operating range of the devices. For instance, Melles-Griot can coat a user substrate with a multi-layer coating which has a reflection under 2% across the band of 400–1100 nm, but the reflection increases at longer wavelengths. This may be adequate for our initial ground-based astronomical applications, but for an instrument which would have a high QE all the way from 5 \( \mu m \) (0.25 eV) to 100 nm (>12 eV) we are looking into antireflective materials which are traditionally used...
in room-temperature bolometer work. For these bolometers, primarily used for the detection of far infrared ($\lambda > 50 \mu m$), there has been a significant amount of work on making “blacks” of various metals for over 50 years. The most common of these blacks is “gold black”\textsuperscript{44,45} with a relatively simple evaporation procedure.

In a standard Au deposition where film quality is important, the chamber is evacuated using a diffusion pump and liquid-$N_2$ trap to ensure a low residual chamber pressure. In contrast, during a Au-black deposition the chamber is back-filled with 1–4 Torr of an inert gas, typically $N_2$ or He. This high pressure ensures that the Au atoms are subject to multiple scatterings before adhering to the film surface. The final film density can be as low as $10^{-4}$ the bulk density of gold with a reflectivity below 2% across the optical/IR band\textsuperscript{44,45}

In our trial depositions of Au-black we were successful in creating a stunningly absorptive film across our devices. The reflectivity of this film was measured in the band of 400–700 nm to be below that measurable by our Nanospec reflectometer. This gives an upper bound on the reflectivity of 0.1% across the optical. The resistance of the black was measured to be $\sim 10 \, k\Omega/\square$ at room temperature. Figure 4.10 shows a photograph of a 1 cm × 1 cm die with a shadow-masked region of Au-black covering some test devices. The full effect of this spongy, normal-metal coating on our devices is not known, however initial tests seem to indicate a poor electrical coupling between the device and the Au at 40 mK. We have not yet determined whether this poor coupling is due to a thin insulating barrier between the W and the Au or to intrinsic properties of this “fluffy” gold at low temperature. The
electrical and thermal properties of Au-black at low temperatures need to be studied to determine the feasibility of its use as a high-QE absorber for our devices.
Chapter 5

Results

In this chapter I present the bulk of the experimental results from the our TES spectrophotometers. The sections are presented roughly chronologically and follow our design considerations and exploration of these novel devices.

5.1 First Generation Devices

The first devices for this work were designed with the CDMS device fabrication process in mind. This fabrication procedure, outlined in Section 3.3, results in W sensors with Al wiring. W may be left covering this wiring, or, if desired, the W may be removed from the Al. A photo of our first single-pixel design is shown in Figure 5.1 on the next page. The goal was to create a simple square pixel with two Al bias lines at top and bottom of the pixel. For simplicity of fabrication, the devices were designed with 5 μm-wide bias rails. Since W is much more resistant to physical damage than Al we opted to cover nearly all the Al wiring and bonding pads with a layer of W.

5.1.1 Design Details

In this first-generation design the only portions of the wiring to have all W removed are small gaps 5 μm long where the rails meet the sensor. In operation the sensor is at its
transition temperature $T_c \approx 100 \text{mK}$ and, as such, the average electron energy is much lower than the gap energy of the Al bias rails. This high gap acts to confine thermal excitations to the active W region. If, however, the protective W overlap on the bias rails were to be extended to fully meet the active region, its lower gap would not provide adequate confinement to hot electrons in the heated electron system and could constitute an energy loss mechanism as hot electrons escape down the rail. Additionally, such W would provide a small additional current path near the rails which could complicate the electrical and thermal device characteristics.

Since TES devices had never before been used for optical spectrophotometry, our prototype design consisted of four devices of varying active area to explore a range of device sizes. As discussed in Chapter 3 the active area defines the heat capacity and, therefore, the saturation energy and energy resolution. By designing our first pixels, all square, with
linear dimension of 12 $\mu$m, 18 $\mu$m, 25 $\mu$m, and 36 $\mu$m we explored a factor of 9 in heat capacity. We successfully tested devices of each size, however the 12 $\mu$m devices were always problematic. During a significant fraction of the runs the 12 $\mu$m sensors would stay completely normal. Since these devices are so small, they have a small heat budget before they saturate. Subsequent to these first tests many noise sources in the cryostat (most significantly, microphonics and AC-pickup) have been reduced and we have successfully run square devices with a linear dimension of 10 $\mu$m.

5.1.2 First Light

![Graph](image)

Figure 5.2: First detected photons from an optical TES using an LED source. The top plot shows the device response when an AC current bias is applied to a source LED. The bottom plot is the voltage across the LED.
CHAPTER 5. RESULTS

The first tests of an optical transition-edge sensor yielded quite exciting results. Six pixels, of various sizes as described above, were wired to the six available SQUID channels. Of these six, only one (18 μm square active area) was seen to successfully go through its transition at about 80 mK and was able to be biased. As this was my first successful attempt at wiring devices, it is not terribly surprising that the remaining five pixels were nonfunctional due to wiring errors, not intrinsic device failures.

Figure 5.2 on the preceding page displays the initial observation that Sae Woo Nam and I made of this first device*. For a crude light source, a CDMS-style red LED† was placed on the cold stage of the KO-15 as to be in close proximity to the sensors. The top plot shows, in arbitrary units, the sensor response as the current was varied through the source LED. The bottom plot shows the voltage drop across the LED as the current was ramped up and down in a sawtooth-like pattern. The voltage drop across the LED is seen to plateau at ∼2 V—the turn-on voltage for the diode. At this point we can clearly see the small exponentially-decaying pulses in the sensor output. Multiple periods are shown concurrently since the average number of photons per LED current-ramp cycle was approximately one. The dip in the sensor baseline following the pulses is caused as the LED current is quickly ramped down. This large change in LED current produces a significant electrical crosstalk signal in the TES current loop. The crosstalk was able to be reduced by slowing the LED bias ramp, however fast ramping of the current ensured the LED was biased only for a short time and prevented undesirable warming of the cold stage.

For these analyses the sensor output was digitized at 10 MHz using a VXI-based Joerger digitizing card. The photon events were recorded to disk to allow offline processing. The events were filtered using digital high and low-pass filters to increase the signal-to-noise, and then binned according to peak height. These results are shown in Figure 5.3 on the next page. Normalizing the output histogram to the energy of the LED photons (∼1.92 eV) allows the estimation of the peak widths. The width of the LED peak corresponds to an energy resolution of ∼0.46 eV. The higher energy peak in the histogram near 5 eV is the

*The excitement of which prompted a 3 A.M. phone call to the Cabrera residence.
†The LED was of the same variety as is used for crystal neutralization in the CDMS experiment.
Figure 5.3: Spectrum from a red \((E \approx 1.92 \text{ eV}, \lambda \approx 650 \text{ nm})\) LED with an electronic pulser summed with the sensor output. The width of the LED peak is \(0.46 \text{ eV}\) and the width of the pulser is \(0.25 \text{ eV}\).

A signal from an electronic pulser set to give pulses with similar rise and fall time constants to the real photon events. The signal of the pulser was summed with the sensor output to provide a measure of the intrinsic device noise and was not actually heating the device in any way. As is clearly seen, the pulser peak is narrower than the peak from the photons. This pulser width corresponds to an effective resolution of \(\sim 0.25 \text{ eV}\). This gives an estimate of the intrinsic device-related baseline fluctuations independent of the spectral width of the LED source.

After this trial run the LED was removed and fiber optic cables were installed into the cryostat, as discussed in Section 4.3. For all subsequent measurements these fibers were used to provide a convenient and controllable light source. From the first runs with the fibers, and using spectrally-narrow sources, we confirmed that our measurement of the sensor resolution was limited by the use of the LED source.

Of course, the addition of fibers to the cryostat also allows the illumination of the devices with different photon energies. Figure 5.4 shows the response of a device to a blue
Figure 5.4: Current pulse from a blue photon of energy 3.1 eV (400 nm wavelength). The inset shows the characteristic $I_{\text{sensor}}$ vs. $I_{\text{bias}}$ plot.

