Abstract

A transition-edge-sensor-based instrument for the measurement of individual He2* excimers in a superfluid 4He bath at 100 mK

Faustin Wirkus Carter

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This dissertation is an account of the first calorimetric detection of individual He^{*}₂ excimers within a bath of superfluid ⁴He. When superfluid helium is subject to ionizing radiation, diatomic He molecules are created in both the singlet and triplet states. The singlet He^{*}₂ molecules decay within nanoseconds, but due to a forbidden spin-flip the triplet molecules have a relatively long lifetime of 13 seconds in superfluid He. When He^{*}₂ molecules decay, they emit a ~15 eV photon. Nearly all matter is opaque to these vacuum-UV photons, although they do propagate through liquid helium. The triplet state excimers propagate ballistically through the superfluid until they quench upon a surface; this process deposits a large amount of energy into the surface. The prospect of detecting both excimer states is the motivation for building a detector immersed directly in the superfluid bath.

The detector used in this work is a single superconducting titanium transition edge sensor (TES). The TES is mounted inside a hermetically sealed chamber at the baseplate of a dilution refrigerator. The chamber contains superfluid helium at 100 mK. Excimers are created during the relaxation of high-energy electrons, which are introduced into the superfluid bath either in situ via a sharp tungsten tip held above the field-emission voltage, or by using an external gamma-ray source to ionize He atoms. These excimers either propagate through the LHe bath and quench on a surface, or decay and emit vacuumultraviolet photons that can be collected by the detector.

This dissertation discusses the design, construction, and calibration of the TES-based excimer detecting instrument. It also presents the first spectra resulting from the direct detection of individual singlet and triplet helium excimers.

A transition-edge-sensor-based instrument for the measurement of individual He2* excimers in a superfluid 4He bath at 100 mK

A Dissertation Presented to the Faculty of the Graduate School of Yale University in Candidacy for the Degree of Doctor of Philosophy

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Introduction

This dissertation is an account of the construction of an instrument that is capable of calorimetric detection of individual He^{*}₂ excimers within in a bath of superfluid ⁴He. When superfluid helium is subject to ionizing radiation, diatomic He molecules are created in both the singlet and triplet states. The singlet He^{*}₂ molecules decay within nanoseconds, but due to a forbidden spin-flip the triplet molecules have a relatively long lifetime of 13 seconds in superfluid He. For this reason, triplet He^{*}₂ molecules are useful as tracers for studying fluid flow and turbulence in liquid helium (LHe) (Guo et al., 2014). The singlet molecules also may be useful in the search for dark matter as some He molecules should be created by recoiling ⁴He atoms scattered by weakly interacting massive particles (WIMPs) passing through a reservoir of LHe (Guo and McKinsey, 2013). When a He^{*}₂ molecule decays, it emits a ~15 eV photon. Nearly all matter is opaque to these vacuum-UV photons, although they do propagate through liquid helium, which is the motivation for building a detector immersed directly in the superfluid bath. The detection of He^{*}₂ excimers in general is discussed in more detail in chapter 1.

The detector used in this work consists of a single superconducting titanium transition edge sensor (TES). TES physics and operating principles are the subject of chapter 2. The TES can operate at any temperature from the cryostat base temperature of ≈ 20 mK to just below its transition temperature ($T_c = 430$ mK) and so this, in principle, allows one to study He^{*}₂ excimers over a wide range of temperatures. The design and fabrication of the TESs used in this project are the subject of chapter 4, and the initial characterization of the TESs is detailed in chapter 5. The TESs are mounted inside a hermetically sealed chamber attached to the bottom of a dilution refrigerator. The chamber is filled with superfluid helium. The chamber and all the associated experimental hardware are described in chapter 3. Inside the chamber is a sharp tungsten tip that may be operated at a high voltage (up to a few kV) in order to ionize He atoms and create He^{*}₂ excimers. These excimers either propagate through the LHe bath and then quench on a surface, or decay into vacuum-ultraviolet photons that are collected by the detector. This basic experiment is not new. Zmeev et al. (2013a,b) have recently accomplished the detection of a cloud of He^{*}₂ excimers over a range of temperatures. Their detector relies on ionizing an excimer and collecting the resulting free electron on either a copper plate or a fine wire mesh. This process is very inefficient and requires averaging the data over several days to achieve a reasonable signal-to-noise ratio. The TES-based detector described in this work is sensitive to individual excimers, requires no averaging, and can also detect the energy spectrum of the detected molecules (or photons). The first detections of individual helium excimers are the subject of chapter 7, and the calibration process required to interpret the helium excimer data is discussed in chapter 6.

One of the original aims of this project was to not only make a TES detector that could see individual excimers, but to make a detector that was readily scalable in area to be up to several millimeters long with some position resolution. Several prototype devices designed with scalability and position resolution in mind were fabricated, but an unforseen issue with the measurement electronics (see section 4.3.5) precluded any of them from being successfully measured. Regardless, given the success of the detectors that were measured, there is no reason why the unmeasured prototypes should not work as designed. The operating principles of this scalable device, as well as a calculation of expected performance (based on an extrapolation of the working TESs measured over the course of this project) is available in appendix A.

Finally, several decisions were made during the initial planning stages of the experiment that, with the benefit of hindsight, turned out to be suboptimal. The concluding chapter discusses these lessons learned, and will hopefully be of use to anyone who wishes to try something similar.

Chapter

Helium excimers

A HELIUM excimer is a diatomic molecule of helium atoms, which exists in an excited state (the word excimer is a portmanteau of "excited" and "dimer"). Ordinarily, helium does not form a bound state as it is a noble gas, and all of its electron orbitals are full. However, when a helium atom has one of its electrons excited to a higher energy level, the potential energy as a function of inter-atomic spacing (usually a curve that increases monotonically with decreasing separation distance) develops a shallow local minimum, allowing a metastable bound state of two atoms to form. This bound state, called He^{*}₂ (the "*" denotes excitation) has an energy that is 13–20 eV above the He ground state, and so releases a vacuum UV photon upon decay. The singlet state He₂($A^1\Sigma_u$) decays within a few ns. The triplet state He₂($a^3\Sigma_u$) decay process involves a spin flip that is forbidden by selection rules and so its lifetime is ~13 s in superfluid helium (McKinsey et al., 1999).

The production of He₂^{*} in superfluid helium can be straightforward: any process that either ionizes helium atoms (He⁺ + He \longrightarrow He₂⁺, He₂⁺ + He + e⁻ \longrightarrow He₂^{*} + He) or excites helium atoms with sufficient energy (He^{*} + 2 He \longrightarrow He₂^{*} + He) can result in the creation of excimers. This includes (but is not necessarily limited to) nuclear scattering from neutrons and alpha particles, electronic scattering from gamma-rays, beta particles, and high-energy electrons (Keto et al., 1972, 1974; Tokaryk et al., 1993), and ionization from femtosecond laser pulses (Benderskii et al., 1999). A common way to create high-energy electrons in situ is to bias a sharp tungsten tip at a voltage above the electron-emission threshold. In this work, excimers were created in two ways: through the electron-emission of a tungsten tip, and through gamma-ray scattering using a ²²Na gamma-ray emitter, which emits 511 keV and 1.3 MeV gamma-rays. Both of these processes create excimers through electronic scattering, which results in the production of excimers in a roughly 4:1 singlet:triplet ratio (Sato et al., 1974), and also through the geminate recombination of electron ion pairs, which results in a 1:1 singlet:triplet ratio (Adams, 2001).

The detection of individual He_2^* molecules in superfluid helium is the subject of this dissertation. The following two sections contain brief examples of applications where one might be interested in detecting He_2^* , and the final section in this chapter gives an overview of He_2^* detection methods that are currently available.

1.1 Vortices in superfluid helium

When liquid helium undergoes a phase transition to the superfluid state, the superfluid component does not admit angular momentum; the curl of the velocity is zero. Instead, angular momentum is confined to quantized vortices with normal fluid cores, which align parallel to the axis of rotation. This is analogous to how a type-II superconductor expels magnetic flux, confining it in quantized amounts through small normal regions. Each vortex is associated with a quantum of angular momentum. For a volume of superfluid rotating at a constant angular velocity, these vortices will form a regular lattice with the angular momentum parallel to the axis of rotation. However, for turbulent systems, the vortices will become chaotic and tangled, a condition known as quantum turbulence (see Aarts and de Waele (1994) for a discussion of vortex tangles and some excellent visualizations). The rotational energy of a vortex is $\propto \ln(r/r_0)$ where r is the separation between vortices and r_0 is the radius of the vortex core (McClintock et al., 1984). Consequently, the energy of the vortex is reduced by increasing the radius; this promotes the entrainment of small particles in the vortex core. The "decoration" of vortices by small particles, which may then be imaged by standard means, is one of the primary methods of studying superfluid vortices and quantum turbulence (Zhang et al., 2004; Zhang and Van Sciver, 2005).

The particles used for tagging the vortices in this way would ideally be easily observed, long-lived, and small in diameter so as not to perturb the vortex dynamics under study. Micron-scale hydrogen ice particles have been used to visualize vortices, observe vortex reconnection, study Kelvin waves, and to measure thermal counterflow (Bewley et al., 2006; La Mantia et al., 2012; Bewley et al., 2008; Paoletti et al., 2008; Sergeev and Barenghi, 2009). Despite the success with hydrogen ice, He^{*}₂ excimers produced in situ through electron bombardment or laser ionization offer significant advantages. He^{*}₂ is the third smallest helium-only tracer particle (only ³He atoms and He⁺₂ ions are smaller) and is efficiently and permanently trapped by quantum vortices (trapping radius ~100 nm (Zmeev et al., 2013a)). Unlike ³He atoms, He^{*}₂ excimers do not constitute an impurity in a superfluid ⁴He bath in the sense that they arise from, and decay to, ⁴He atoms. Although there are ongoing efforts to observe trapped triplet state excimers using laser fluorescence (Rellergert et al., 2008; McKinsey et al., 2005), this trapped state has, so far, been observed only through surface quenching (Zmeev et al., 2013b,a).

This work aims to improve on the previous surface quenching observation studies through the use of a calorimetric sensing technique, which is sensitive to direct photon absorption (from the singlet decay) as well as surface quenching of the triplet excimers.

1.2 Direct dark matter detection

The weakly interacting massive particle (WIMP) model of dark matter posits that dark matter can only interact with normal matter through gravity and the weak interaction. Two well-known experiments to detect WIMP dark matter are the Large Underground Xenon dark matter experiment (LUX) and the Cryogenic Dark Matter Search (CDMS). These experiments are both predicated on measuring two secondary effects initiated by the WIMP scattering off of some detector material. In LUX, the detector material is liquid xenon, and the two signal channels are scintillation and ionization. In CDMS, the detector material is germanium, and the two signals are phonons and electron-hole pairs. In both cases, the amount of signal produced in each channel depends on the interaction cross section and the mass of the detector material. A liquid-helium based instrument (Guo and McKinsey, 2013) would have an advantage when searching for low-mass WIMPs (a few GeV/c^2) for three reasons:

- 1. The low mass of the helium atoms would be well-matched to a light dark matter particle, giving a helium-based detector a large advantage over, say, a xenon-based detector. As an analogy, compare the different reactions experienced by a stationary ping-pong ball and a stationary bowling ball to an incident ping-pong ball; only the stationary ping-pong ball will be appreciably displaced by the collision.
- 2. Ito and Seidel (2013) show that a nuclear low-mass WIMP event in helium produces at least a factor of ten more scintillation light than the same event in xenon.
- 3. The ratio of singlet excimers to triplet excimers produced via a nuclear WIMP interaction is very different than the ratio produced via either gamma- or X-ray electronic scattering events, which constitute the majority of the background signal in a dark matter search (Guo and McKinsey, 2013).

In order for a helium-based instrument to work, a detector must be developed that is sensitive to individual excimers both through absorption of the scintillation photon and through surface quenching of the triplet state excimer. Discrimination of the two types of signal is also crucial. This detector should be scalable to large size $\sim mm^2$, easily multiplexed (to allow many detectors to be operated on the same signal line), and operable in situ at temperatures below 200 mK. This work aims to develop such a detector.

1.3 Candidate technologies for detecting He^{*}₂ excimers

The goal of this project was to have a detector that is both easily scalable in area up to several square millimeters and sensitive to individual He_2^* excimers, either through direct detection of the triplet state excimer, or through collection of the ultra-violet (UV) photon emitted by the singlet excimer decay. The detector should also operate below 200 mK, as that is the temperature regime where the excimers switch from diffusive to ballistic propagation through the superfluid (Zmeev et al., 2013b). Finally, high efficiency, low dark

counts, and a fast (< 100 μ s) detector response are all desirable. Because the UV photons released by the excimers upon decay are absorbed by almost everything (liquid helium being one notable exception), any detection scheme must either first down-convert the UV photons to photons that can pass through a transparent container, or must immerse the detector element directly in the helium bath. Following is a brief list of some technologies that are capable of detecting He excimers, along with a statement on why each technology was not pursued.

1.3.1 Photomultipliers and avalanche photodiodes

Photomultipliers (PMTs) and avalanche photodiodes (APDs) are extremely sensitive and have been used in many applications for detecting vacuum UV. In order to use PMTs, one must coat an optically transparent box with a fluorescing material to down-convert the vacuum UV photons to the visible wavelength and then surround the box with PMTs or APDs. In fact, this is currently the main approach used to detect helium scintillation. However, the low quantum efficiency of PMTs (especially below 4 K) and the reluctance of APDs to work well at sub-K temperatures do not justify the effort required to integrate such a system into a dilution refrigerator.