$(E = 3.1 \text{ eV}, \lambda = 400 \text{ nm})$ photon. This device can be seen to have an ETF fall-time of approximately 30 $\mu$s. The inset of the figure shows the characteristic $I_{\text{sensor}}$ vs. $I_{\text{bias}}$ plot of the device.

### 5.1.3 Energy Response Analysis

By installing fibers into the cryostat we were able to use a variety of room-temperature sources to characterize device behavior. The primary source is a grating monochromator with either a halogen or deuterium lamp providing the light. The halogen has its UV-blocking filter removed to increase the near UV flux though the lamp is prohibitively dim for wavelengths shorter than $\sim 350 \text{ nm}$. The deuterium source has UV light extended out to beyond 180 nm. The output of the monochromator was focussed using a 5× or 10× microscope objective onto the polished end of a fiber patch cable to the cryostat.

Figure 5.5 shows the device output for varying source energies. The monochromator
grating was adjusted to provide source light at wavelengths from 800 nm to 360 nm in 20 nm increments. As the source energy is increased (back-to-front in the figure) the primary peak location increases, as expected. The linearity of this primary peak is shown in the figure inset. A secondary peak is seen to scale with energy at about half the output bin of the primary peak. Finally, a low-energy peak (at $\sim$ bin 50) is seen to emerge from the noise when the monochromator flux is low (spectra nearest the front).

The data for the front spectrum (placed near 4 eV), showing only the low-energy peak, were taken with the fiber patch cable disconnected from the cryostat and the fridge connector capped off to eliminate all room light. These photons, independent of energy, are a result of the high-energy tail of the 300 K blackbody spectrum. The dip in the spectrum below bin 50 is from the long-wavelength OH absorption in the fiber itself which prevents much light above $\lambda = 3 \mu$m from reaching the devices. This absorption is critical for our
ability to run the devices since the heat-loading from unattenuated 300 K blackbody radiation would far exceed the small (∼20–50 fW) power budget for the sensors as discussed in Section 4.3.2.

To understand the low-energy features of our devices, we performed an experiment in which two different illumination schemes were used to provide light to the devices. The two resulting spectra are shown in Figure 5.6. The upper spectrum is the device output for the case of monochromatic light illuminating the active W, Al/W bias rails, and silicon substrate nearby. This was accomplished using a fiber that was pulled back from the devices by several millimeters to provide a relatively uniform illumination of the sensor and surrounding rails and substrate. With this indiscriminate illumination, a significant number of low-collection events are clearly seen. At ∼1.2 eV, about half the energy of the direct-absorption events, is the prominent secondary “rail-hit” peak also seen in Figure 5.5 on the previous page. The events which contribute to this peak are attributed to photons absorbed by the Al/W bias rails, discussed in more detail later.

At lower energy there is a significant number of events, increasing in number with decreasing energy. These events are attributed to the small residual energy collection from events which are absorbed by the silicon substrate near the device. These substrate events form a continuum into the noise of the sensors and increase drastically in rate at lower energies. Such low energy depositions (<0.3 eV) are not individually resolved as photon events by the device. This large set of unresolved events act as a stochastic noise source
which can degrade the device resolution if not reduced.*

If we now look at the lower spectrum of Figure 5.6 on the preceding page, we see much cleaner low-energy device response. The optical coupling to this device was provided using a small-core fiber (core diameter $\sim 3\,\mu\text{m}$) in direct physical contact with the active area of the TES, as shown in Figure 4.6 on page 58. The fiber was aligned to within $5\,\mu\text{m}$ of the device center to ensure low event rates outside of the active $W$. In comparison to the upper spectrum, we see that the rail-hit events and substrate events have been reduced significantly leaving a clean noise floor below $\sim 0.5\,\text{eV}$. We should expect a higher energy resolution from a device run in this way due to the elimination of the stochastic baseline variations, however the lower spectrum shows a worse energy resolution than the upper. This broadening was caused by an unrelated noise source which cropped up between the two runs and unfortunately prevented the measurement of the intrinsic resolution of the ferruled device.

It is interesting to consider the substrate and rail events in more detail. A qualitative understanding of the substrate events is relatively simple. If we assume that the collection of energy from the substrate is due to phonons from an event in the Si reaching the device, then as the events occur farther from the active $W$ the resulting sensor response will drop. However, the area of the substrate which contributes to this collected energy increases with distance. This results in an increasing number of events at lower energies. These events can be dramatically reduced by covering the substrate with a high-reflectivity metal (such as Al). This has been tested in our more recent device designs with great success. Presumably, the substrate events can be reduced by using a high electronic-gap substrate (such as quartz, sapphire, or diamond) which is transparent across the full band of the incident light, though this has not been tested with our devices yet. Of course, there still exists the possibility of substrate-mediated thermal crosstalk between pixels in a high-density array of TES devices, though such crosstalk has not been observed so far. Such issues will need to be explored in more detail as the sensitivity of close-proximity devices is increased.

*Using a substrate that has a high electronic gap and is transparent in the optical (e.g. diamond, sapphire, quartz) could be one solution.
Figure 5.7: Normalized spectra from an 18 $\mu$m pixel for the wavelengths of 460 nm to 680 nm in 20 nm steps. Labeled are peaks from the residual room-temperature blackbody radiation, rail-hit events, and active-area events.

The rail-hit events are not as easily eliminated as the substrate events and they cause more problems for the deconvolution of data since they are of higher energy. Additionally, they are a device-related phenomenon and thus we studied them in a bit more detail. Figure 5.7 shows the central spectra from Figure 5.5 on page 72 (460 nm–680 nm in 20 nm steps) each with normalized peak height and normalized main-peak location. The similarity of the energy point-spread function (PSF) is quite apparent. The ratio of events in the rail-hit peak to the events in the direct absorption peak is constant as a function of energy and is roughly 1:3, though this underestimates the rail hits since they tail to energies below the peak. Since the two Al/W rails are each 5 $\mu$m wide and the sensor active area is 18 $\mu$m, the
expected rail-to-active ratio is $\sim 1:1.8$.

Understanding the position of the rail-hit peak requires a look at the differences between a photon absorption event in the active W and an event in the rails. By measuring the device resistance we are probing the temperature of the electron system of the active W film between the two bias rails. A photon absorbed by the active region gives its energy to an electron which rapidly scatters and distributes its energy to the electron system via electron-electron and phonon-mediated electron-electron interactions while losing a portion of the energy to phonon emission into the substrate. Since the W is not superconducting when it is biased, it has no minimum electron excitation and the thermalization proceeds until the electron system is in thermal equilibrium. Subsequently, ETF kicks in and the electron temperature is measured as it cools, as detailed in Section 3.1.1.

$$\frac{\Delta_{Al}}{\Delta_{W}} \geq \frac{\Delta_{TES}}{\Delta_{W}}$$

Figure 5.8: Diagram illustrating the energy capture process for a rail-hit event in a first-generation optical TES. Shown is a diagram of a physical cross-section of a device (bottom) and a schematic of the variation in superconducting gap parameter ($\Delta$) as a function of position (top). A photon hitting a rail breaks Cooper pairs in the rail creating hot quasiparticles, some of which get trapped by the TES and some by the inactive W.

However, if instead of being absorbed by the TES directly the photon is absorbed by the Al/W bias rails, the thermalization process is slightly different. A schematic diagram
of the process is shown in Figure 5.8 on the previous page. In contrast to the biased TES, the rails are superconducting \(T_c \approx 1\text{K}\) and have a minimum electronic excitation of \(\Delta \approx 150\text{meV per quasiparticle}\). An incoming photon (labeled \(\gamma\) in Figure 5.8) has sufficient energy to break a Cooper pair in the Al/W system creating two hot quasiparticles. These quasiparticles further disturb the Cooper pair system liberating additional quasiparticles (again losing a portion of their energy to phonons into the substrate) until the average quasiparticle energy is too small to further break Cooper pairs. Due to the existence of the energy gap the quasiparticle lifetime can be extremely long giving large diffusion lengths (hundreds of microns). Since this quasiparticle cascade is identical to the photon-absorption process in a superconducting tunnel junction (briefly discussed in Section 2.6) there has been a substantial effort made toward its understanding. Especially relevant is the work done by Paul Brink with Al films and the absorption of low-energy x-rays.

Once the quasiparticles are excited out of the paired state, they diffuse through the bias rail rapidly and will find one of two lower-gap trapping regions: the gapless TES, or the inactive-W outside the rails. When a quasiparticle enters the biased TES region it thermalizes with the electron system and its energy is measured via ETF. However, if the quasiparticle diffuses into the inactive-W region it continues its quasiparticle cascade, breaking Cooper pairs in the W and creating more quasiparticles of lower gap. These quasiparticles now have insufficient energy to surmount the high-gap Al/W rail region between them and the TES. They are trapped and eventually condense back into the superconducting ground-state losing their energy to the phonon system, unmeasured.

We can now see how to account for the half-energy peak of the rail-hit events in this first-generation geometry—approximately half of the excited quasiparticles in the rail are trapped in each low-gap region and we only measure those which enter the TES. This, of course, suggests improvements to the device design which would eliminate trapping regions other than the biased active-W region. Such a design is discussed in Section 5.1.4.
5.1.4 Observational Results

In order to illustrate the potential of these devices as unique astronomical instruments we tested a first-generation prototype on two telescopes: Blas’ personal 8-inch (0.2 m) diameter Celestron, and the 24-inch (0.6 m) diameter telescope at Stanford Student Observatory (SSO) on campus. Before working to get light from the sky, we demonstrated the working system in the lab with various calibration sources. The energy calibrations, as discussed above, were one main component of the tests. The second main component was to test the timing abilities of the device. Our first demonstration of the timing was performed using a 120 VAC neon indicator lamp powered from a wall outlet.

![Figure 5.9: Two histograms of the same data from an orange neon indicator lamp. Shown are a histogram of the photon arrival times modulo one period of the wall voltage (top) and a cumulative energy spectrum of the emitted light (bottom).](image)

Two views of a portion of this data are shown in Figure 5.9. The neon lamp “light curve” is highly pulsed with a roughly even duty cycle, as seen in the top histogram. The energy histogram shows an upper visible emission in the red and a lower IR emission, probably
thermal. The low-energy roll-off is due to the existence of a trigger threshold near \( \sim 0.5 \text{eV} \).

These two views of the data are simple projections onto the time or energy axis of our data cube. Of course, the actual time-stamp and energy of each photon is recorded allowing much more detailed off-line analyses.

![Graphs showing astronomical data](image)

**Figure 5.10**: First spectra of astronomical objects using a cryogenic spectrophotometer, taken the night of June 16, 1998.

Our first astronomical application of these devices was a relatively simple one. The cryostat was kept in the Varian Building basement as usual and we attached a 40 m fiber between the cryostat and the physics “beach” just outside the building. The fiber had a small (7 \( \mu \text{m} \)) core and was coupled to the center of a 25 \( \mu \text{m} \) device to reduce the low-energy rail and substrate events. From our vantage point on the beach we were able to see a small portion of the sky with Blas’ 8-inch telescope. A summary of the data taken during this run is shown in Figure 5.10. The top two spectra are zeroth magnitude stars—Arcturus, with a red spectrum and Vega with a blue spectrum. The color difference of these two stars is quite
apparent in our observed spectra. Next on the left is a spectrum of a magnitude 8 planetary nebula (NGC6572) with a slew of strong emission lines. The highest energy peak near bin 430 is a combination of the strong OIII (500.7 nm, 2.48 eV) and Hβ (486.1 nm, 2.55 eV) emission lines. The next peak down (bin 350) is a combination of OI (630.0 nm, 1.97 eV), OII (∼ 732 nm, 1.70 eV), and Hα (656.3 nm, 1.89 eV). The remaining two peaks below bin 300 are due to the sky background, as can be seen in the histogram labeled “sky background”. The “street-lamp” spectrum was taken by aiming the fiber toward a nearby street-lamp. Evidence of the bright lines of the lamp can be seen to contribute to the sky background spectrum. The final histogram is an energy calibration spectrum from the monochromator set for 1 eV (1.24 µm) with three additional higher orders visible. This spectrum is on a log-plot to show the higher orders clearly.

These tests were quite exciting, though they were not valuable for the astronomical results. To get a taste for the potential astronomical value of our TES photon counters, an ambitious effort was made to move the setup to a more serious telescope. All of the pieces of our trial system were assembled together for the observing run: the prototype DAQ, machined-Stycast 1266 GRIN/Ball lens holder, and 15 meters of cold 50 µm core high-OH fiber. In the winter of 1998-1999 the dilution refrigerator was packed into a truck and transported to the SSO. This facility was convenient for our first serious attempts at astrophysically-interesting data since we were not far from home-base when unexpected problems arose.

Our first challenge at the observatory was the need for 3-phase 220 VAC power for the sealed rotary pump which circulates the mixture in the dilution fridge. Since the observatory was wired for residential (single-phase) 240 VAC used by the electric heaters, we wished to use a phase-converter to generate the 3-phase power required to run the pump. After a month of failed attempts to use the phase-converter with a spare pump we found that the magnetic switch for the pump would not stay on when wired into the derived third phase line. A simple permutation of the pump wiring (ensuring that the pump would still rotate the correct direction) allowed the pump to start up and give no further problems.
Unfortunately a working phase-converter increases the power requirements for the system. Care had to be taken to never run the leak detector, sealed pump with phase-converter, and the heat-gun at the same time or the circuit breaker would enforce this for us.

Electrical challenges aside, the disassembly and reassembly of the DR went well, though we did lose enough \(^3\text{He}/\(^4\text{He}\) mixture through mistakes in the disassembly to require the addition of some \(^3\text{He}\) at the observatory. Since the fridge itself is run in a storage dewar (which has wheels) we felt it could be conveniently and safely transported in the dewar, and at 4 K. We already had a device in the cryostat that was characterized and optically coupled well to the 50 \(\mu\text{m}\) fiber, so if all went well the entire cryostat could be transported at 4 K and recooled with a minimum of effort at the SSO. Not surprisingly, once we cooled the device to 40 mK and tested the system we found that the optical efficiency was terrible, implying that the lens system had moved during transport. We warmed up, performed a bit of repair work at the observatory and back at the lab, and were able to cool a working device in late December of 1998.

The primary object we set out to observe was the Crab Pulsar (PSR B0531+21). This object is a familiar bright time-variable source which allows the full testing of the abilities of our new instrument. It has a well-known optical spectrum and light-curve (intensity vs. time). Our observation of this object would constitute a success on a number of fronts. This would be the first astronomical application of an energy-resolving photon counter (cryogenic or not), the first simultaneous IR-optical-UV measurement of the Crab ever made, and, more personally, the completion of a major milestone of the optical TES project by our group.

Guiding the telescope to our desired location turned out to be more difficult than anticipated. Even though the fiber position was monitored using a beam-splitter and CCD as discussed in Section 4.3, this only provided integrated positioning information on the minute time-scale, so at any instant we did not have enough information to determine the position of our target object. Therefore, using the CCD for anything other than rough alignment was not feasible. Additionally, the telescope did not have an operational periodic-error correction system for the guiding causing relatively large positional shifts on the minute
time-scale. As it turned out, the easiest way to determine whether we had the telescope adequately positioned on the source was the count rate in the TES itself. With a single aperture on the sky it was not possible to determine the correct direction to drive the telescope in order to maximize the flux without dithering the telescope around the object. The telescope was able to respond to guiding commands on the few-second time-scale, so we continually adjusted the pointing manually in an attempt to keep the photon rate as high as possible.

![Normalized Photon Count vs Pulsar Phase](image)

Figure 5.11: Light-curve of the Crab Pulsar from the Stanford Student Observatory. Shown are an IR band 0.7–0.9 eV (1.4–1.75 µm) and an optical band 1.6–3.3 eV (375–775 nm). The band distinction was made in software offline as all photons in the range from 0.7 eV to 3.3 eV were recorded simultaneously. Figure courtesy of Roger Romani.