1.3.2 CCDs

The Extreme Ultraviolet Imaging Telescope (EIT) has been imaging the sun's corona in the vacuum UV bands since the early nineties using special CCDs with a vacuum UV semitransparent optical filter (Delaboudinière et al., 1995). CCDs are a very mature technology, relatively inexpensive, and can cover large areas easily. A cooled CCD is even capable of single-photon sensitive operation. Unfortunately, CCDs have a minimum operating temperature in the neighborhood of 60 K (Wagner et al., 1994). Moreover, all the above caveats listed for PMTs and APDs also apply to CCDs. CCDs will not considered for this work.

1.3.3 Optical pumping measurements of He^{*}₂ excimers

Exciting a triplet He^{*}₂ molecule with a 905 nm laser will induce fluorescence as the excimer molecules cycle and emit 640 nm photons. The McKinsey group at Yale has successfully

imaged triplets created by a tip-discharge and mapped their flow (Rellergert et al., 2008; Guo et al., 2009). This experiment was performed at 2 K, and used a pumped-He cryostat with a window for coupling in the lasers and imaging the fluorescence with a CCD. Although it was able to image triplet state excimers in aggregate, detection of individual excimers was not accomplished. More recently, Guo et al. (2014) have produced excimers via laser ionization of helium, and used the optical pumping method to visualize thermal counterflow at 1.8 K. Repeating these types of measurements at very low temperatures (< 100 mK) will require creating an optical path from the lowest temperature state up to a temperature favorable for CCD readout. Furthermore, these types of measurements are only useful for detecting the long-lived triplet state of He₂; the singlet state is too short lived and relaxes before the pump-measure cycle can complete. Since the goal of this work includes developing a detector that is sensitive to individual singlet and triplet excimers, the optical pumping method was set aside.

1.3.4 Superconducting tunnel junctions

Wilson et al. (2003) reported on a tantalum (Ta) superconducting tunnel junction detector (STJ) designed for UV detection with resolution approaching 1 eV at operating temperatures of about 300 mK. This detector is certainly single-photon sensitive and could operate directly in a superfluid He bath. There are two major challenges one must overcome to adapt the STJ for the present application. The first is the detector area, which is limited by the quasiparticle diffusion constant of the Ta absorber; at a maximum of 20–100 μ m long, it would take an unreasonably large number of detectors to cover the necessary solid angle. The second is a materials engineering issue. The geometry of a standard STJ detector is to use an Al tunnel junction and a superconductor (like Ta or Nb) with a higher T_c as an absorber. The higher energy gap of the absorber relative to Al allows for quasiparticle trapping, which facilitates tunneling. The present work requires a large area absorber, which means quasiparticles must diffuse a long distance along the absorber before reaching a detector. Evaporated Al is the best choice, out of the available superconductors, for an absorber metal with its low diffusive loss. Wang et al. (2014), at Yale, have measured quasiparticle lifetimes of ~ ms in electron-beam evaporated Al (compare this to ~ μ s lifetimes

in Ta). This means the tunnel junction portion of an STJ with an aluminum absorber would have to be composed of a superconductor with a lower T_c than Al (either Ti or W) and that metal's respective oxide. The properties of Ti and W oxide junctions are not well developed, and engineering good junctions from scratch (using either metal) could take several months or more of dedicated work. The engineering hurdles required to utilize such a tunnel junction are high enough that the STJ detector may be ruled out as a suitable candidate.

An aluminum absorber with a detector at each end that collects excited quasiparticles is a good design to achieve large collection area, and should be scalable to several millimeters long provided that the best reports of the Al diffusion constant can be replicated (see appendix A). Instead of a tunnel junction, one might use a TES to collect the quasiparticles. The same caveats apply to a TES as to an STJ: it must be made from a material with a lower T_c than Al, but a single-element TES is a simple, well-understood technology and so requires very little engineering (relative to an STJ) to be successful. Finally, when read out by a superconducting quantum interference device (SQUID), the TES is easily multiplexed. In fact, this is the very technology used by the CDMS group to detect phonons in their search for dark matter. For these reasons, the TES was chosen as the technology to be developed. The rest of this dissertation discusses the implementation of a titanium TES for the detection of He^{*}₂ excimers in a superfluid helium bath. Although a scalable, largearea, position-sensitive device was not successfully measured (due to hardware-related issues discussed in section 4.3.5), a small, single TES detector was used to make the first direct detection of both individual singlet and triplet helium excimers. With more robust readout electronics, there is no reason why the scalable version of this device should not also be successful.

Transition edge sensors

Chapter

TN 1878 the astronomer Samuel P. Langley invented the bolometer—the most sensitive power meter of the day (Langley, 1880). His invention consisted of a platinum strip coated in lamp-black. Exposing the coated strip to incident radiation heated it, and therefore raised the resistance proportionally to the power absorbed. Langley used his bolometer to make the first measurement of the full solar spectrum and this ushered in the age of the bolometer; since the late 1800's, bolometers have been the astronomer's detector of choice for measuring radiation in the micron-millimeter wavelength range. When the COBE satellite measured the temperature of the cosmic microwave background (CMB) one-hundredsixteen years later, in 1994, with mK precision, the active detector was a bolometer (Mather et al., 1994). In this case the sensor was a piece of silicon, rather than a platinum film, but the fundamental measurement still used the variation of the resistance of some material with changes in temperature as a thermometer. Silicon and germanium bolometers were the technology of choice for astronomical measurements through to the late 90's when the superconducting transition edge sensor (TES) bolometer took over. A TES keeps to the time-honored tradition of measuring a temperature-dependent resistance, but uses the very sharp resistive transition of a superconductor as a thermistor. The TES was invented in the 1940's (Andrews et al., 1942), but was difficult to bias stably, had poor dynamic range, and was hard to read out. In 1994 a proposal to voltage bias a TES coupled to a SQUID amplifier neatly solved all of those problems at once (Irwin, 1995) and set the modern standard for TES-based instruments. TES detectors are not just for sub-mm astronomy. There are single-photon sensitive TESs operating in the mid-IR band (Karasik et al., 2012), to the hard X-rays (Fukuda, 2002), and beyond. The choice of a TES detector is discussed in more detail in section 1.3. This chapter reviews the basic TES operating principles and then uses a numerical simulation to explore the results of varying different important TES parameters. The parameter values used in the model TES throughout this chapter were chosen to model an actual Ti TES as closely as possible, and are listed in table 5.1.

2.1 Electro-thermal feedback

A TES uses the resistive transition of a superconductor to map small temperature changes to large resistance changes. Resistance is a very simple quantity to measure: simply apply a current, measure a voltage, and then use Ohm's law. However, this simple method, when applied to a TES, gives rise to a vexing problem. Consider a superconducting film at a temperature just below T_c with applied current I. In the fully superconducting state, there is no voltage drop across the film and the resistance R_{TES} is zero. Thus, the Joule power dissipated by the film, $I^2 R_{\text{TES}}$, is also zero. However, if the film absorbs enough heat for R_{TES} to become nonzero, the Joule power will also become non-zero. This increase in Joule power will act to heat the superconducting film up further, thereby increasing R_{TES} , and possibly (depending on I) entering into a positive feedback loop that ends with the film fully normal, with $R_{\text{TES}} = R_{\text{N}}$. This positive feedback problem and the limited temperature range of the superconducting transition were the primary impediments to the widespread adoption of TESs until 1994, when the idea of negative electro-thermal feedback was first put forward by Irwin (1995). In the negative electro-thermal feedback mode of operation, the TES is effectively voltage biased by placing it in parallel with a small shunt resistor $R_{\rm s} \ll R_{\rm N}$. The Joule power is then given by $V^2/R_{\rm TES}$ where $V = I(R_{\rm s}||R_{\rm TES})$ (|| denotes the parallel combination). If some small addition of heat (due to photon absorption, or otherwise) raises the temperature of the superconductor, and so also raises R_{TES} , the Joule power dissipated in the film will actually drop, assisting the cooling of the film, and nearly resetting it back to the state it was in before the heat was absorbed. The physics of the TES in electro-thermal feedback is governed by two simple coupled differential equations, one that describes the electrical behavior and one that describes the thermal behavior.

The following sections will often refer to the resistance of the TES, which depends on the TES temperature T, the current flowing through the TES I_{TES} , and material parameters that define the critical current and temperature. Any sort of numerical TES model will only be as good as the model for the TES resistance, as it is this non-linear, temperature/current-dependent resistance that defines a TES. Wang et al. (2012) discuss some different functions for modeling resistance, as well as a very different approach to modeling a TES using only electrical circuits. In the following analysis, the TES resistance is modeled by (2.1) where T_c is the superconducting critical temperature, ΔT_c is the 10-90% transition width, and I_c is the zero-temperature critical current from the Ginzburg-Landau relation $I(T) = I_c (1-T/T_c)^{3/2}$.

$$R_{\rm TES} = \frac{R_{\rm N}}{2} \left(1 + \tanh\left(\frac{T - T_{\rm c}(1 - (I_{\rm TES}/I_{\rm c})^{2/3}))}{\Delta T_{\rm c}/(2\log 3)}\right) \right)$$
(2.1)

2.1.1 TES thermal circuit

Figure 2.1 shows the basic thermal circuit for any TES: a thermal absorber with heat capacity C is weakly coupled to a cold bath through some thermal conductance G, and strongly coupled to a superconducting thermometer. In some applications, the thermal absorber and the TES are entirely different physical structures, and a separate circuit element is required to account for the absorber. For the TESs described in this work, so-called hot-electron TESs, a superconducting thin film serves as both the absorber $(C = C_e)$ and the thermometer (through R_{TES}). The thermal bath is the phonon system of the same thin film, and the electron-phonon coupling sets the thermal conductance $(G = G_{e-ph})$.

In the absence of any external heat input, the only source of input power is the Joule power, and the only sink for cooling (for a hot-electron style TES) is the phonon bath. Equation 2.2 describes this system as a function of time, where T is the electron temperature, T_{bath} is the phonon temperature of the TES (typically this is equal to the cryostat temperature), V is the TES volume, Σ_{e-ph} is the electron-phonon coupling constant in the



Figure 2.1: The simplest possible thermal circuit for a hot-electron style TES calorimeter. The energy from a single photon (E_{phot}) is absorbed in the electron system of the TES and is converted to heat through the electron heat capacity $(C_{\rm e})$. The TES is biased with some current $(I_{\rm TES})$ and the TES resistance $(R_{\rm TES})$ is used as a sensitive thermistor to monitor the TES temperature. Eventually the hot electrons cool through electron-phonon scattering $(G_{\rm e-ph})$ and the hot phonons escape into the substrate, which is held at the cryostat base temperature $(T_{\rm bath})$.

superconductor, and n is the power-law exponent that describes the cooling. Typically, n is between 4 and 6 for electron-phonon coupling (Irwin and Hilton, 2005).

$$C_{\rm e}\frac{\partial T}{\partial t} = I_{\rm TES}^2 R_{\rm TES} - V\Sigma_{\rm e-ph}(T^n - T_{\rm bath}^n)$$
(2.2)

2.1.2 TES electrical circuit

Figure 2.2 shows the simplest version of the electrical circuit used for electro-thermal feedback operation. An inductor L is placed in series with the TES and then coupled to a superconducting quantum interference device (SQUID) to read out I_{TES} , which is typically on the order of tens or hundreds of nA during operation. In any real circuit, there will also always be some parasitic resistance $R_{\rm p}$ in series with the TES. Equation 2.3 gives the response of the TES current to an input bias current $I_{\rm b}$.

$$R_{\rm s}(I_{\rm b} - I_{\rm TES}) = I_{\rm TES}(R_{\rm p} + R_{\rm TES}) - L\frac{\partial I_{\rm TES}}{\partial t}$$
(2.3)



Figure 2.2: A simple TES readout circuit. The TES (R_{TES}) is in series with an inductor (L) that couples the TES current into the SQUID, and in parallel with a shunt resistor $(R_{\rm s})$ that provides the electro-thermal feedback. There is also some parasitic resistance $(R_{\rm p})$ in series with the TES. V_{SQUID} is proportional to the TES current (I_{TES}) within the operating range of the SQUID.

2.2 Numerical solutions to TES equations

Equations 2.1, 2.2, and 2.3 combine to a set of two coupled differential equations that fully describe the behavior of an ideal TES. It is not possible to reduce these equations to any fully analytical solution, but obtaining analytical expressions is possible in the small signal limit, and that will be discussed in section 2.3. It is a simple matter, however, to program a computer to solve this system numerically. The remainder of this section is devoted to calculating the TES current I_{TES} as a function of an input current I_{b} . This curve is the natural place to begin, as I_{TES} is the only thing that may be measured, and I_{b} is the only variable that may be controlled once the detector is inside the cryostat. Once this curve is determined, it may be used to calculate TES resistance, Joule power, and voltage as functions of I_{b} .

Solving for TES current as a function of bias current

Although it is not possible to solve the full system analytically, it is almost trivial to solve for the regions $I_{\rm b} < I_{\rm c}$ and $I_{\rm b} \gg I_{\rm c}$. For the first case, $R_{\rm TES} = 0$ and $T = T_{\rm bath}$. Thus, one may completely disregard the first two equations. As long as $I_{\rm b}$ is changed slowly enough in time to neglect the inductance term, the third equation is simplified to $I_{\rm TES} = I_{\rm b}R_{\rm s}/(R_{\rm s} + R_{\rm p})$. Similarly, at large enough bias current, the TES will be completely normal $(R_{\text{TES}} = R_{\text{N}})$ and so $I_{\text{TES}} = I_{\text{b}}R_{\text{s}}/(R_{\text{s}} + R_{\text{p}} + R_{\text{N}})$. The normal and superconducting branches are plotted on figure 2.3 as dashed lines for the case $R_{\text{s}} = 200 \text{ m}\Omega$, $R_{\text{p}} = 5 \text{ m}\Omega$, and $R_{\text{N}} = 50 \Omega$.