On the night of December 28, 1998 we made our first successful detection of the Crab Pulsar. This first night we had an average photon rate from the pulsar of only 18 cts/s on a
background of $\sim 300\text{cts/s}$, but by averaging over many cycles of the pulsar the distinctive lightcurve of the Crab emerged. On subsequent nights in December and early January, after improving the telescope focus and improving our skill at rate-assisted manual guiding, we achieved a peak count rate of $120\text{cts/s}$ from the pulsar.

In general, since we record the time and energy of each photon independently we are able to make energy cuts and perform the phase-averaging of the data offline. This gives us the flexibility to average together the highest signal-to-noise portions of the data, contiguous or not. Shown in Figure 5.11 is a distilled result from the SSO runs. Shown is the familiar light-curve from the Crab Pulsar in two bands, and IR band from $0.7-0.9\text{eV}$ ($1.4-1.75\mu\text{m}$) and an optical/UV band from $1.6-3.3\text{eV}$ ($375-775\text{nm}$). Notice the apparent reduction of flux in the IR relative to the optical band. This lack of IR flux could be indicative of IR self-absorption of the pulsar plasma itself. This measurement marks the first simultaneous IR/optical observation of the Crab Pulsar. The ability to make a simultaneous wide-band observation significantly reduces the systematic errors when performing a comparison of the chromatic variations of a source. Any time-dependent effects in the system (e.g. device-related drifts, or changes in seeing conditions), to first order, will affect all bands equally. However, due to the chromaticity of the atmosphere itself, there can be external chromatic variations which are not able to be detected by our use of a single aperture on the sky. Such effects could account for the suppression of the IR flux since we were actively guiding the telescope by count rate. Using this procedure we will systematically collect more photons in the energy band where the flux is the highest. Future multi-pixel imaging arrays will aid in the reduction of these errors by allowing the collection of all energies using multiple pixels.

### 5.2 Second Generation Devices

The second generation optical TES devices were designed with the possibility in mind of their use at the focal plane of a telescope. This guided the design toward higher pixel counts and a high filling-factor while incorporating the new information obtained from the
first generation devices. The final result of these changes is shown in Figure 5.12 with details covered in the following sections.

5.2.1 Design Details

A detailed view of a subset of the second-generation array was shown in Figure 3.1 on page 18. In comparison to the first generation devices, the bias rails were made much narrower, as were the gaps between pixels. A concerted effort went into testing and refining the fabrication process to ensure the 1 $\mu$m wiring was intact for the final devices. The central pixels have a center-to-center spacing of 21 $\mu$m which, eliminating the rails from the active area, gives a filling-factor at the center of 82%. The filling-factor drops by 9% per column toward the edges. If the central 36 pixels are wired in this manner the total filling-factor is approximately 73%. For our initial tests with this array we planned to instrument only
four central pixels giving the 82% filling-factor.

Similar to the first generation devices, the bias rails were covered with a protective layer of W to make them more robust and to ensure good electrical contact between the Al and W. In this design, however, the inactive-W overlap was removed. The efficiency of trapping energy from the Al into the W was measured in prior quasiparticle diffusion and trapping experiments by our group to be better than 90%. This high trapping efficiency combined with the elimination of the inactive-W gave us the expectation that we would see good energy collection from a rail-hit event. Ideally, this collection would match the collection of the active-W region giving no satellite peaks to our active-W peak. If this were the case, the filling-factor would improve by 9% for the entire array since the area of the rails would not need to be rejected.

In order to increase the filling-factor, the pixels in a row share a common ground rail with a small 1 \( \mu \text{m} \times 1 \mu \text{m} \) bare Al square to prevent quasiparticle leakage between pixels. When we tested pairs of shared-rail pixels from this design it became apparent that there was significant thermal coupling between the devices, sometimes so great that biasing two adjacent pixels simultaneously was impossible. The reason may be that the 1 \( \mu \text{m} \) Al does not provide an adequate potential barrier to hot quasiparticles injected into the rails by the biased TES. It is possible, due to the proximity effect, that the gap of the Al square is sufficiently suppressed by the nearby biased TES and Al/W rails that it becomes a much narrower quasiparticle barrier than its physical 1 \( \mu \text{m} \) extent. Future shared-rails designs would need to include longer (3–5 \( \mu \text{m} \)) stretches of Al to thermally isolate the devices, however this will not solve all of the problems with having a shared rail. The electrical crosstalk of pixels which share a bias rail has been measured to be as large as 5% due to the common parasitic resistance of the shared ground. The combination of thermal and electrical cross-talk from the shared rail may necessitate separate bias and return lines for each pixel. Unfortunately, adding additional wires to each pixel impacts the spatial filling-factor of the array significantly until designs which allow larger pixels or buried-wiring structures can be implemented.
The procedure used to fabricate these second generation devices was similar to that used for the first generation devices. The few changes included migrating to 10 cm diameter wafers instead of 8 cm wafers, and the use of a full-wafer contact mask aligner instead of a projection aligner. Unfortunately, we encountered numerous difficulties with the contact aligner including photoresist adhesion to the mask, exposure nonuniformities, and inconsistent die-to-die alignment. For our recent fabrication process we have moved back to the projection aligner with great success.

5.2.2 Energy Response Analysis

To test the energy PSF of the new design we used the improved two-piece machined-Al optical mount as discussed in Section 4.3.5 together with 200 μm fibers. The combination of the high fraction of substrate area covered by devices, and the well-focused fiber spot resulted in a low rate of substrate events. A typical spectrum is shown in Figure 5.13. Labeled from low-energy to high energy, are the Planck blackbody events, events from room-light leaking into the fiber, active-W events, and a higher-energy satellite peak that we can only conclude are the rail-hit events*. 

In the first generation devices the peak collection from a rail absorption event was about 53%. Since we eliminated the inactive-W trapping region in this new design, we expected

*The ratio of the counts in the satellite peak to main peak depends a bit on the illumination pattern, but always comes out near the expected ratio of $\frac{1}{11} \approx 0.11$
nearly 100% collection of the rail-hit energy and, hopefully, no low-energy PSF artifacts. In fact, the new design eliminated all low-energy rail artifacts, but as seen in Figure 5.13, we introduced a new high-energy artifact.

I was quite surprised to see the energy collection of the rails actually exceed the collection of the active area. Blas suggested the following elegant explanation. The difference between the energy-capture process in a rail hit event and a direct TES event is illustrated schematically in Figure 5.14. The right side of the figure is meant to illustrate an absorption event in the TES itself. As discussed in Section 5.1.3, the photon ($\gamma$) gives its energy to an electron in the W which rapidly thermalizes with the other electrons in the (gapless) biased TES. During this thermalization process approximately 58% ($1 - \varepsilon$) of the initial photon energy escapes into the substrate by phonon emission and is not recovered.

![Figure 5.14: Illustration of the energy capture process for rail-hit events and active-area events in a second-generation optical TES. In a rail hit (left side) a portion of the above-gap phonons produced in the quasiparticle cascade are recaptured via quasiparticle excitation in the Al. In contrast, in a direct TES event (right side) high-energy phonons have a greater chance of escaping the thin W film.](image)

For absorption in the rail, a photon breaks a Cooper pair in the top 30nm or so of
the rail creating high-energy quasiparticles which cascade (emitting phonons) down to the Al/W gap. These quasiparticles rapidly diffuse to the only trapping region nearby and give their energy to the TES to be measured, as expected. However, the phonons emitted during the quasiparticle cascade, instead of being able to exit immediately into the substrate must travel down through the rail itself before escaping into the substrate. Many of these phonons are of sufficient energy to break Cooper pairs in the bulk of the rail creating additional quasiparticles which can diffuse to the TES and contribute their energy to the W electron system. This process has been measured to recover over 20% of phonon energy that is lost in a direct-absorption event. This corresponds to the recovery of an additional 12% of the initial photon energy*. The higher energy-collection efficiency of the rails produces an undesirable high-energy satellite peak in our energy PSF.

Another undesirable feature of these devices, it appeared, was degradation in energy resolution from the 0.15 eV FWHM observed in the first-generation devices to the 0.20 eV or so routinely seen in tests of these devices. I now think this not a device issue, but a consequence of changing bias-resistor arrangements as alluded to in Section 3.2.2. Most of the first-generation device tests used a combination of four 20 mΩ shunt resistors at 1K and two 5 mΩ resistors at 40 mK for the six SQUID channels, with the two 5 mΩ channels used most heavily for important devices. During the testing cycle of the second-generation devices the original Hypres SQUID-array amplifiers, mounted on the 1K pot, were replaced with higher-performance NIST SQUID array amplifiers. At the same time the six channels were all wired to use the 10 mΩ shunt resistors integrated on the SQUID amplifier chip. As shown in Section 3.2.2 the noise contribution of a 10 mΩ, 1K shunt resistor is significant, the impact of which was not realized until recently.

5.2.3 Response Function Modeling

For the observing run at the McDonald Observatory we implemented four devices, each with a PSF nearly identical to that shown in Figure 5.13 on page 86. The low-energy device

*This higher collection of initial photon energy in the rails suggests alternative pixel designs which exploit this increased energy collection.
response is fairly clean, however the higher-energy rail peak causes problems above the main peak. There is significant “pollution” of real high-energy events by the rail hits from lower energy photons. The problem is exacerbated by the fact that the low-intensity blue flux from some faint astronomical sources is of great interest and, therefore, the number of real high-energy photons from these faint sources is small and is easily diluted by rail-hits from lower energies. Since the rail-events are identical in pulse-shape to direct TES events, they cannot be removed from the data on an event-by-event basis. The best we can hope to achieve is a statistical removal off-line, which requires a good model of the energy point-spread function.

The approach I took for modeling the PSF was to define a high-collection (rail) region and a lower collection (sensor) region with a simple gaussian “blurring” of the energy collection in the transition region between the two. The choice of a gaussian was made with the assumption that the heat from the initial event would isotropically diffuse outward from the event location to a characteristic size before cooling below the Al/W gap. Under this assumption, the energy distribution assumes a gaussian profile. The portion of the gaussian that is in the rail region has a high collection efficiency and the portion in the active region has a low collection efficiency. Therefore, for each position in the sensor we can estimate the total energy collection efficiency.

To further simplify the model I assume that the collection efficiency does not depend on the distance from the edge of the device, just the distance from the rail (i.e. the collection is independent of position along the rail). This leaves us with a one-dimensional efficiency relation of the form

$$
\varepsilon(x) = \varepsilon_s + \frac{\varepsilon_r - \varepsilon_s}{2} \text{erfc} \left( \frac{x}{\sqrt{2 \sigma}} \right)
$$

(5.1)

where $\varepsilon_r$ and $\varepsilon_s$ are the rail and sensor efficiency respectively, and $\sigma$ is the standard deviation of the gaussian describing the heat-diffusion. This equation is only valid for the range of $x = -W_r$ to $x = +W_s$, where $W_r$ is the width of one rail and $W_s$ is the half-width of the active-W. The model assumes that the two rails are identical and the device, therefore, has
a reflection symmetry about $x = +W_s$. In this case, Equation 5.1 can be used to model the noiseless energy-response of the entire device. Once the noiseless PSF is determined, it may be convolved with a gaussian to model the intrinsic sensor noise.

Normalizing the sensor active area $W_s$ and active-$W$ collection efficiency $\varepsilon_s$ each to unity, the model has five free parameters: relative rail area $W_r$, relative rail collection efficiency $\varepsilon_r$, gaussian “blurring” width $\sigma$, device resolution, and photon energy. A least-squares minimization between the model and a sample of the data is shown in Figure 5.15. Note that in the figure the noiseless PSF histogram has been scaled up by a factor of five to allow
the inter-peak region to be seen. The parameters used for the model, scaling back into real units, are:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>photon energy</td>
<td>2.023 eV</td>
</tr>
<tr>
<td>relative sensor efficiency, $\varepsilon_s$</td>
<td>1.0</td>
</tr>
<tr>
<td>relative rail efficiency, $\varepsilon_r$</td>
<td>1.282</td>
</tr>
<tr>
<td>sensor area, $W_s$</td>
<td>9 $\mu$m</td>
</tr>
<tr>
<td>rail area, $W_r$</td>
<td>0.8 $\mu$m</td>
</tr>
<tr>
<td>hot-electron diffusion FWHM, $2\sqrt{2\ln 2}\sigma$</td>
<td>0.77 $\mu$m</td>
</tr>
<tr>
<td>gaussian noise FWHM</td>
<td>0.195 eV</td>
</tr>
</tbody>
</table>

Shown in the figure are both the PSF model including the device noise and the noiseless PSF. It is interesting to note that the noiseless PSF rail efficiency appears higher than a simple gaussian fit to the rail-hit peak would indicate. This shift is simply due to the large ratio of inter-peak events to rail-hit events. This continuum of events shifts the rail-hit peak to lower energy when convolving the noiseless PSF with the gaussian noise. This shift to higher energies is less noticeable in the main peak since the ratio of peak events to inter-peak events is much greater.

Given the parameters above we can fit a single energy-PSF fairly well. However, to model the full energy response of a device we must require some additional information. First, each of the devices is not perfectly linear and so energy calibrations were done to provide enough information to linearize the device response. It is important that the devices be calibrated against an absolute scale to ensure that all of the spectra can be compared and possibly combined together into one spectrum. Ideally the devices are all identical when they are fabricated and should give the similar results for linearity and intrinsic resolution. In the fabrication so far, this has not been the case. The devices are quite similar, however the specific shape of the and $T_c$ of the superconducting transition vary slightly from pixel to pixel. Therefore the parameters used for the linearization are slightly different for each device. This variability means that, assuming the devices have the same intrinsic resolution,
the effective device resolution as a function of energy may vary pixel-to-pixel. This energy-resolution degradation is one of the additional parameters used to characterize each pixel and create a device energy-response matrix.

Finally, as discussed in Section 4.3.5, due to the highly chromatic focusing elements used to couple the fiber to the detectors the focussed spot size varies with photon energy. This chromaticity can cause the rail-hit fraction to vary significantly with energy as, say, one rail is illuminated by blue light, but both rails are illuminated by infrared. The dependence of rail-hit fraction on energy was the final parameter used to fully characterize the device response.

All of the necessary parameters just discussed were extracted by using calibration spectra of various types. The position of the main peak as a function of energy was determined primarily from a monochromator set for 0.5 eV (2.48 μm) light, with higher orders. Though the first order from the 0.5 eV setting is fully absorbed by the fiber, the high density of the higher orders gave six active-area peaks to use for a linearity measurement. However, at higher orders the rail-hit peak is of sufficient energy to be superimposed on the active-area peak of lower energy and, therefore, the 0.5 eV spacing is too small to allow the extraction of meaningful information about the rail events. For the rail-hit parameters (rail-hit fraction, rail-hit position) the monochromator was set to give energies spaced at 1 eV (1.24 μm) and ∼2 eV (612 nm).

With these spectra a decent job was done of characterizing the four devices used for the observing run. Of course, in hindsight, further calibrations should have been made in order to better characterize the IR device response. Since there is a window in the fiber absorption at 0.7–0.8 eV (1.55–1.75 μm) and none of the calibration sources mentioned above have a line which falls in this region, a special calibration setting of 0.75 eV (1.65 μm) or so would have been convenient for the IR characterization. As it was, the lowest energy calibration available was the 1 eV first-order peak, even though we were required to calibrate the observational data down to 0.7 eV.

Figure 5.16 on the following page shows the end result of the PSF model for a particular
pixel and illumination. Shown are the modeled PSFs of unit area for photon energies of 0.5 eV, 1.5 eV, 2.5 eV, and 3.5 eV corresponding to wavelengths of 2.48 µm, 827 nm, 496 nm, and 354 nm respectively.

This simple empirical model does a good job of fitting the PSF shape, however it is not perfect. The model tends to systematically overestimate the photons in the inter-peak region near the rail-hit peak, as evidenced by the slight overshoot of the model at $\sim 2.4$ eV in Figure 5.15. Time could be spent refining the model to include further adjustments, however the correct long-term approach is to design a device and optical system which eliminate these artifacts altogether. Various plans toward this end are described in Section 6.