In the operating regime where $0 < R_{\text{TES}} < R_{\text{N}}$, (2.2) and (2.3) must be solved numerically. In this case (and for all other examples in this chapter), Mathematica was used for solving the differential equations (see appendix C for the code, as well as a discussion on how to use it). Mathematica has the advantage of having a very advanced built in routine for determining the most efficient numerical method to use. Figure 2.3 shows the full curve from the numerical solutions to (2.1), (2.2), and (2.3). The full solutions to the TES equations are hysteretic; the solution in between the two linear regions is different depending on whether one is increasing or decreasing $I_{\rm b}$. This is because the TES critical current is a function of temperature. When the bias current is increasing from zero, the TES temperature is at base temperature, and the critical current is very nearly the zero-temperature value. The device will stay on the supercurrent branch until this critical current is reached, and then transition abruptly. On the other hand, when the bias current starts high, the TES is experiencing some Joule heating and the critical current is decreased. Thus, the device will switch back to the supercurrent branch at a smaller value of $I_{\rm b}$. These two branches are differentiated in figure 2.3 by arrowheads indicating the sign of the derivative of the bias current. The transition with increasing bias current is abrupt as the device temperature experiences a step function when the upper critical current is reached. The transition at decreasing bias current is smooth and stable in the sense that, as long as one stays above the lower critical current value, one may adjust $I_{\rm b}$ in either direction and stay on the curve. In practice, the device is always biased on the lower branch.

It is interesting to see how each of the parameters that enter in to the TES equations affect the resulting solution. Each sub-figure of figure 2.4 depicts a set of curves corresponding to varying a different parameter (T_c , ΔT_c , Σ_{e-ph} , n, T_{bath} , I_c , and C_{e} —see sections 2.1.1 and 2.1.2 for definitions). This allows one to gain an intuitive understanding of how these parameters affect the I_{TES} vs. I_b (henceforth referred to as I_b/I_{TES}) curve. The values chosen for the non-varying parameters are listed in appendix C.



Figure 2.3: TES current (I_{TES}) vs. bias current (I_b) numerical solution. Note the hysteresis (denoted by arrows), due to the combination of a temperature-dependent critical current and Joule heating. The dashed gray lines indicate the currents expected for $R_{\text{TES}} = 0$ and $R_{\text{TES}} = R_{\text{N}}$.

Calculating TES resistance, power, and voltage from the current response

Once one has acquired an $I_{\rm b}/I_{\rm TES}$ curve, one may immediately obtain curves for resistance, power, voltage, and temperature through the following relations:

$$R_{\rm TES} = R_{\rm s} \left(\frac{I_{\rm b}}{I_{\rm TES}} - 1 \right) - R_{\rm p} \tag{2.4}$$

$$P_{\rm TES} = I_{\rm TES}^2 R_{\rm TES} \tag{2.5}$$

$$V_{\rm TES} = I_{\rm TES} R_{\rm TES} \tag{2.6}$$

$$T_{\rm TES} = \left(\frac{P_{\rm TES}}{V\Sigma_{\rm e-ph}} - T_{\rm b}^n\right)^{1/n} \tag{2.7}$$

Figure 2.5 shows the resistance, power, and voltage curves derived from the $I_{\rm b}/I_{\rm TES}$ curve depicted in figure 2.3. Each of these curves is useful for calculating a different TES parameter. The resistance and temperature curves together give a measure of TES sensitivity $\alpha = d \ln R/d \ln T$, several power curves at different temperatures allow one to measure n and G, and the voltage curve is required to convert the measured TES current pulse from a detection event into absorbed energy. All of these measurements will be described in more



Figure 2.4: TES current vs. bias current for several parameter variations. The non-varying values in each plot are listed in appendix C. The vertical lines terminated with arrows correspond to the bias current at which the zero-temperature critical current of the TES is exceeded. See figure 2.3 for a zoomed out example of the full curve.



Figure 2.5: Calculated resistance, temperature, power, and voltage as functions of bias current. These curves were calculated from the lower branch of the $I_{\rm b}/I_{\rm TES}$ curve in figure 2.3.

detail in chapter 5.

Both the temperature of the TES and the Joule power dissipated by the TES are relatively constant in the transition region $0 < R_{\text{TES}} \leq R_{\text{N}}$. This region is where the TES is biased during operation. The flatness of these two curves also depends heavily on the actual shape of the resistive transition and is discussed in more detail in section 5.2.

2.3 Small signal response

Although it is not possible to derive an analytic expression for the TES current and TES temperature in general, it is possible to solve the equations analytically for very small changes in these two variables. This is very useful for studying the time dependent response of the TES to small energy inputs like single photons. As long as the TES temperature increase (due to the absorption of a photon, or otherwise) is small compared to the overall transition width, then the TES resistance will be linear in both temperature and current. One may use a simplified linear model for the transition, expand the temperature and current expressions in the TES differential equations to first order, and add an energy input term to (2.2) to account for the photon input. The process involved in arriving at a solution

Table 2.1: Definitions of quantities used in the small-signal model described in this section. More details may be found in Irwin and Hilton (2005). In all cases, the subscript "0" indicates an equilibrium value. $P_{\rm sig}$ is the signal power, or energy input, term.

$$\begin{split} \delta P &= P_{\text{sig}} - P_0 \\ \delta V &= V_{\text{b}} - V_0 \\ G &= n \Sigma V T^{n-1} \end{split} \begin{vmatrix} \delta I &= I_{\text{TES}} - I_0 \\ \alpha_I &= \frac{T_0}{R_0} \frac{\partial R}{\partial T} \Big|_{I_0} \\ \tau &= \frac{C}{G} \end{vmatrix} \begin{vmatrix} \delta T &= T_{\text{TES}} - T_0 \\ \beta_I &= \frac{I_0}{R_0} \frac{\partial R}{\partial I} \Big|_{T_0} \\ \mathcal{L}_I &= \frac{P_0 \alpha_I}{GT_0} \end{split}$$

is beyond the scope of this chapter, but is well documented in extensive detail in Irwin and Hilton (2005). The following sections will quote and discuss two results of that analysis: the equations for TES response to an incident photon, and the equations describing the TES noise sources.

2.3.1 Pulse model

The Irwin/Hilton model uses the Thevenin-equivalent circuit for the one depicted in figure 2.2. The bias current and shunt resistor are replaced by a bias voltage $V = I_b R_s$ and a load resistor $R_L = R_s + R_p$ in series with the TES and the sense inductor. When the circuit is held at a constant voltage bias (by supplying an appropriate bias current), the TES current, temperature, resistance, and power terms may all be expanded about their equilibrium values (I_0, T_0, R_0, P_0) to first order. If the input power of a small signal is given as P_{sig} , then the final linearized equations are given as (2.8) and (2.9) with the definitions given in table 2.1.

$$\frac{\mathrm{d}\delta I}{\mathrm{d}t} = -\frac{R_{\mathrm{L}} + R_{0}(1+\beta_{I})}{L}\delta I - \frac{\mathscr{L}_{I}G}{I_{0}L}\delta T + \frac{\delta V}{L}$$
(2.8)

$$\frac{\mathrm{d}\delta T}{\mathrm{d}t} = \frac{I_0 R_0 (2+\beta_I)}{C} \delta I - \frac{(1-\mathscr{L}_I)}{\tau} \delta T + \frac{\delta P}{C}$$
(2.9)

Solving these two coupled linear equations for δI is tedious, but straightforward. The response to an incoming photon with energy E_{phot} , modeled as a delta-function impulse, is
given as:

$$\delta I(t) = \left(\frac{\tau_I}{\tau_+} - 1\right) \left(\frac{\tau_I}{\tau_-} - 1\right) \frac{1}{(2+\beta_I)} \frac{E_{\text{phot}}}{I_0 R_0 \tau_I^2} \frac{\left(e^{-t/\tau_+} - e^{-t/\tau_-}\right)}{(1/\tau_+ - 1/\tau_-)}$$
(2.10)

with the following definitions:

$$\begin{aligned} \tau_{I} &= \frac{\tau}{1 - \mathscr{L}_{I}} \\ \tau_{el} &= \frac{L}{R_{L} + R_{0}(1 + \beta_{I})} \\ \frac{1}{\tau_{\pm}} &= \frac{1}{2\tau_{el}} + \frac{1}{2\tau_{I}} \pm \frac{1}{2} \sqrt{\left(\frac{1}{\tau_{el}} - \frac{1}{\tau_{I}}\right)^{2} - 4\frac{R_{0}}{L}\frac{\mathscr{L}_{I}(2 + \beta_{I})}{\tau}}{\tau} \end{aligned}$$

Equation 2.10 assumes that all the photon energy is coupled very rapidly into the detector to produce a thermal electron distribution at an initial temperature > T_0 . In practice, the fraction of energy absorbed (η) is closer to one half (Brink, 1995), and when using (2.10) to fit actual pulse data, E_{phot} is replaced with ηE_{phot} . Although the above equation appears cumbersome, it is essentially just an exponential pulse with a rise-time τ_+ set mostly by the inductance L and the parameter β_I , and a fall-time τ_- that depends mostly on the ratio C/G and the parameter α_I .

Figure 2.6 shows a plot of (2.10) vs. time for a single blue photon ($\hbar \omega = 2.6$ eV, $\eta = 0.5$). The current axis has been flipped to show the pulse as positive, although in reality the current through the TES drops during a detection event. The TES parameters are the same as those used in the previous section to model the $I_{\rm b}/I_{\rm TES}$ curve shown in figure 2.3, and may be found in appendix C. The only parameters that are new in this section are those that define the linearized resistance of the TES (in the previous section, a hyperbolic tangent was used to model the resistance instead). For these two parameters, realistic values of $\alpha_I = 100$ and $\beta_I = 1.5$ have been chosen. The inductance has been set to L = 50 nH to simulate the real-world effects of long wires between the TES and the SQUID amplifier. Finally, the bias current was set to $I_{\rm b} = 18 \ \mu \text{A}$, which corresponds to a steady-state resistance of $R_0 = 1.4 \ \Omega \ (R_{\rm N} \approx 50\Omega)$.

One of the major benefits of a TES detector is that, in the limits of strong electro-



Figure 2.6: Simulated response of a TES to a single blue photon (2.6 eV) with an energy absorption factor of $\eta = 0.5$. Other simulation parameters are given in appendix C.

thermal feedback and a signal power much less than the TES saturation power, the pulse area is proportional to the absorbed energy. Multiplying the detector current by the bias voltage gives a plot of power dissipated by the TES as function of time. Integrating this power gives the total energy absorbed in the pulse. For the simulated pulse in figure 2.6, the integral equals 1.34 eV, which is very close to half of the 2.6 eV input energy, as expected. The slight ($\approx 3\%$) mismatch between the model input energy and the model output energy is due to the fact that this linearized model ignores second-order effects.

Figure 2.7 shows the effect on the rise time (τ_+) and fall time (τ_-) of varying several parameters. The vertical axes are constant between plots for easy comparison. The horizontal axis is either linear or logarithmic depending on the range of values. Ideally, a TES would be designed such that both relevant time constants are within the amplifier bandwidth, and the fall-time is fast enough to handle the incoming photon rate without experiencing any pulse overlap.

2.3.2 TES noise and energy resolution

A microscopic theory of TES noise based on the superconducting transition is not readily available. Instead, the traditional approach is to assign four main sources of noise for a TES detector connected in electro-thermal feedback mode. The TES and the shunt resistor



Figure 2.7: Pulse rise time (blue) and fall time (red) for a number of different varying parameters. The vertical axes are constant between plots for easy comparison. The horizontal axis is either linear or logarithmic depending on the range of values. The non-varying values in each plot are listed in appendix C, and are the same as those used to make figure 2.6.

each have Johnson noise. The TES electron system experiences small thermal (energy) fluctuations, which will be referred to as thermal-fluctuation noise (TFN). Finally, the SQUID amplifier adds noise. These four noise sources determine the energy resolution of the detector.