### 5.2.4 Observational Results

In January of 2000 we again packed the cryostat into a truck to head to the McDonald Observatory in west Texas. Though not conceptually much more difficult than packing up to observe at the SSO, this run was very different. As opposed to the indefinite-duration run at the SSO, we had only seven nights of observing time at McDonald. We no longer
had the benefit of being able to lope down to the lab in Varian to repair broken essentials, so we packed and moved enough equipment to allow the most critical of such repairs to be made on location.

Not only was the duration of our run at McDonald fixed, but the dates were also fixed. As problems cropped up to delay our lab-testing schedule we had to sacrifice some device calibrations in order to ensure we had working devices to run at the telescope. In the end, the entire system of four pixels, with the new digital SQUID feedback system from NIST, was only briefly characterized before we had to leave for the observatory. Nevertheless, we were graced with three nights whereby the combination of clear skies and a complete working system provided over 375 million recorded photons from a variety of sources.

As discussed in Chapter 4, the digital SQUID feedback system allowed the readout of four channels simultaneously. Since our cryogenic optics were only capable of focusing the output of the 200 $\mu$m fiber down to a diameter of about 60 $\mu$m and the implemented devices were each $20 \times 20 \mu m$, we were unable to collect all of the light with only four devices. However, the cryostat was instrumented with six SQUID channels, and thus we were able to wire six pixels, measure the relative count rates in the pixels, and choose the four pixels with the highest optical efficiency.

The dilution refrigerator was transported in a custom-made wooden shipping crate with the devices packaged separately. Before leaving for the observatory, two independent device mounts were fully prepared. Each had its cryogenic optics package (as shown in Figure 4.8 on page 61) positioned and epoxied in place and had six or more pixels wire-bonded. These two device packages were tested in the two weeks prior to packing up the lab and a primary and secondary array were chosen based on the device operating characteristics. The primary array had all six pixels in good working order with similar $T_c$ among the devices ($\sim 65$ mK) and, correspondingly, similar ETF recovery times ($\tau_{etf} \approx 5 \mu s$). In this preliminary lab test, the optical coupling efficiency was measured using the calibrated photon source to be about 3% from the bulkhead to the devices. This includes all fiber transmission losses, reflection

*Thanks to Mike Hennessy for his capable hands.
losses from the lens surfaces, 50% reflection from the W, and incomplete area coverage by the devices. This coupling efficiency was lower than expected, but would be adequate for the observations.

The secondary array was much less exciting. There were five working pixels, however the operating characteristics were not consistent. The decay times varied from 10 µs in one pixel to over 50 µs in another. The high-current behavior was indicative of bias rail nonuniformities causing the rails to be driven normal at higher currents. Additionally, the device I-V curves indicated non-ideal power dissipation and device resistances. Not surprisingly, the energy resolution of these devices was degraded. Two pixels were determined to be acceptable with the per pixel optical efficiency slightly higher than that measured for the primary array but with the total optical efficiency for the two devices together at only 2%.

After our first cool-down at McDonald Observatory we measured an optical efficiency that was a factor of 3.1 reduced from our peak efficiency of 3% at Stanford. This < 1% efficiency was confirmed on our first night of observation when the flux from the astronomical sources as well as the sky itself came in well under expectations. The decision was made to warm the probe, inspect the cryogenic optics, repolish the fiber, and cool again in an attempt improve the optical coupling, hopefully with a minimum of effort. Upon opening the IVC, however, we could see that the cryogenic optics mount had broken off of the substrate during warm-up requiring us to start at ground-zero with the realigning of the optics to the pixels.

This was probably a blessing in disguise since we had the opportunity now to inspect, clean, and realign each optical component, though it was a bit risky with the limited equipment on hand. The GRIN/ball-lens assembly was carefully disassembled, cleaned, reassembled, and realigned to the devices under a microscope. The lens assembly was then epoxied back onto the substrate using 5-minute epoxy. The fibers throughput was measured and the cryogenic end was polished. This was the first time we had used the pitched-connector polishing technique discussed in Section 4.3.3. This gave an extremely clean polish to the fiber end. The result of this careful reassembly and cool was an increase
CHAPTER 5. RESULTS

<table>
<thead>
<tr>
<th>Source-to-GRIN transmission</th>
<th>75%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmission into GRIN lens ($n_{grin} \approx 1.6$)</td>
<td>95%</td>
</tr>
<tr>
<td>Transmission out of GRIN-lens</td>
<td>95%</td>
</tr>
<tr>
<td>Transmission into ball-lens ($n_{ball} = 1.86$)</td>
<td>91%</td>
</tr>
<tr>
<td>Transmission out of ball-lens</td>
<td>91%</td>
</tr>
<tr>
<td>W absorption</td>
<td>50%</td>
</tr>
<tr>
<td>Area of focussed spot covered by pixels</td>
<td>44%</td>
</tr>
<tr>
<td><strong>Cumulative efficiency</strong></td>
<td><strong>12%</strong></td>
</tr>
</tbody>
</table>

Table 5.1: Expected optical inefficiencies when coupling light from a the cryostat bulkhead to the devices.

in the optical efficiency to 9%—about a factor of 10 over the previous cool-down, and a factor of 3 better than we had ever achieved in the lab.

The expected optical efficiency was estimated from a combination of fiber throughput measurements, reflection-loss calculations for the vacuum-glass interfaces, and measured pixel area coverage. Table 5.1 lists the component and cumulative efficiencies for the final optical setup used at the observatory. The final measured efficiency of 9% was close enough to the calculated 12% efficiency to satisfy us that all major sources of light loss had been determined. Since we wished to collect more light from the focus of the telescope by using a larger aperture than even the 200 $\mu$m core fiber into the cryostat, we used a 400 $\mu$m to 200 $\mu$m tapered fiber. The 400 $\mu$m, $f/18$ feed from the telescope emerges from the taper as a 200 $\mu$m, $f/9$ beam—well within the $\sim f/3$ acceptance of the cryostat fiber. Unfortunately, for unknown reasons, the coupling between this tapered fiber and the 200 $\mu$m fiber to the cryostat was quite poor, losing half of the incoming light. This led to a maximum efficiency on the sky of roughly 4%.

Even with this somewhat disappointing absolute efficiency we were able to obtain interesting results from some of the nights’ observations. The crab pulsar was still a major target since it provides a well-known calibration source for our acquisition system. Since the time behavior of the pulsar is very well documented using the radio signal our measurements of the pulsar timing could be confirmed against these radio measurements.\(^{46}\)

As discussed in Section 5.2.2, the energy PSF of the devices was not as simple as we would
have liked. In theory, direct deconvolution of the PSF from the data is possible, however this method is traditionally unstable due to the high-frequency bin-to-bin fluctuations inherent in real data. More stable methods must be used to remove the effects of the PSF from underlying spectrum. Effort was put into two different methods—direct PSF subtraction and a filtered deconvolution technique described by Kahn and Blisset developed for the deconvolution of X-ray spectra. These two techniques were explored thoroughly, though they tended to have residual artifacts and undesirable error propagation. As a consequence, these techniques were eventually abandoned in favor of convolving a hypothetical source spectrum with the PSF model of Section 5.2.3 and comparing the result to the data directly.

Though the full analysis is not complete, the Crab Pulsar data is impressive. We used the Crab as a convenient test target at the beginning of each night. A phase-averaged summary of the best portion of these data are presented in Figure 5.17 on the following page. The upper histogram shows all of the events during the $\sim 3400$ s over which these data were recorded. Since the source is highly pulsed a small section of pre-pulse phase bins may be averaged together and subtracted from all of the data. This procedure allows the constant (non-time-variable) spectral features to be effectively removed from the histogram. The result of this subtraction is shown in the bottom histogram of Figure 5.17. Since these data have not been corrected for the extinction due to fiber absorption, strong spectral dips are seen around $1$ eV and below.
Figure 5.17: Crab Pulsar (PSR B0531+21) time and energy histogram for a live-time of $\sim 3400$ s at the McDonald Observatory. Shown is the raw phase-averaged data (top) and the off-pulse sky subtracted data (bottom).
Chapter 6

Conclusions

This work has been quite exciting. In just over four years we have demonstrated the operation first TES devices for use as broadband, fast spectrophotometers—both in laboratory tests and in “the field” as a novel astronomical instrument. The rapid progress of this optical TES project continues the legacy of success of TES devices in other fields. Because this project is young, the most exciting developments and device revolutions are yet to come. To get a taste of the future, below I outline a few of the foreseeable developments.