The Johnson noise for the TES and Thevenin-equivalent load resistor follow the typical Johnson noise formula with voltage spectral density $S_V = 4k_{\rm B}TR$, which has units of V²/Hz. It is important to remember, however, that $R_{\rm L}$ is at base temperature, while the TES is approximately at $T_{\rm c}$. Thus, $S_{V_{\rm TES}} = 4k_{\rm B}T_{\rm c}R_{\rm TES}$ and $S_{V_{\rm L}} = 4k_{\rm B}T_{\rm bath}R_{\rm L}$. The thermal noise formula for power spectral density is similar and is given by $S_{P_{\text{TFN}}} = 4k_{\text{B}}T_0^2G$, where G is the thermal conductance (Mather, 1982) and has units of W^2/Hz . Finally, the SQUID amplifier noise is typically quoted as a flux spectral density $(S_{\phi_{\text{amp}}})$ or current spectral density $(S_{I_{\text{amp}}})$ and must be either measured or acquired from the SQUID manufacturer. The total noise spectral density of the TES is the sum of the four independent noise sources. In order to perform this sum, the sources must be referred to a common quantity. The two most useful are current noise (as this is the easiest thing to measure) and power noise, as the energy resolution is calculated from this quantity. In order to refer a voltage noise to a power (or current) noise, the voltage to power (or current) responsivity must be calculated. This is a quantity that describes how changes in voltage (as a function of frequency) result in changes of power (or current). This calculation is complicated, but in the small signal limit discussed in the previous section, one may arrive at an analytical expression for the total power-referred TES noise. The details of the calculation, again, are meticulously covered in Irwin and Hilton (2005).

$$S_{P_{\text{tot}}}(\omega) = S_{P_{\text{TFN}}} + S_{V_{\text{TES}}} I_0^2 \frac{1}{\mathscr{L}_I^2} (1 + \omega^2 \tau^2) + S_{V_{\text{L}}} I_0^2 \frac{(\mathscr{L}_I - 1)^2}{\mathscr{L}_I^2} (1 + \omega^2 \tau_I^2) + \frac{S_{I_{\text{amp}}}(\omega)}{|s_I(w)|^2}$$
(2.11)

All the symbols used are defined in the previous section except for the power to current responsivity $(s_I(\omega))$ which is given by:

$$s_I(\omega) = -\frac{1}{I_0 R_0} \frac{1}{(2+\beta_I)} \frac{(1-\tau_+/\tau_I)}{(1+i\omega\tau_+)} \frac{(1-\tau_-/\tau_I)}{(1+i\omega\tau_-)}$$
(2.12)



Figure 2.8: The current spectral densities are plotted here in pA^2/Hz as a function of frequency $(f = \omega/2\pi)$ for the TES parameters given in table 5.1. The dashed black curve is the sum of the other curves. The red curve is TES Johnson noise, the orange curve is shunt resistor Johnson noise, and the blue curve is the thermal-fluctuation noise of the TES. The SQUID amplifier noise has not been included here.

Figure 2.8 shows the three different noise spectral densities as a function of frequency for a TES with the parameters given in table 5.1. The noise has been referred to current spectral density, and is plotted in pA^2/Hz over a frequency range of 100 Hz–10 MHz (which approaches the range of most commercial SQUID amplifier systems). For this model TES, the thermal fluctuation noise is clearly the dominant source. There are really only two parameters one may engineer to reduce this noise; one must either lower the device critical temperature, or increase the thermal impedance between the TES electrons and the thermal bath. Since the intrinsic TES response time is proportional to the thermal impedance between the TES and the thermal bath, critical temperature is the preferred parameter to vary when one is designing a TES for fast response times.

The energy resolution of the TES is then given by:

$$\delta E_{\rm FWHM} = 2\sqrt{2\ln 2} \left(\int_0^\infty \frac{4}{S_{P_{\rm tot}}(\omega)} d\omega \right)^{-1/2}$$
(2.13)

In the limit where amplifier noise is much less than any other source, the solution to this integral is (terms indicate RMS unless FWHM is specified):

$$\delta E_{\rm FWHM} = 2\sqrt{2\ln 2} \frac{\sqrt{\tau}}{\mathscr{L}_I} [(\mathscr{L}_I^2 S_{P_{\rm TFN}} + I_0^2 S_{V_{\rm TES}} + (\mathscr{L}_I - 1)^2 I_0^2 S_{V_{\rm L}}) \times (I_0^2 S_{V_{\rm TES}} + I_0^2 S_{V_{\rm L}})]^{1/4} \quad (2.14)$$

In the further limits of strong electro-thermal feedback and a base temperature well below the critical temperature, the above equation reduces to a much simplified expression:

$$\delta E_{\rm FWHM} = 2\sqrt{2\ln 2} \sqrt{\frac{4k_{\rm B}T_0^2 C_{\rm e}\sqrt{n}}{\alpha_I}} \tag{2.15}$$

This simplified version, although only strictly true in the above limits, is still a very useful expression for estimating potential device performance. It captures the strongest predictors of TES energy resolution: critical temperature, volume (through the heat capacity), the width of the transition (through the parameter α_I), and the thermal conductance (through the thermal exponent n). Fortunately, these are all parameters (except for α_I) that are relatively straightforward to engineer. For the example TES that has been studied so far in this chapter, the full-form energy resolution given by (2.14) is $\delta E_{\rm FWHM} = 0.08$ eV, while the simplified expression gives $\delta E_{\rm FWHM} = 0.11$ eV. In either case, these numbers are well below what is actually realized in practice, as they entirely neglect amplifier and environment noise, but they are a good starting point. In practice, the best detectors measured in the course of this work had a FWHM energy resolution just over an order of magnitude larger than the estimate calculated from (2.15).

Experiment design

3 Chapter

The experiment was conducted in a custom-designed chamber bolted to the cold stage of an Oxford Triton cryogen-free dilution refrigerator. The design posed several technical challenges, which fell into three broad categories:

- 1. Designing feedthroughs to pass all the electrical lines and the optical fiber from the vacuum of the cryostat through to the hermetically sealed chamber containing the superfluid He bath.
- 2. Filling the experimental chamber with helium.
- 3. Ensuring that the large volume of superfluid never became an inadvertent bomb, by emptying the chamber sufficiently fast (yet non-destructively) in the case of a rapid unscheduled warmup.

Figure 3.1 shows a computer rendering of a cross-section of the experimental chamber. The baseplate and the mounting bracket are machined from oxygen-free high thermal conductivity (OFHC) copper. The "L" shaped lid is machined from a solid block of aluminum and sealed to the baseplate with an indium seal. The chamber contains feedthroughs for low-voltage signal and amplifier wires, high-voltage wires for biasing the tungsten tip, a fiber optic line for detector characterization, and ports for filling and venting helium. Each of these sub-systems is described in this chapter.



(a) © IEEE 2014



Figure 3.1: The left panel is a computer render of the experimental chamber and is reprinted with permission from Carter et al. (2014). The right panel shows a photo of the actual experiment.

3.1 Helium plumbing

Condensing a large volume of liquid helium into a chamber at the bottom stage of a cryostat (and keeping it there) is a tricky business. When liquid helium is cooled below 2.2 K, it becomes a superfluid. Superfluid He has practically zero viscosity and can leak through even the smallest of holes. This means that special care must be taken when joining together different sections of plumbing, as many standard joints are not superfluid tight. Furthermore, superfluid He is essentially a superconductor of heat. This fact, coupled with the superfluid's proclivity for climbing walls, means that one must take care that the bottom stages of one's cryostat are not inadvertently thermally shorted together by the superfluid film. There are three ways to prevent this from happening. One might use a superfluidtight value that is closed once the reservoir has been filled to capacity; one might employ a so-called film-burner to interrupt the climbing superfluid film either via heat or a very sharp edge; or one may simply reduce the diameter of the filling tube sufficiently that even when the tube's walls are fully coated with a superfluid film, it does not present enough of a heat leak to overwhelm the cooling power available at the cryostat base plate (for a more in depth discussion of each, see Pobell (2007)). The first option is conceptually the simplest, however superfluid-tight valves that may be remotely actuated are not available commercially, though Pobell (2007) discusses how to construct such a valve from scratch (it is not a simple task). The design and manufacture of a good film-burner is one of the few trade secrets left to manufacturers of dilution refrigerators, which is a good indication of the difficulty inherent in building one from scratch. Although film burners (or film interrupters) are conceptually simple (either a small heater to locally heat above 2.2 K or a sharp enough edge to break the superfluid surface tension), the execution can require a large amount of either experience or trial and error. For this experiment the third method was employed; helium is both injected into, and extracted from, the experimental chamber using a thin stainless steel capillary. In order to avoid ice blockages in the capillary, the helium must be sufficiently cleaned of impurities before injection. To this end, the room temperature He gas was circulated through a liquid nitrogen cold trap for several hours prior to injection.

Figure 3.2 depicts the entire fill circuit, both in and out of the cryostat. Appendix B



Figure 3.2: Plumbing diagram for a system designed to handle the ultra-high purity 4 He. See appendix B for operational modes, and the text for description.

details every mode of operation discussed in this chapter.

3.1.1 Plumbing inside the cryostat

A colleague at Yale, Fragner (2013), found through trial and error that the optimal inner diameter of a He fill capillary is around 1 mm. He found that diameters below about 0.7 mm were prone to ice blockage, and that 1 mm is a good compromise between heat leak (through the superfluid Rollin film, $\propto r$)¹ and fill time ($\propto r^4$)². The capillary is heat-sunk by brazing it into spiral grooves cut into OFHC copper posts, which are then bolted to each cryostat stage. Because the capillary tubing for this experiment was purchased in five foot sections, a flange was required to join individual segments. A custom-made, circular, bolt-together, indium-sealed flange brazed or soldered to the capillary works well for this, as do the swage-style connectors from HIP³. To connect the capillary to the experimental chamber in this experiment, a circular indium-sealed flange was used, similar in design to the one used for joining sections of capillary.

The original design called for a capillary tube from room temperature to base temper-

^{1.} For a fixed film thickness, the circumference sets the heat leak.

^{2.} See the Hagen-Poiseuille equation.

^{3.} High Pressure Equipment Company, part number 15-21AF1, http://www.highpressure.com.

ature, but it was found that even the 1 mm diameter capillary was prone to frequent ice blockages. This was in part due to the initial plumbing configuration, which only allowed the helium gas to pass through a LN_2 cold trap once, several hours before it was injected into the cryostat. The more advanced setup used currently is described in the next section. The current filling tube design only employs a capillary below the 4 K stage of the cryostat, the temperature regime where it is possible to form a superfluid. Above this stage, the helium is entirely in gaseous form, and the superfluid heat-leak no longer limits the fill-tube diameter. From room temperature down to 4 K, 1/4"-diameter stainless steel bellows are used, which are brazed to copper heat-sinking blocks. The internal plumbing diagram is depicted in detail in figure 3.3.



Figure 3.3: Internal plumbing diagram. The heatsink locations are all indicated, and the legend indicates which type of connection was used at each joint: VCR is a compression-type fitting with a metal gasket, Indium is a circular bolt-together flange with an indium seal, and Swage is a flared compression fitting that crimps to the pipe. The copper blocks are directly brazed to the connecting pipe. The gray area in the chamber indicates the level of the LHe when full.

To fill the chamber, a 50 L volume of isotopically pure ⁴He (less than 1 part in 10^{12} ³He; obtained from the research group of Peter McClintock, Lancaster University, UK) gas pressurized to 2 bar (100 L at STP) is opened to the capillary through an adjustable impedance when the cryostat baseplate reaches 4 K. The reason the helium is not opened to the capillary at once is because the optical fiber feedthrough (see section 3.5) does not become sufficiently vacuum tight until well below 70 K and it is undesirable to leak helium gas into the cryostat vacuum space. The adjustable impedance is used to keep the injection pressure below about 20 Torr. This limits the heat load and keeps the dilution refrigerator from entering into an unstable mode of operation. He gas is subsequently cryo-pumped into the fill lines and eventually condensed into the chamber as the cryostat cools to base temperature. During this process, the impedance is continually adjusted (opened more and more) to keep the injection pressure constant.

To empty the chamber, heat is slowly applied to boil the liquid helium back into the 50 L gas storage vessel through the capillary. During this process, the compressor is used to keep the pressure at the top of the capillary low. This fully-closed system is useful for two reasons: no liquid level measure is required as a known quantity of gas is used, and as it is a closed system, no helium is lost. This second point is crucial, as isotopically pure 4 He is very expensive!

In the event of an ice blockage in the capillary or a rapid warm-up event due to cryostat failure, the capillary may prove incapable of emptying the chamber fast enough to avoid dangerous pressures (helium has a liquid-to-gas expansion ratio of \approx 750). To allow for the emergency decompression of the chamber, a large-diameter path from the chamber to an evacuated 50 L volume at room temperature was constructed. This emergency relief path was sealed from the chamber with a 3 bar burst-disk⁴ at the cold stage to contain the superfluid. To accommodate the thermally expanding gas while minimizing the stainless steel thermal link, the burst line is constructed from a welded series of thin-walled tubes (10 mil)⁵ of increasing diameter towards warmer stages to accommodate the gas expansion. Thermal

^{4.} Oseco, http://www.oseco.com/.

^{5.} Vita Needle Company, http://vitaneedle.com.

baffles inside the burst line shield the cold stages from blackbody radiation emanating from the warmer stages. The burst line connects to the chamber using a VCR fitting, and to a room temperature stainless steel bellows using a special metal O-ring⁶. The addition of the burst line did not add a significant heat load to the base-plate of the cryostat, and only raised the base temperature from 15 mK to about 25 mK. It did, however, make the cryostat temperature more susceptible to building vibrations produced by large air handlers on the top floor.

3.1.2 Plumbing outside the cryostat

The external plumbing system must accomplish three goals. It must be able to circulate the He through a cold trap in a closed cycle prior to filling, to remove air contamination; it must be able to both fill and empty the chamber; and it must be able to recover any He vented in the case of a burst-disk rupture. These goals are accomplished with a circulator pump, two off-the-shelf 50 L beer kegs (purchased clean and new for this experiment), two nitrogen cold-traps, and a menagerie of valves, gauges, and kwik-flange (KF) hardware. One beer keg is used as the fill volume, and one is kept at vacuum for collecting any helium that vents through the burst-disk during a failure. Beer kegs are cheaper than any vacuum/pressure vessel that is sold explicitly for scientific work and they also ship food-grade clean. To attach the kegs to the vacuum system, $KF50^7$ flanges were welded to them. Figure 3.2 shows the pumping circuit and highlights the different modes of operation, and figure 3.4 shows the beer kegs mounted overhead the experiment. Because most of the external plumbing uses compression joints with rubber O-rings that are not UHV leak-tight, the He is passed through a second cold trap right before it enters the internal fill lines in the cryostat. All the plumbing between the final cold-trap and the internal fill lines utilizes metal-to-metal UHV seals to prevent any air contamination that could result in an ice blockage. In order to evenly circulate the helium through the cold trap from a keg with only one opening, a small-diameter length of Cu pipe was inserted through the neck of the fill keg to the bottom;

^{6.} Kurt J. Lesker Company, http://lesker.com.

^{7.} Kurt J. Lesker Company, http://lesker.com.



Figure 3.4: Photograph showing the beer kegs installed overhead. The cryostat is to the lower-right, just outside the frame.

helium was pulled from the pipe at the bottom of the keg, and returned through the neck at the top of the keg. All the modes of operation are detailed in appendix B.

3.2 SQUID amplifiers

Each TES is connected to a superconducting quantum interference device (SQUID) amplifier. The SQUID amplifiers are operated in the flux locked loop (FLL) mode, and the feedback voltage (corresponding to the TES current) is monitored by a fast digital oscilloscope⁸. The SQUIDs along with the feedback and biasing electronics were purchased from Magnicon as an integrated package. The SQUIDs are low noise ($\sim pA/\sqrt{Hz}$ referred to the TES), have an input inductance of 5 nH, and a measurement bandwidth of about 6 MHz⁹. In order to keep the parasitic resistance between the SQUID amplifiers and the TESs as small as possible, the SQUIDs are mounted directly in the chamber next to the TESs and magnetically shielded on four sides by a niobium enclosure. Figure 3.5 shows the placement of the SQUID amplifiers relative to the TES detectors. The wiring distance between the TES and the SQUID is about 50 mm round trip (circuit-board trace, not twisted pair), and an estimate of 50 nH of extra inductance (the typical nH/mm estimate) is included in the circuit models to account for this.

^{8.} Agilent (now Keysight) 54855A Infiniium 6 GHz, 20 GSa/s oscilloscope

^{9.} Magnicon, XXF-1 SQUID Readout Electronics, http://www.magnicon.com.



Figure 3.5: The left panel shows a diagram of a top-down view of the copper base plate of the experimental chamber. The TES chip is on the bottom and the low-voltage feedthroughs are on the top. The three small squares in the center are the locations of the three SQUID amplifiers. For a size reference, the TES chip is 25 mm on a side. The center panel shows the actual top down view of the experimental baseplate. The right panel shows the schematic of the full electrical circuit used to read out the TES detectors and is reprinted with permission from Carter et al. (2014). The wavy wires represent either twisted-pair, or twisted-triplet. The SQUID chip uses an array of SQUIDs, rather than one single SQUID, but the operating principles are the same.

3.3 Low voltage wiring

Each of the three SQUID amplifier channels requires seven wires. In addition to these signal wires, extra wiring was installed for general use (thermometry, level sensing, heaters, etc). Copper wire was used from room temperature to 4 K, and NbTi wire from 4 K to base temperature. All 48 wires were assembled into two flat ribbon cables, which were heat sunk at each stage and fed into the superfluid volume through two 25-pin micro-D hermetic flanges¹⁰, which were laser welded into a circular flange and bolted to the chamber with an indium seal.

3.4 High voltage electronics and wiring

Although the ionization potential of He is large, it is possible to create He^{*}₂ excimers through electron discharge from a sharp needle. To maximize electric field (and minimize the required voltage), a tungsten needle was fabricated with a ≈ 100 nm tip radius following a sodium-hydroxide etch recipe published by Golov and Ishimoto (1998) (see figure 3.6). A metallic mesh connected to ground was placed just after the needle to collect the electrons emitted from the tip. Figure 3.6 shows the basic circuit diagram for the tip, as well as a photograph of the circuit installed in the chamber.

To access the tip and grid, GPO thread-in hermetic feedthroughs¹¹ were used. They are both resilient at high voltage (up to about 2 kV) and are superfluid-tight when the supplied rubber O-ring is replaced with an indium seal. The HV lines used the same wire as the low-voltage ribbon cables, but with the addition of insulating teflon sleeves. Custom designed heatsinking clamps for each stage were used to thermally anchor the HV lines without shorting them electrically, by counteracting the necessarily thick insulating layers with a large contact area (figure 3.7).

Initially, the high voltage for the tip was to be supplied by small switched-mode pro-

^{10.} SRI Hermetics Inc., Part number SRIMD505-25-B, http://www.srihermetics.com. The Ceramax proprietary ceramic forms a superfluid-tight seal between each beryllium-copper pin and the surrounding stainless steel body.

^{11.} Corning Gilbert, part number 0119-783-1, http://corning.com.



Figure 3.6: The upper left panel shows an SEM image of a sharp tungsten needle with an overlay indicating the tip radius. The upper right panel shows the housing designed to hold the tip and the grounding grid. The bottom left panel shows the housing installed in the chamber lid. The bottom right panel shows two different tip currents vs. applied voltage. The electron emission threshold is indicated by the corner in the two datasets.



Figure 3.7: These photos are of the heatsink system designed for the high-voltage wiring. The right panel shows one of the heat-sinks with the copper cap removed. The wires are soldered to the large copper pads, and a thin sheet of kapton is used to electrically isolate them from the copper cap. The left panel shows all of the heatsinks wired up and ready to be installed (one per temperature stage).

grammable DC-DC converters¹² that take an input of 0–5 V and output 0–1000 V. This small power supply was wired in series with a fast DC-DC amplifier that can output short pulses (~ μ s) of a few hundred volts. This configuration was intended to hold the tip just below the He ionization threshold and then momentarily push it over and realize a pulse of He^{*}₂ excimers. However, there were two reasons this setup was abandoned. The first is that, contrary to expectations (Guo et al. (2009) achieved excimer creation with only 400 V), the voltage required at the tip to create excimers was more than 1700 V. This was greater than the intended supply could output. Secondly the small power supplies were very noisy at the switching frequency (~ 100 kHz), which is right in the middle of the measurement bandwidth. A low-pass filter bank was added according to methods described in a technical note published by Crane Aerospace (2006), but it was not enough to damp out the interference completely.

Eventually, a commercial high-voltage power supply capable of outputting 5000 V was used¹³. It was necessary to float it using a ground-isolating plug. The internal capacitance of the supply was very high and so, when coupled to the large resistance of the tip/grid circuit, the maximum response time was on the order of several seconds. This made pulsed operation impossible. Instead, the supply was simply set to a voltage such that the detector experienced an event rate of ~ 1 Hz.

3.5 Fiber optics

It is useful to have an optical fiber mounted directly over the TES detectors in order to characterize them with photons of a known energy. To this end, a multi-mode fiber with a 300 μ m diameter¹⁴ was suspended a few cm above the TES chip. The fiber entered the cryostat through a hermetic seal at room temperature¹⁵. No attempt was made to heat-sink the fiber, and the base temperature of the dilution refrigerator was insensitive to whether

^{12.} American Power, part number M5-S1000, http://http://apowerdesign.com/.

^{13.} Stanford Research Systems, part number PS350, http://www.thinksrs.com.

^{14.} ThorLabs, part number FT300UMT, http://www.thorlabs.com/.

^{15.} Ocean Optics, part number VFT-400-UV-16, http://www.oceanoptics.com/.

or not the fiber was installed. The fiber entered the chamber through a superfluid-tight feedthrough, which was created following the procedure of Butterworth et al. (1998). In this method the seal is made through the thermal contraction of a length of heat-shrink tubing¹⁶ during cool down. Although this feedthrough was not He leak-tight at room temperature, it worked very well when cold, and was thermally cycled many times successfully. It was also, however, very fragile. A small accidental bump was often enough of a disturbance to require rebuilding of the feedthrough; this occurred several times. Finally, it was not resilient to a high pressure difference. A pressure of even 300 mBar inside of the chamber with the cryostat at vacuum and the baseplate at 4 K was enough to destroy the seal.

^{16.} TE Connectivity, part number MFT-MT1000-NO.2-X-SP, http://www.te.com/. Several brands and types of heat shrink tubing were investigated. The part listed above is the only one that tested superfluid-leak-tight.

TES design and fabrication

Chapter

D ESIGNING a detector is an exercise in compromises. The materials used and the physical shape are not only defined by what physical characteristics are desired (heat capacity, collection area, critical temperature, etc...), but also by what fabrication processing is available and how complex a process one is willing to undertake. The resulting design used in this experiment was a titanium TES with aluminum leads, which was then, in some cases, coated with a thin layer of either gold or platinum. This chapter starts with a discussion of the desired operating characteristics that are required of a detector. This is followed by a discussion of what materials and fabrication processes were available. Finally, a description is given of the steps used to fabricate the detectors. All the detectors were fabricated at Yale by the author.

4.1 TES materials

The critical temperature of pure Al is about 1.2 K, so if Al is used as an absorber, the detector TES must have a lower $T_{\rm c}$, preferably by a factor of three or more in order to efficiently trap quasiparticles in the TES. For a TES held near $T_{\rm c}^{\rm TES}$, the number of quasiparticles above the Al gap that may escape is described by a Boltzmann distribution and is $\propto \exp(-\Delta/k_{\rm B}T_{\rm c}^{\rm TES})$, where the superconducting energy gap $\Delta = 1.75k_{\rm B}T_{\rm c}^{\rm Al}$ (Bardeen

et al., 1957). For $T_c^{AI}/T_c^{TES} \geq 3$, the Boltzmann factor is $\leq 10^{-2}$. Also, the sensitivity of a TES improves with decreasing critical temperature, so the lower the T_c of the TES in general, the better. Although it is common to achieve a low T_c by combining a bilayer of a normal metal and a superconductor, the added fabrication and engineering challenges involved in tuning the bilayer properties ruled out that approach for this work. There are only a few natural superconductors that may be reliably produced in thin-films, that have a low enough critical temperature to trap quasiparticles, and have a high enough critical temperature to operate above ~50 mK in a dilution refrigerator; they are uranium (U), hafnium (Hf), tungsten (W), titanium (Ti), and iridium (Ir), and each will be discussed separately. One thing that will not be considered here is the coupling of triplet state excimers to the TES surface. The mechanism for this is highly dependent on the surface density of states of the TES, which may altered at will by depositing a very thin layer of some other metal (or oxide) on top of the TES. This is discussed more in chapter 7.

Uranium

Uranium has a T_c of 200 mK, which would be perfect if it weren't for the two facts that uranium is highly radioactive and one of the most controlled materials in the world.

Iridium

Iridium has a bulk T_c of about 100 mK. Iridium does not tarnish or oxidize. From a fabrication perspective, this is very appealing, as one may deposit a layer of Ir, process that layer in atmosphere, and deposit another layer of metal onto the processed Ir without worrying about the formation of an oxide tunnel barrier. Iridium may be either evaporated or sputtered, although successful evaporation requires ultra-high vacuum and a heated substrate (Irwin and Hilton, 2005). Iridium is easily RF sputtered to achieve a thin film with a T_c of 120 mK (Bogorin and Galeazzi, 2008), and that process has been meticulously documented by Bogorin (2008). Iridium has two drawbacks. The first is that it can suffer from phase separation (where the material is partially normal and partially superconducting) when used as a calorimeter due to its low thermal conductivity and this can result in non-uniform phase across the TES, which negatively affects the response (Fukuda, 2002). The second, and more important, is that Ir is extremely expensive. Since Yale lacks the facilities to properly evaporate Ir, it would have to be sputtered. Sputtering targets are very wasteful in the sense that once they are used up, there is still a large amount of metal left over. In the end, the high expense of Ir is what removed it from consideration as a detector material.

Tungsten

Tungsten has a phase-dependent critical temperature. The α -phase has a T_c of about 15 mK, and the β -phase T_c is between 1 K and 4 K. Thin film W is typically a mixture of the two phases depending on deposition parameters, and may be tuned to exhibit either a pure phase or some mixture of the two. Lita et al. (2005) have characterized how the T_c of sputtered W varies with sputtering power and pressure. Tungsten has a much higher thermal conductivity than Ir and therefore does not suffer from the phase-separation issue as much. For these reasons, W was the initial choice for making the sensors. However, despite several attempts over some months, obtaining sputtered W with a $T_{\rm c}$ above 20 mK proved to be untenable. After several discussions with the authors of Lita et al. (2005), it became clear that the failure to successfully sputter W was due to two reasons. The sputtering chamber at Yale does not have the ability to heat the substrate, and the wafers were coated in PMMA e-beam resist (to pattern the W using a lift-off process), which outgassed during deposition and affected the resultant W phase. In order to achieve a good phase mixture, and therefore an appropriate $T_{\rm c}$, the sputtering chamber must be absolutely clean; the outgassing of the PMMA was sufficient to derail the process entirely. In fact, Lita found that even sputtering a different metal in the same sputtering chamber was sufficient to force any W sputtered in the same chamber into the α phase. For these reasons, it was decided to abandon the idea of a tungsten TES.

Hafnium

Hafnium has a critical temperature around 120 mK and has been used successfully for TESs (Lita et al., 2009). It is also relatively inexpensive (compared to Ir). However, after several unsuccessful months attempting to engineer W thin-films that were acceptable for

TES fabrication, the decision to avoid trying to characterize another new material was made. Instead, Ti was chosen as it was readily available in an evaporator and already well characterized at Yale.