One of the primary lessons learned from the experiments to date is the importance of a clean energy PSF to the proper deconvolution of the data. In the regions of the spectrum where the source flux is low (but important) or the device sensitivity is low we desire very few false events. Ideally, fewer than 1% of the high-rate events would be falsely tagged as low-rate events. Obviously, the present high-energy rail-hit fraction of \(\sim 10\%\) is catastrophic to the low-flux region of the UV.

Figure 6.1 shows one idea for reducing the significance of would-be rail-hit events. Following the standard W-TES fabrication process, layers of a low-temperature insulator (e.g. a-Si) and Al are deposited over the finished devices. Using the same mask, the Al and insulator are patterned and removed only over the active-W area of the sensors. Therefore, the bias rails and substrate are shielded from direct illumination. Since the Al is \(\sim 90\%\)
reflective, a good fraction of the incoming photons which would have produced rail or substrate artifacts are eliminated altogether. The remaining 10% that are absorbed thermalize rapidly in the Al. This thermal signal can only communicate with the TES via the phonon system since the Al is electrically isolated from the TES system. At worst, this signal should appear in the TES as a substrate event at low enough energy collection to be effectively rejected.

Such masking has the significant drawback, however, of reducing the filling-factor of closely-packed sensors. An alternate micro-machined rail mask is being pursued in which the Al mask, instead of reflecting the rail photons away, deflect the photons into the active area of the sensors. Such a masking concentrator has the potential to increase the array filling-factor to nearly 100% while simultaneously eliminating the rail hits.27

Instead of being used to mask the rails, the secondary Al layer, as described above, could instead be used for pixel wiring. In such a four-mask design the pixel wiring would be able to run over the pixels and out to bonding pads allowing a high filling-factor and high pixel-count. In such a configuration, the pixels would need to be illuminated through the substrate and, hence, development of TES

Figure 6.1: Diagram of three-mask W-TES device with a-Si/Al masking layer to prevent unwanted rail-hit events. (Not to scale)
devices on transparent substrates (e.g., quartz, sapphire, diamond) needs to be demonstrated*. Unfortunately, illumination through the substrate makes rail masking difficult. From the underside, the rails are Al, so the rail-hit fraction is expected to drop to $\sim 2\%$ from 10% which may be acceptable for certain applications.

Other properties of the device performance may be able to be improved in new designs as well. As discussed in Section 3.2.1 the energy resolution of our devices is proportional to our energy collection efficiency $\varepsilon$. Since $\varepsilon$ is estimated at 0.42 we can make over a factor of two improvement to the energy resolution by increasing our energy collection. Researchers using TES devices in the x-ray band routinely fabricate their devices on low-stress silicon nitride membranes to allow detailed control over the dominant thermal impedance of the system. Since these groups do not use electron-phonon decoupling as the thermal bottleneck in device operation, such measures are necessary for proper device operation. We wish to continue using electron-phonon decoupling as the dominant thermal impedance in our W-TES devices. However, isolating a W-TES on a membrane may provide just enough of a barrier to allow the high-energy phonons to thermalize in the W electron system while providing the device with a good thermal heat-sink to the surrounding substrate. Any improvement from such an arrangement translates directly into improved energy resolution.

Though this thesis describes the technical work done on this project, it has not detailed the exciting applications of the completed instrument. This is primarily due to my lack of a full understanding of the impact such an instrument will have on faint-object astrophysics. As with the development of any new physical instrument, we may have to wait quite some time before the scientific importance of this instrument is fully realized. However, it is apparent from the interest of the astrophysical community in this instrument that our research efforts may be on the right track to developing a near-ideal IR/optical/UV imaging spectrophotometer.

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*At present, our W films have demonstrated acceptable $T_c$'s on Si, Ge, a-Si, and Silicon Nitride.
Appendix A

First Generation DAQ

Our prototype data acquisition system was built, instead of purchased, for the primary reason of cost. Additionally, however, the ideal commercial acquisition system capable of the simultaneous time- and energy-tagging of events did not exist. The requisite capabilities could have been provided by multiple components (such as existing NIM or CAMAC amplifiers and scalers), but the completed system would not have been easily scaled to more than a single channel and would have been prohibitively expensive.

The decision was made to prototype a DAQ system ourselves. The design goals of this system were as follows:

- Compact for easy transport
- Scalable to four channels
- Capable of the logging time-of-arrival and energy of up to $10^4$ photons/sec per channel
- Less than $\$10K$ for a four-channel system.

Since we wish to determine the time of each arriving photon to \(~1\mu\text{s}\) and eventually reference each to absolute UTC, a time reference is provided by a Datum BC647PCI GPS-conditioned time and frequency processor card. This card is placed into the acquisition
computer and provides a GPS-synchronized external 10 MHz clock signal that drives the DAQ circuitry. Figure A.1 shows the schematic of this digitizing and scaler circuitry.

Also in the host computer is a National Instruments DIO-32-HS digital interface board. The DAQ circuitry connects to this interface board via 32 digital I/O lines and 2 handshaking lines. The handshaking and data flow is controlled by a Microchip brand PIC 16C84 which uses the 10 MHz GPS signal as its processor clock. Due to the timing constraints of this processor and its code (listed at the end of this chapter) the average dead time for an event is $\sim 12 \mu s$ and can vary by a few $\mu s$ depending on the code state when a trigger arrives.

Since this is a prototype system, certain aspects of its operation are not ideal. The pulse-height determination is noisier than expected since the circuitry was not built into a final RF-shielded enclosure. Furthermore, though the system was designed with four-channel expansion in mind, only one channel was fully implemented because each channel required an external NIM-based spectroscopy amplifier to shape the pulses. Ideally, this pulse shaping would be implemented in the DAQ circuitry to prevent the need for an external NIM crate.

This system, though limited, did allow the successful time- and energy-tagging of the requisite rate of photons in one channel and enabled the successful demonstration of our devices for wide-band GPS-synchronized spectrophotometry, as discussed in Section 5.1.4.
APPENDIX A. FIRST GENERATION DAQ

; Version 2. This is the new code to implement the flip-flop trigger lock.

PROCESSOR 16C84 ; PIC16C84 is the target processor
_CONFIG _CP_OFF & _PWRTE_ON & _WDT_OFF & _HS_OSC

#include <p16c84.inc>

#define ACK_TRY_COUNT 5

; I/O definitions
; Port A– outputs
#define REQBIT 0
#define REQ PORTA,REQBIT
#define OEBIT 1
#define OE PORTA,OEBIT
#define UNLATCHBIT 2
#define UNLATCH PORTA,UNLATCHBIT
#define ERRORBIT 3
#define ERROR PORTA,ERRORBIT

; Port B– inputs
#define TRIGBIT 0
#define TRIG PORTB,TRIGBIT
#define ACKBIT 1
#define ACK PORTB,ACKBIT
#define TRIGHOLDBIT 2
#define TRIGHOLD PORTB,TRIGHOLDBIT
#define QUICK_OUT b’00000000’

eeprom_data org 0x2100 ; Initialize EEPROM Data

; Register definitions
ram equ 0x0C
counter equ 0x0C+1

; Macro definitions
set_req macro
  bsf REQ
endm

clear_req macro
  bcf REQ
endm

unlatch_time macro
  bcf UNLATCH
  bsf UNLATCH ;toggle to reset JK flip flop
endm

time2bus macro
  bcf OE ;enable latched time outputs, disable ADC
endm

ADC2bus macro
  bsf OE ;enables ADC outputs, disables time outputs
endm

all_reset macro
  clear_req ;clear the request line
APPENDIX A. FIRST GENERATION DAQ