Titanium

Titanium has a bulk $T_{\rm c}$ of about 400 mK. It is easily evaporated onto a room temperature substrate and the quality of the vacuum in the evaporator does not seem to influence the $T_{\rm c}$ very much. Although 400 mK is a little higher than the ideal temperature of ~100 mK, the advantages of using Ti for these initial studies far outweighed the disadvantage for Ti of losing some signal due to incomplete quasiparticle trapping. Additionally, Yale has an evaporation chamber that has both Ti and Al targets, which means a bilayer may be deposited without breaking vacuum, ensuring very good contact between metals. Furthermore, Ti devices created with the same evaporation chamber have been well characterized in prior years (Santavicca et al., 2009, 2010). The T_c of Ti is also tunable (in general) by combining the Ti with a thick layer of normal metal and using the proximity effect to lower the $T_{\rm c}$ (Ventura et al., 2002). This was not attempted however, as this work was meant as a proof of concept rather than a best-possible-implementation. In retrospect, the 400 mK transition temperature was somewhat advantageous for studying the dynamics of He^{*}₂ excimers as, near the end of the experiment, a malfunctioning air-handler in the building dramatically increased the mechanical vibrations of the cryostat, raising the base temperature to nearly 100 mK.

4.2 Fabrication

All devices discussed in this dissertation were fabricated on bare (unoxidized) high-resistivity silicon wafers¹. All the metal depositions were accomplished using electron beam evaporation in a commercial evaporator from Plasma Systems². The patterning was done using electron-beam lithography in a Raith EBPG 5000+ system. In Chapter 5 several configura-

^{1.} Crystec, (100) oriented, 500 μ m thick, single-side polished, 2 inch Si wafers with resistivity > 10 k Ω cm

^{2.} Plassys UMS300 UHV, http://plassys.com

tions of detectors are described (no shield, shield, reflective substrate). The device without a shield and the device with a reflective substrate were made following the same steps. The device with a shield required an extra step. Detailed recipes for each process step are provided in appendix D.

4.2.1 Alignment marks

The wafer is cleaned, and a bilayer of electron beam (E-beam) resist (see section D.2) is applied. A pattern of $20 \times 20 \ \mu m^2$ squares are written via E-beam, and then 400 nm of Cu is evaporated and lifted-off to define the alignment marks. These marks are used to precisely position the etch window over the region destined to become the TES.

4.2.2 Ti/Al bilayer

A bilayer of resist is applied. The outline of the detectors, wiring, and absorbers is written via E-beam. Then a bilayer of 15 nm of Ti and 300 nm of Al is evaporated and lifted-off.

4.2.3 Al etch

A single layer of resist is applied. Windows are opened in the resist via E-beam lithography directly over the areas that are to become the TESs. The exposed Al is then etched down to the Ti, defining the detectors (Ti is a natural etch stop for the etchant used). This completes the fabrication process for the unshielded device and the device with a metalized substrate, the only difference being the pattern written in the previous step.

4.2.4 Shield fabrication

To make a substrate photon shield, the following steps are followed after the final step above. The device is coated with a 1 μ m thick layer of E-beam resist. Then a bilayer of 50 nm of Cu and 50 nm of Al is evaporated. A single layer of resist is applied, and a window is opened up over the TES. The Al and Cu are both etched away, leaving the 1 μ m layer of PMMA. This layer may be developed away, as it received a weak dose of E-beam current during the earlier E-beam write. This development process is the same as that described in appendix D, but requires 10 min.

Name	TES Area (μ m ²)	Substrate shield	Device type	
А	40 imes 40	None	Single pixel	
В	20 imes 20	Lithographed shield	Single pixel	
С	20 imes 20	Reflective substrate	Single pixel	
D, E, & F	10×15	Lithographed shield	Single pixel	
G	40 imes 40	None	Two-pixels with Al absorber	
Н	20 imes 20	Lithographed shield	Two-pixels with Al absorber	
I	20×20	Reflective substrate	Two-pixels with Al absorber	

Table 4.1: A list of TESs measured in this work.

4.3 Description of TESs used in experiment

This section contains a short description of each of the TESs fabricated and measured for this dissertation. All the devices listed here were fabricated with the same process (except where otherwise noted), deposited on the same type of substrate (high-resistivity Si, 400 μ m thick wafers), and have a Ti thickness of 15–20 nm and an Al thickness of 300 nm. Table 4.1 gives a basic overview of the TESs measured in this work.

4.3.1 TES A: bare TES

TES A (pictured in figure 4.1a) was a $40 \times 40 \ \mu m^2$ single pixel with 5 μm wide leads. This device was useful for measuring the electron-phonon coupling of the Ti (and thereby the thermal conductance), and also the system noise, but had a very poor effective energy resolution. This was because substrate heating due to photon absorption was the dominant signal measured, and a complicated fitting procedure was required to extract the relevant TES signal (see section 6.1); this could have been mitigated by carefully aligning the fiber directly above the TES, but that would have meant blocking out the He^{*}₂ signal.

4.3.2 TES B: shielded TES number 1

TES B (pictured in figure 4.1b) was a $20 \times 20 \ \mu m^2$ single pixel with 5 μm wide leads. In an attempt to rectify the problem of substrate heating, this detector was constructed



(a) Optical microscope image of TES A. The Ti square is $40 \times 40 \ \mu m^2$ and the Al leads are 5 μm wide.



(b) Optical microscope image of TES B. The Ti square is $20 \times 20 \ \mu m^2$ and the Al leads are $5 \ \mu m$ wide, and are barely visible under the substrate shield, which is a Cu/Al bilayer. The thick black square is an optical artifact and the horizontal color bands are interference fringes.



(c) Optical microscope image of TES C. The Ti square is $20 \times 20 \ \mu m^2$ and the Al leads are 5 μm wide at the TES. The substrate is also coated in Al, save for a 3 μm gap to electrically isolate the TES and wiring.

Figure 4.1: Optical microscope images of TESs A, B, and C

with a shield as outlined above. This device had the best energy resolution of any of the devices fabricated. However, the time constant of this device was larger than any other by a factor of ~ 100 and the resistance was also much larger, indicating that perhaps the electron-phonon coupling of the Ti was modified somehow. During the shield fabrication, the Ti film was baked while coated with PMMA, which altered the film properties, likely resulting in the anomalous behavior. Unfortunately, this TES was accidentally destroyed during an accident involving a high-voltage discharge.

4.3.3 TES C: TES with reflective substrate

TES C (pictured in figure 4.1c) was a $20 \times 20 \ \mu m^2$ single pixel with 5 μm wide leads. This TES was fabricated without a shield. Instead of a metallic shield on a layer of PMMA, the substrate of this device was coated entirely in aluminum except for a small $\sim 2 \ \mu m$ wide channel surrounding the device to keep it electrically isolated. The intent of the design was that any photons incident on the substrate would reflect, rather than be absorbed. This TES had a similar time constant and similar resistivity to TES A. The device performance was much better than TES A, but a substrate contribution to the signal was still observed. This was the first TES that was immersed in superfluid helium, and also the first TES to detect the excimer signal. However, the performance was not nearly as good as either TES B or TES D.

4.3.4 TES D, E, and F: shielded TES number 2

TES D (pictured in figure 4.2) was a $10 \times 15 \ \mu m^2$ single pixel with 5 μm wide leads. This TES was fabricated with a substrate shield, but in a slightly different way from TES B. Instead of performing the aluminum etch that exposed the Ti surface before the PMMA shield spacer was added, this Al etch was performed last, after the shield had been added; essentially the final two fabrication steps outlined above were swapped. This reordering of steps was so that the Al would protect the Ti surface from contamination from the PMMA during the shield fabrication. This TES had similar resistivity and similar time constants to TESs A and C, indicating that the altered fabrication recipe protected the Ti. The energy resolution was still not as good as TES B, but it was sufficient to resolve single blue photons. This TES (along with TESs E and F) was used to take all the helium excimer data described in chapter 7.

TESs E and F were identical to TES D, save for an extra layer of sputtered metal coating the detector. TES E was coated with 10–20 nm of gold, and TES F was coated with 10–20 nm of platinum. These thicknesses are estimates based on past sputter-tool performance and were not measured. The Ti surfaces were not cleaned in any way prior to the sputter coating.



Figure 4.2: The left panel is an optical image of TES D. The Ti TES is $10 \times 15 \ \mu m^2$ and is visible underneath the substrate shield. The leads are also just barely visible in the color image. The right panel, a scanning electron microscope image of TES D (in the same orientation as in the left panel), shows the cross section of the shield, which is a Cu/Al bilayer on a thick layer of electron-beam resist. One may also see the edges of the Ti TES where it meets the Si substrate. The dimpling of the shield around the edges of the TES is due to the top layer of PMMA reacting with the electron beam from the SEM.

4.3.5 Devices G, H, and I: the two-TES detector

Devices G, H, and I (pictured in figure 4.3) were fabricated simultaneously (on the same wafer) with TESs A, B, and C, respectively. The geometry consisted of two Ti TESs connected with a long aluminum absorber. The hope was that these devices could be used as large-area excimer detectors with position resolution. The operating principles of these devices are discussed in appendix A. Operation of these devices required that the ground wires of two individual TESs (and consequently their respective SQUID amplifiers) be tied together. Unfortunately the SQUID control electronics package that was supplied with the amplifiers was not capable of operating in this mode. When biased individually, the TESs that made up Devices G and I had similar properties to TESs A and C respectively, although they did not have as good energy resolution (due to the large Al absorbers). TES H never went superconducting (the reason is unknown) and so was not measured.



Figure 4.3: Optical microscope images of TESs G, H, and I. Each device consists of an aluminum absorber between two Ti TES pixels. In the image of TES H, the two pixels are covered with a shield layer and are not visible. Although the TES H leads are visible, they are also covered by a shield; the aperture is only over the absorber area.

Detector characterization

Chapter

TES parameters may be measured and presents some measurements from the devices described in section 4.3. The final section discusses the basics of photon detection. In practice, for single-photon detection, a careful calibration of all the TES parameters is not really necessary. This is because any device that is sensitive to single-photons is self-calibrating through fitting the response histogram of the TES (to a known energy source) with a Poisson distribution—a process described in section 5.5 and chapter 6. For this reason, not all the devices used in this experiment were exhaustively characterized. At least one example of each type of measurement is given in this chapter, but they are not all necessarily of the same TES.

Ideally, the characterization of a TES detector would simply consist of measuring every single parameter listed in chapter 2. At this point, one could appeal to the small-signal pulse model (discussed in section 2.3) to create a model pulse response to an incoming photon, use this model to construct an optimal filter template, and then be done with characterization and calibration in one fell swoop. Unfortunately, some parameters are harder to measure than others, and not all may be directly measured while the TES is wired in the electrothermal feedback circuit. An example of two such parameters are the sensitivities of the resistance to temperature (α_I) and to TES current (β_I). These are difficult to measure



Figure 5.1: $I_{\rm b}/I_{\rm TES}$ data (a) and photon-detection response (b) fit by the numerical models from chapter 2. Data are from TES D. The pulse data is an average of several hundred single-photon absorption events. Data is colored in light blue, and the fits are black, dashed lines. Table 5.1 gives the relevant fit parameters. It is clear that the pulse data in the right panel is not well-fit by a single exponential fall time. This is discussed in more detail in chapter 6

when the TES is in parallel with a small shunt resistor, and the long time constant (~week) involved in cycling the dilution refrigerator means that dedicating a single cool-down of the cryostat just to get these two numbers is not the most efficient use of time.

Luckily, many of the TES parameters that are difficult to measure directly may be inferred by making several measurements of the TES current as a function of bias current at different temperatures. With these curves in hand, one may extract out many of the important TES parameters. An example of using the numerical model to estimate several parameters simultaneously is depicted in figure 5.1. The numerical model from chapter 2 is fit to the I_b/I_{TES} data (from TES D) and also to a photon-detection pulse (also from TES D), and the parameters used to fit the model are listed in table 5.1. One should not put too much stock in these parameter values as the fit was largely by hand (least-squares optimization proved to be too computationally expensive to be worth pursuing) and there are likely several degenerate sets of parameter values that give a similar-looking curve. This fit could be improved by carefully measuring as many of the values in the central column of table 5.1 as possible in order to reduce the number of free parameters. Despite the relatively non-rigorous fitting process, the parameter values returned by the fit are all very reasonable in the sense that they are well in line with measurements made in this work and also with

Parameter	Value	Parameter	Value	Parameter	Value
Width	$10 \ \mu { m m}$	γ	$304 \text{ J/m}^3 \text{K}^2$	L	50 nH
Length	$15~\mu{ m m}$	$\Sigma_{ m e-ph}$	$1 imes 10^9 \ \mathrm{W/m^3 K^n}$	α_I	60
Thickness	15 nm	n	5	β_I	1
$R_{ m N}$	$48.6~\Omega$	T_{c}	$345 \mathrm{~mK}$	$E_{ m phot}$	2.6 eV
$R_{ m s}$	$200 \ \mathrm{m}\Omega$	$T_{\rm b}$	$132 \mathrm{~mK}$	η	0.4
$R_{ m p}$	$5~\mathrm{m}\Omega$	Ic	$70 \ \mu A$	Ib	18 µA

Table 5.1: Parameter values corresponding to the numerical fits depicted in figure 5.1.

other measurements found in the literature for micron-scale Ti TES detectors (Portesi et al., 2015; Taralli et al., 2010; Santavicca et al., 2009). One way to improve the quality of this by-hand fitting process would be to simultaneously fit several $I_{\rm b}/I_{\rm TES}$ curves at different base temperatures with the same set of values. This was not attempted here as it is a fairly laborious process and, as the detectors are largely self-calibrating (see chapter 6), is not necessary for the process of detecting He^{*}₂ excimers.

5.1 TES current (I_{TES}) vs. bias current (I_{b})

The first (and most important) measurement is to sweep the bias current while measuring the current through the TES at several temperatures. The resulting curves may be used to determine the critical current as a function of temperature, the parasitic resistance, and the TES normal-state resistance.

5.1.1 Parasitic (R_p) and normal (R_N) resistance

Figure 2.3 shows a simulated I_{TES} vs. $I_{\rm b}$ curve in which the bias current has been swept from zero to well above the critical current and then back to zero. At zero bias current, the TES is in the superconducting state and the amount of current flowing through the TES is set by the parallel combination of the shunt resistor and any parasitic resistance in series with the TES. If the parasitic resistance is zero, all the bias current will flow through the TES and this part of the curve will be a straight line with a slope of 1 A/A. Fitting this



Figure 5.2: The left and right panels show I_{TES} and R_{TES} , respectively, as functions of decreasing $I_{\rm b}$ for TES D. The data was taken at 130 mK and is an average of 256 measurements. $R_{\rm N}$ is shown in the right panel as a dashed line, and $R_{\rm p} = 5 \text{ m}\Omega$.

portion of the curve to a straight line and measuring the slope gives a direct measure of the parasitic resistance, provided the value of the shunt resistance is already known.

Eventually the current through the TES will exceed the critical current of the superconductor and the resistance of the TES will begin to increase as the superconductor transitions to its normal state. As this transition happens, the amount of current flowing through the TES decreases with increasing TES resistance. Eventually the TES is driven completely normal and the curve again becomes a straight line. Fitting this portion of the curve to a straight line and measuring the slope gives a direct measurement of the normal resistance.

Alternatively, one could simply transform I_{TES} to R_{TES} via the first term on the righthand side of (2.4) and plot the resulting curve as a function of bias current. The parasitic resistance will then be the zero-resistance offset at $I_{\text{b}} < I_{\text{c}}$. Once this is subtracted off, the normal resistance may be read off the other end of the plot as the value to which the plot flattens out at.

Figure 5.2 shows measured $I_{\rm b}/I_{\rm TES}$ and resistance curves for TES D. The dashed lines on The $I_{\rm b}/I_{\rm TES}$ curve in 5.2a indicate the slopes associated with the normal and parasitic resistances. The dashed line on the resistance curve in 5.2b indicates the normal resistance. The $I_{\rm b}/I_{\rm TES}$ curve was taken by sweeping $I_{\rm b}$ from high to low.

5.1.2 Critical current (I_c) and critical temperature (T_c)

There is some hysteresis of the critical current because the critical current is a function of temperature; a device that is warm from Joule heating will have a lower critical current than a device that is fully superconducting and at base temperature. The critical current measured as I_b is increased can be recorded at several temperatures and the resulting curve may be fit to the Ginzburg-Landau relation $I(T) = I_c(1 - T/T_c)^{3/2}$ and used to extract the zero-temperature critical current I_c and the zero-current critical temperature T_c . It is entirely possible that the Ginzburg-Landau relationship will not fit the data well as it is based on the assumption of a perfectly homogeneous one-dimensional superconductor and is only valid near T_c . If this is the case, trial and error may be used to find a better fit function, and this fit function may be used in (2.1) to make a better model of the resistive transition vs. current.

5.2 TES Joule power (P_{TES}) vs. bias current (I_{b})

The Joule power is given by (2.5). Ideally P_{TES} as a function of bias current will be zero while the TES is superconducting, some constant value while the device is held on the transition and the electro-thermal feedback perfectly balances the input and output power, and then quadratic in $I_{\rm b}$ once the TES is driven fully normal. There are two major reasons why a TES might exhibit a behavior in the transition region that deviates from the expected constant value.

1. A TES may experience phase separation during the superconducting transition. Typically, a TES should transition smoothly from being all superconducting to all normal as it is heated. However, it is possible that instead it can separate into multiple spatial regions that have slightly different transition temperatures and critical currents. This effectively turns the TES into multiple TESs in series and the effect on the Joule power curve is the introduction of a number of steps into the region that should be smooth. Phase separation happens when the internal thermal conductance of the TES (typically dominated by electron-electron interaction and electron diffusion) is sufficiently lower than the dominant cooling mechanism (electron-phonon interaction) that regions of the TES cool into the substrate faster than the TES can equilibrate.

2. It is also possible for the "constant" power region of the $P_{\rm J}$ curve to have a uniform slope. The slope of this portion of the curve is a measure of the width (in temperature) of the superconducting transition.

In practice, both of these effects may be present with different contribution strengths. The power curves depicted in figure 5.3b, from TES A, exhibit one step-like feature as well as a region that has a uniform slope. This suggests that the TES is experiencing some minor phase separation, but it still has a large linear section that is fairly wide in temperature. The simple thermal model from chapter 2 would require a more complicated equation to accurately model these power curves. Compare these to the power curve measured from TES D in figure 5.3d. Although the curve from TES D has a slope in the bias region, it is very smooth with no kinks or steps, indicating that there is no phase separation present. This is not surprising since TES D is much smaller than TES A.

The TES power vs. bias current curve may be used to infer values for thermal conductance as well as the exponent, n, that determines the power-law for TES cooling.

5.2.1 Thermal conductance (G_{e-ph}) and thermal exponent (n)

The thermal conductance may be measured indirectly by measuring the TES Joule power at a fixed bias current at a number of different bath temperatures. In steady state operation (2.2) becomes $I_{\text{TES}}^2 R_{\text{TES}} = P_{\text{TES}} = V \Sigma_{\text{e-ph}} (T_{\text{c}}^n - T_{\text{b}}^n)$. A plot is then made of P_{TES} vs. T_{b} and the above power law is fit to the data, allowing n and $\Sigma_{\text{e-ph}}$ to vary. G is the derivative of the power law and is given by $G = nV \Sigma_{\text{e-ph}} T_{\text{c}}^{(n-1)}$.

Figure 5.3 shows bias curves at three temperatures and their associated calculated TES power curves from TES A. Figure 5.3c shows the steady state power as a function of temperature for two different bias points (indicated by dashed gray lines on the power plot). Each data-point on the third panel corresponds to an $I_{\rm b}/I_{\rm TES}$ curve taken at a different cryostat temperature; only three are shown in the first two panels for clarity. The fits give values for $K = \Sigma_{\rm e-ph}V$ and n. Note that at different bias points the values for



Figure 5.3: The first three panels depict the process of using several $I_{\rm b}/I_{\rm TES}$ measurements to calculate $K = \Sigma_{\rm e-ph} V$ and *n* for TES A. The two dashed vertical lines in the second panel indicate the bias points that were used to take the two datasets depicted in the third panel. The last panel shows a power vs. bias current curve calculated from the $I_{\rm b}/I_{\rm TES}$ curve depicted in figure 5.2 for TES D. Note the lack of any cusp-like features in the transition region.
thermal conductance and n are slightly different. It is also interesting to note that, for TES A (see figure 5.3b), there appears to be a cusp in what should be the smooth linear region of each power curve. As discussed earlier in this section, it is likely that this TES, which was the largest one measured, was experiencing a small amount of phase separation. For comparison, the power curve from TES D, depicted in figure 5.3d, does not contain any cusp-like features. Throughout the course of this experiment, TES A was the only subject of an attempt to measure Σ_{e-ph} and n as the values from the fits in figure 5.3 are in reasonably good agreement with values measured by Wei et al. (2008).

For a TES that cools predominately through electron-phonon coupling in the superconductor n = 5 is the value predicted by theory for a pure metal (Irwin and Hilton, 2005). However, a range of values of n may be reasonably expected for the two following reasons:

- 1. Measurements of n can be highly dependent on the device resistance. As an example, Lindeman et al. (2008) report that using the same method used here, they found values of n ranging from 2 to 8 for the same system (a Ti/Au TES on a SiN membrane), depending on which resistance they chose to measure at. When they developed a more accurate method, they found that n = 3 for their system (as would be expected for a system that cools predominantly through phonon-phonon interactions).
- 2. Sergeev and Mitin (2000) calculate an expected range of n between 4 and 6 for electronphonon coupling depending on film disorder. Gershenson et al. (2001) report values of n between 4 and 6 for Hf and Ti films. Wei et al. (2008) also report values of n between 4 and 6 for Ti TESs.

Another way to arrive at a value for G is to measure the power spectral-density of the TES as a function of temperature. This is difficult and was not attempted. If the thermal-fluctuation noise dominates over the amplifier noise, then the equations in section 2.3.2 may be used to infer the TES thermal conductance. On the other hand, if the amplifier noise dominates, a good measurement of G may be used to subtract out the thermal-fluctuation noise contribution to the power spectral-density and get a reasonable estimate of environmental and amplifier noise contributions.



Figure 5.4: Simulations of resistance vs. temperature at zero bias current for a bare model TES (red) and resistance vs. temperature for the same model TES configured for electro-thermal feedback with a shunt resistor (blue).

5.3 Temperature (T_{TES}) vs. bias current (I_{b})

At steady state operation (2.2) may be solved for TES temperature and the result is given as (2.7). One may now plot the calculated resistance against the calculated temperature. This R vs. T curve will not be as sharp as one would expect from a direct measurement without the presence of the shunt resistor. Figure 5.4 shows two resistance curves. One is a plot of (2.1) with $I_{\text{TES}} = 0$ and the other is the resistance corresponding to plotting (2.4) vs. (2.7) for the solved $I_{\rm b}/I_{\rm TES}$ curve. Accurately generating this R vs. T curve from real data requires a careful measurement of the thermal conductance parameter.

In ETF mode, the TES current varies with resistance and so the derivative (dR/dT) of this curve is a measure of the sensitivity of the TES to both temperature and current, and contains information about both α_I and β_I .

5.3.1 TES sensitivity to temperature (α_I) and current (β_I)

Both α_I and β_I (defined in table 2.1) are fairly straightforward to measure if one has the ability to measure the complex TES impedance as a function of frequency. This requires a special measurement setup that was not available during this work; the process is described by Kinnunen (2011). Alternatively, α_I may be very nearly obtained by differentiating the R vs. T curve of a bare TES (one without any shunt resistance) measured at a very small current (ideally zero, but that is not practically possible). Measuring α_I and β_I individually, however, is not necessary as a third quantity may be used to relate them.

The combined sensitivity of the TES to both temperature and current may be calculated from the R vs. T curve measured while the TES is configured in ETF mode (blue curve on figure 5.4), is defined as $\alpha_{IV} \equiv d \log R/d \log T$, and is related to α_I and β_I by Kinnunen (2011):

$$\alpha_{\rm IV} = \frac{2\alpha_I + \frac{n}{\phi}\beta_I}{2\beta_I} \tag{5.1}$$

where the parameter $\phi = (1 - T_{\text{bath}}^n/T_c^n)$. With this equation in hand, one can calculate α_{IV} and then relate α_I to β_I . Thus, depending on experimental setup, one may choose to measure whichever is easiest. In this work, the typical procedure was to measure α_{IV} , relate β_I to α_I via (5.1), and then fit a measured photon pulse with the model from section 2.3, treating α_I as a free parameter. This saved the amount of time it would take (roughly a week) to devote an entire cool-down to measuring a single parameter. Figure 5.5 shows the R vs. T curve calculated for TES D as well as a calculation of α_{IV} vs. bias current. The temperature calculation relies on knowing both Σ_{e-ph} and n. For this calculation, the fit parameters from table 5.1 were used. The jagged nature of the α_{IV} curve is an artifact resulting from taking a numerical derivative of noisy data. Decimating and then smoothing the data can help make a numerical derivative less jagged (both of those operations were applied to the data prior to calculating α_{IV}), but will not entirely remove the effect.

5.3.2 TES heat capacity $(C_{\rm e})$

The heat capacity is the most difficult parameter to measure. A direct measurement would require a totally dedicated experimental setup. An indirect measurement is the best hope, but from figure 2.4 it is clear that C has a very small effect on the $I_{\rm b}/I_{\rm TES}$ curve and so any determination of the heat capacity from fitting the numerical model to data will likely be dominated by uncertainties in variables that couple more strongly to the $I_{\rm b}/I_{\rm TES}$ curve.

There are two measurable quantities where the heat capacity factors in strongly, and those are the device time constant and the energy resolution. If all other parameters have



Figure 5.5: Calculated α_{IV} plotted against bias current for TES D (a). Calculated temperature plotted against measured resistance for TES D (b). The temperature was calculated according to (2.7). Values for Σ_{e-ph} and *n* were taken from table 5.1.

been carefully measured, the heat capacity may be determined by fitting a TES pulse with the model from section 2.3, and treating C as a free parameter. If (as previously mentioned) α_I is also being treated as a free parameter, this task is somewhat more difficult, as both quantities affect the TES fall-time strongly. One possible option (that was not explored in this work) is to bias the TES detector in such a way that the operating resistance of the TES is equal to the shunt resistance. In this configuration, the electro-thermal feedback should be zero, and the TES time constant will be the intrinsic time constant $\tau = C/G$. Finally, if the thermal noise is the dominant system noise contribution, then the measured energy resolution could be used to calculate C. However, from (2.15) it is clear that this method has the same difficulty as using the time constant; the energy resolution also depends strongly on α_I . For the purposes of this experiment, it was decided to use the value measured by Taralli et al. (2010) for evaporated Ti on Si, which is very near the book value.