ADC2bus  ; raises the RD line on the ADC to allow a new conversion
unlatch_time  ; unlatches the time buffers and allows a new latch
endm

skip_trig  macro
btfss TRIG  ; skip if trig line is high (we have an event)
endm

skip_no_trig  macro
btfs TRIG  ; skip if trig line is low (we have no event)
endm

skip_trighold  macro
btfs TRIGHOLD  ; skip if trigger holdoff line is low, i.e. previous trigger went low
endm

skip_ack  macro
btfss ACK  ; skip if we have an ack signal on the bus
endm

skip_no_ack  macro
btfs ACK  ; skip if we have an ack signal on the bus
endm

wait_for_notrig  macro
local wfnt
wfnt  skip_trighold
goto wfnt
endm

wait_for_event  macro
local wfe
wfe  skip_trig
goto wfe
endm

handshake  macro
local wait_ack, got_ack
set_req
wait_ack  skip_no_ack  ; skip if PC is ready to receive
goto got_ack
decfsz counter, F
goto wait_ack
movlw ACK_TRY_COUNT
movwf counter
bsf ERROR

goto wait_ack
endm

got_ack  clear_req
bcf ERROR
endm

; Start of code
reset  org 0x0000

main  call init
APPENDIX A. FIRST GENERATION DAQ

start_here

wait_for_event

; Now trigger line has gone high. At this point the time has been latched
; and the ADC conversion has started. Since we had to make a jump out of
; the trigger check routine, we have already waited longer than 360ns (ADC time)
; so clock the data to the computer...
    handshake

; This clocks in the ADC data to the Digital DAQ card.
; Next, remove ADC from bus, enable latch outputs
    time2bus
    handshake

; Reset the JK flip flop and start over
    wait_for_notrig

    ; this is a kludge to allow debugging
    ; using a long trigger pulse. If all
    ; triggers coming in are between 200ns
    ; and a few microseconds in width then
    ; this line is unnecessary.

unlatch_time

ADC2bus
goto start_here

init

bsf STATUS, RP0 ; Select register page 1
clrf TRISA^0x80 ; Set all of PORTA as outputs
clrf TRISB^0x80
comf TRISB^0x80,F ; Set all of PORTB as inputs
bsf STATUS, RP0 ; Select register page 0
clrf INTCFON ; Disable all interrupts and clear any pending interrupts

all_reset

movlw ACK,TRY,COUNT
movwf counter
return

END
Figure A.1: Schematic of first generation DAQ with trigger circuitry
Appendix B

Numerical Modeling of Sensor Properties

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Pulse, Fig. 3.7</th>
<th>Ringing, Fig. 3.8(a)</th>
<th>Osc., Fig. 3.8(b)</th>
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<tbody>
<tr>
<td>Heat Capacity, $C$ [fJ/K]</td>
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<td>0.54</td>
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<tr>
<td>Sensor Power, $P_s$ [fW]</td>
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</tr>
<tr>
<td>Substrate Temperature, $T_s$ [mK]</td>
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<tr>
<td>Transition Temperature, $T_c$ [mK]</td>
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<td>SQUID Inductance, $L_\omega$ [$\mu$H]</td>
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<tr>
<td>Shunt Resistance, $R_{bias}$ [m$\Omega$]</td>
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<td>5</td>
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<tr>
<td>TES Normal Resistance, $R_n$ [$\Omega$]</td>
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<td>5</td>
</tr>
<tr>
<td>Transition Width, $W$ [mK]</td>
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<td>1</td>
<td>1</td>
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<tr>
<td>TES Bias Voltage, $V$ [nV]</td>
<td>55</td>
<td>38</td>
<td>31</td>
</tr>
</tbody>
</table>

Table B.1: ETF simulation parameters

The superconducting transition is given the following form for the pulse modeling:

$$R(T) = \frac{R_n}{2} \left\{ \text{erf} \left( \frac{T - T_c}{2W} \right) + 1 \right\}$$  \hspace{1cm} (B.1)
Appendix C

Milestones

- Mar97 first optical TES design
- Jun97 CIS fab with Roland, first devices out
- Jul97 no Tc to 35mK, new fab with smaller detectors
- Aug97 light baffles to cut down flux
- Sep97 using a red LED on cold stage for light source
- Oct97 learning about power dissipation on the cold stage
- Oct97 first optical photons from LED
- Nov97 Measurement of room-temp laser/LED line widths
- Nov97 First fiber installation into KO-15
- Dec97 First measurement of blackbody photons
- Dec97 Modified KO-15 for 5 SMA feedthroughs
- Jan98 Confirmation of rail hit ratio vs. size
- Feb98 installation of 7µm, 3µm, and 50µm fibers
- Feb98 new 90 degree sample mount to facilitate fiber alignment
- Feb98 first noise analysis of sensors
- Mar98 Ib-Is vs. temperature confirms \( P_{\text{e-ph}} \propto T^5 \)
- Mar98 big sweep across wavelengths
- Apr98 prototype DAQ design/Megalon ordered
- May98 First observation with 8" Celestron at Varian
- Aug98 Light-tight box, noise analysis
- Aug98 heatpulse lines installed
- Sep98 relative timing demonstrated
- Oct98 crab tried w/8" Celestron
- Nov98 First test of my DAQ design
- Nov98 GRIN magnification measurement gives reduction of 3.5×
- Dec98 pack fridge and go to Stanford Student Observatory
- Jan99 First Crab data with TES devices!
- Feb99 PSF measurements vs. energy
- Mar99 Roger’s work on barycentering pays off
- Mar99 SMA connector loss measured to be high
- Mar99 fiber loss measurements at 77 K not different than R.T.
- May99 2D current/thermal model with Tali
- Jun99 6×6 Array designed
- Jul99 ST-ST losses measured to be acceptable
- Jul99 Calibrated attenuator completed
- Jul99 6×6 Array fabrication
- Aug99 First tests of array
- Sep99 coincident event detection with two sensors with David Weld
- Sep99 Fiber IR cutoff measurement is \( \sim 1.7 \mu m \)
- Sep99 resolution/PSF as a function of rate
- Sep99 6eV UV photons into sensors
- Oct99 NIST SQUID arrays installed for better noise and biasing
- Oct99 KO-15 rewired for on-chip 10 mΩ bias R
- Oct99 200 µm high-OH Al clad fibers into fridge
- Oct99 First tests of NIST SQUID rewire
- Oct99 200 µm IR absorption measurement
- Nov99 GRIN/ball focusing measurement
- Nov99 Al coating of fibers suspected for heat load on M.C.
- Nov99 new devices show strange junction-like behavior---unabated we trod forth
- Nov99 new Al machined GRIN/ball holder tests
- Dec99 Salvage of older array devices, known to have Tc around 65 mK
- Dec99 6 detectors working simultaneously
- Dec99 ball mount changed to prevent contact with sensor
- Dec99 measurement of absolute rate with Roger’s CCD
- Jan00 confirmation of our power meter with Chu group’s meter
- Jan00 Ti/Au backing applied to 1 cm dies, long pulses, heat damage?
- Jan00 Very interesting thermal-crosstalk/cooling across adjacent pixels
- Jan00 More focusing measurements confirm factor of 3 reduction
- Jan00 First 4-ch test of NIST SQUID DFB/DAQ
- Jan00 Throughput measurements with analog/digital systems look good
- Jan00 Pack and move system to McDonald Observatory
- Feb00 Successful detector campaign at McDonald
- Mar00 Analysis begins on McDonald Observatory data
- Apr00 Building comprehensive PSF model and calibrations
- May00 Spectral deconvolution using simple subtraction
- Jun00 Kahn & Blisset deconvolution implementation
- Jul00 Exported device response matrix for Roger to try forward modeling
- Aug00 First depositions and cryogenic tests of Au-black
- Aug00 Tests of quasiparticle collection from ‘‘butterfly’’ pixels
- Aug00 Unsuccessful attempt at polarizing-filter calibrations
- Sep00 Quasiparticle tests show poor diffusion or step-coverage
- Oct00 Further work on Au-black depositions and devices
- Nov00 Cryo-tests on Au-black disappointing
- Nov00 Writing this.
Bibliography

[1] OptoSigma Corp., 2001 Deere Avenue, Santa Ana, California 92705, has such a prism which is quoted to work from 330 nm to 2200 nm.


[27] Personal communication with Blas Cabrera.