5.4 TES noise

Section 2.3.2 discusses the dominant noise sources in a TES. Figure 5.6 depicts the measured current noise for TES A (green trace). The other traces are the calculated curves for the three dominant TES noise sources: Johnson noise in the TES and in the shunt resistor (blue curves), and thermal fluctuation noise in the TES (red curve). The SQUID noise quoted by



Figure 5.6: The measured TES noise (TES A) plotted along with all the major sources of noise. Reprinted with permission from Carter et al. (2014) © IEEE 2014. Further description is in the text.

the manufacturer of the SQUID amplifiers is also plotted (pink curves). The thick black line is the sum of all the calculated noise sources. The dashed black line is the sum of the noise sources, with a numerical low-pass filter added to match the 1.9 MHz low-pass filter that was physically present between the SQUID amplifier output and the oscilloscope input. The measured noise is well-described by the calculated contributions. There are some localized spikes in the measured noise at several frequencies that represent environmental sources of noise. These are discussed in more detail in appendix E. The calculated noise is somewhat larger than the measured noise below 10 kHz. There are two possible explanations for this. The first is that the measured value for thermal conductance used in the calculation may be somewhat high, thereby overestimating the TFN contribution. The second is that the measurement of the noise at low frequencies may not be a very accurate representation of the actual noise. This measurement was accomplished by averaging together several hundred FFTs of oscilloscope traces, and this method is less accurate at low frequencies (the frequency resolution is determined by the length of the oscilloscope trace, which is necessarily finite). For a really good noise measurement, one should use a spectrum analyzer.

The most important take-away from this figure is that, except at low frequencies, all the intrinsic TES noise contributions are much less than the amplifier noise. All the other TESs fabricated in this project are smaller than TES A, which means that their thermal noise contributions are even smaller; in all cases, the dominant noise contribution to the experiment is amplifier noise. Ideally, one would operate in the regime where the TES noise dominates, however ideally one would also have lower-noise amplifiers (lower-noise SQUID amplifiers are readily available, but are also much more expensive).

5.5 Photon detection

In order to act as a photon detector, an appropriate bias current must be applied to the TES in order to hold it on its resistive transition. Enough bias current should be applied to keep the TES in the strong electro-thermal feedback mode (large values of α_{IV}), but still low enough in the transition that the largest expected signal won't push the TES out of the linear operating regime. Over the course of this experiment, the practice was to pick a bias current that would put the TES operating point at the beginning of the "flat", or linear region of the power vs. bias current plot. For instance, TES A was biased at 20 μ A (see figure 5.3b for the TES A power curve) and TES D was biased at 16 μ A (see figure 5.3d for the TES D power curve).

When the TES absorbs a photon it will heat up, and the resistance will increase, diverting current from the TES branch of the circuit to the shunt resistor branch. As the TES cools back down, the current through the TES increases back to the equilibrium value. The result is a negative current pulse. If this current pulse is multiplied by the bias voltage, the result has units of power. Physically, this quantity corresponds to the energy per second leaving the detector through electron-phonon cooling. Integrating this power over the duration of the pulse gives the amount of energy removed from the TES, and by inference, the amount of energy deposited in the TES by the photon (so long as that deposited energy is not too much to saturate the detector).

If one uses a pulsed monochromatic photon source and attenuates it sufficiently, then one would expect to measure a discrete set of pulse areas at the detector corresponding to the absorption by the TES of integer numbers of photons; sometimes there will be one, sometimes two, sometimes three, and so on. The probability of measuring a pulse area $N \times A$ (where A corresponds to the area for a single photon and N is some integer) in this limit is well described by a Poisson distribution where the average photon number per pulse is μ . In reality however, the detector has some measurement noise, the source is not perfectly monochromatic, and the photon absorption process does not always deposit the exact same amount of energy each time, so there is some broadening of this distribution. If the detector noise processes are white (or constant) within the signal bandwidth, then this broadening may be described by convolving the Poisson distribution with a Normal distribution (Hogg et al., 1972). Finally, it is possible that some photons will fall on the substrate, or be absorbed by the detector leads. If this extra energy is constant between laser pulses, then there may also be an offset applied to the broadened distribution, effectively increasing the amount of energy measured per photon. If one repeatedly creates pulses at the light source, measures the resulting energy in the detector, and makes a histogram of the measurements, then that histogram may be fit by:

$$f(x) = \frac{A}{\sigma_{\rm s}\sqrt{2\pi}} \sum_{n=0}^{\infty} \frac{e^{-\mu}\mu^n}{n} exp\left(-\frac{(x-x_0-nx_{\rm s})^2}{2(\sigma_{\rm s})^2}\right)$$
(5.2)

where μ is average photon number, x_s is a scale factor that relates pulse integral to photon number, x_0 is an offset, and $\sigma_s = x_s \delta E_{\rm FWHM} / (2\sqrt{2 \ln 2}E_{\rm phot})$ is related to the full-width at half-maximum (FWHM) energy resolution $\delta E_{\rm FWHM}$ of the detector as well as the deposited photon energy $E_{\rm phot}$. A is a normalization parameter (not the pulse area), and is equal to the integral of the histogram being fit. Figure 5.7 shows three different data sets taken with TES B, fit with (5.2); each dataset consists of 10 000 measured pulses. The incident energy was provided by a 2.6 eV pulsed blue laser and each data curve was taken at a different laser attenuation, and thus a different average photon number, as indicated. This plot showcases the "self-calibrating" nature of the TES detector: by fitting (5.2) to the



Figure 5.7: Histograms of pulse areas at three different attenuations measured with TES B. Reprinted with permission from Carter et al. (2014) © IEEE 2014. The light-source was a pulsed 2.6 eV laser. The histograms are all fit by (5.2).

histogram of measured pulse areas (or pulse heights, as height is proportional to area for an exponential pulse) one may determine the pulse area (or height) that corresponds to the absorption of a single photon of known energy. With this value in-hand, a light-source of unknown energy may be applied to the TES, and its spectrum may be determined. This only works in the limit that the unknown source is attenuated sufficiently that no more than a single photon is ever incident on the TES at a time as simultaneous absorption of two photons of different energy could confuse the issue.

TES B was by far the best functioning TES produced during this research, and the only one that was directly amenable to this simple "self-calibration" routine. For reasons discussed briefly in section 4.3.2, TES B was somehow dirty (as determined by its higherthan-normal resistivity), and likely chemically distinct (due to the fabrication process) from the other TESs measured in this work, which were all elemental Ti. Unfortunately, it met an early demise due to an accident involving high-voltage. Analyzing and understanding the pulse measurements from the other TESs required more care and analysis, and is the subject of the next chapter.

TES calibrations

Chapter

FFICIENCY (η) is one of the most important things to know about a TES that is singlephoton sensitive. Although the TES pulse area is proportional to energy absorbed, one must know what fraction of the photon's energy is absorbed to accurately measure the energy of an unknown incident photon. However, in order to measure η , one must first satisfy the requirement that the TES be single photon sensitive. The simplest way to do this is to use a pulsed monochromatic source, attenuated to an average intensity of < 1 photon incident on the detector per pulse, and fit the resulting pulse area histogram to (5.2). This histogram can also be used to confirm the linearity of the energy response (but not the efficiency) of the TES at higher energies, which is important because the blue photons have lower energy than the intended vacuum UV signal emitted by the helium excimers. This chapter is divided into three main parts. Section 6.1 discusses the first three TESs created for this project and details their response to blue (and in some cases near-IR) photons. For various reasons, each one of these TESs was found unsuitable for the ultimate goal of the project, which was the detection of helium excimers. However, the particular failings of each TES informed the design of the TES that followed, and those points are discussed in this section. Section 6.2 discusses the three TESs (D, E, and F) that were used to detect excimers. The only difference between these three devices is that devices E and F had an extra ~ 20 nm thick layer of sputtered metal; gold for TES E, and platinum for TES F.

Finally, section 6.3 discusses the algorithm used to select the data displayed in chapter 7, and calibrate the energy axis in the presented spectra.

6.1 Photon detection with TESs A, B, and C

This section discusses the response of three different single pixel TESs to pulsed laser light. The TESs are described in section 4.3, and in table 4.1. The data presented in this section were taken by passing short pulses from a blue laser (470 nm, 2.64 eV) through a bank of adjustable neutral density filters, which couple into an optical fiber that terminates ~ 2 cm above the TES. The oscilloscope was triggered on the laser pulse. Data were taken at different attenuation levels for each detector, but there is no simple way to compare attenuation levels across detectors, as the mounting geometry was slightly different for each detector.

6.1.1 TES A: understanding substrate absorption

This section contains a slightly modified version of text originally published by this author in Carter et al. (2014) \bigcirc IEEE 2014. For TES A, the bare 40 × 40 μ m² TES, 18 000 pulses were recorded for two attenuation settings (100% and 50% intensity). Figure 6.1a shows the average of 18 000 pulses and the standard deviation of the same 18 000 pulses for the full intensity case. The corresponding curves calculated from the 50% attenuated pulses are characteristically similar in shape to those in figure 6.1a, but roughly half as large in amplitude (the pre- and post-pulse flat sections of the standard deviation, which describes the system noise, are the same for both attenuations).

At long time scales (> 10 μ s), the pulses are well described by a falling exponential and are precisely repeatable, as may be seen in the standard deviation during this time, which is consistent with the pre-pulse noise. At short times (< 10 μ s), the standard deviation reveals interesting variation between laser pulses, with a falling time constant suggestive of the TES intrinsic fall time of a few microseconds (calculated from the small-signal model in section 2.3). This may be understood in the following way: the large, slow pulse is the result of energy delivered to the TES in the form of phonons, resulting from the large incident



Figure 6.1: The first three panels summarize the response of TES A to blue laser light and are reprinted with permission from Carter et al. (2014). The fourth panel compares the energy resolution of TES A (at two different wavelengths of light) as a function of laser intensity. The final two panels summarize the response of TES A to IR laser light. See the text for more detailed descriptions.

photon flux on the substrate outside the area of the TES. The faster, smaller component (the component which varies from pulse to pulse) arises from direct photon hits to the TES. These small, fast pulses are the more interesting component of the data, as they should obey Poisson statistics and can also be directly modeled by the equations in section 2.3.

The standard deviation can be used as a model pulse template for the fast component if one assumes three sources of fluctuations in the TES pulses: fluctuations due to noise processes that are not related to the photon pulses σ_N , fluctuations due to a varying amount of power absorbed by the substrate σ_{Si} , and fluctuations due to the varying number of photons directly absorbed in the detector σ_{TES} . If one assumes these three sources of fluctuations are uncorrelated then they add in quadrature and the total RMS fluctuations (plotted in figure 6.1a, black curve) are described by $\sigma^2 = \sigma_N^2 + \sigma_{Si}^2 + \sigma_{TES}^2$; this equation is easily rearranged to give σ_{TES} as a function of the other variables. Since the standard deviation of a set of exponential pulses with different amplitudes, but identical rise and fall times, is an exponential pulse of the same character, σ_{TES} is therefore an excellent template for the fast pulse that contains the information about direct photon hits to the TES. From figure 6.1a it is clear that $\sigma_{Si} < \sigma_N$ (since there is no apparent variation on the 20 μ s timescale) and that σ_N is constant over time, and so the model for a good pulse template (σ_{TES}) is easily computed.

One may then use a double exponential (one rising, one falling) pulse shape to fit the rise and fall of σ_{TES} and then use this fit function as a template to extract the fast pulse component from each individual trace. Because all the fast pulses have the same character, only the amplitude should vary; the decay time, rise time, and starting time of the template should be fixed between pulses. This fast-pulse model may then be used, along with the average of the data, to infer a model for the slow pulse (also a double exponential). Finally, as with the fast pulse template, the slow pulse template parameters must be fixed, save for the amplitude, and the full model (now with only the two model pulse amplitudes as free parameters) may be fit to all 18 000 traces. One of these fits is depicted in figure 6.1b. The fast pulse fits were then integrated and histograms were made for both attenuations (figure 6.1c).

The histograms were fit to the first 20 terms of (5.2). The initial guess for x_s was

calculated by plugging all the measured device parameters into the small-signal model, generating a model pulse for a single photon, and integrating the model. Likewise, the initial guess for σ_s was calculated from the small-signal model. The scale factor A is a fixed parameter and is equal to the area of the histogram being fit.

One may calculate $\delta E_{\rm FWHM}$ from $\sigma_{\rm s}$. For the full intensity histogram, $\sigma = \sigma_{\rm s}/x_{\rm s} = 0.39$ and $\delta E_{\rm FWHM} = 2.44$ eV. It is interesting to compare this to the intrinsic device resolution calculated from the small-signal model, $\delta E_{\rm FWHM} = 0.6$ eV. The full system resolution is roughly four times worse than the theoretical value from the model, but that is reasonable given that over much of the bandwidth amplifier and electronic noise dominate (see figure 5.6), rather than intrinsic TES noise.

The fact that x_0 and a component of $\delta E_{\rm FWHM}$ are both linearly proportional to μ implies that there is some extra signal that is unaccounted for in the two-pulse model. If the contribution from the constant external input from substrate events (the slow pulse) is imperfectly modeled, then there will be a residual amount of energy in every fast pulse. This residual energy will be constant across measured pulses, independent of how many photons directly hit the TES, and will manifest as a constant offset from zero for the histogram that scales with laser intensity. TES A's energy resolution in the absence of a substrate signal may be estimated by fitting a straight line to a plot of $\delta E_{\rm FWHM}$ vs. μ , and extracting the y-intercept. This calculation gives $\delta E_{\rm FWHM} = 1.52$ eV, and is depicted in figure 6.1d.

One way to test the assumption that the slow pulse is due to photon absorption in the substrate is to repeat the experiment with an infrared laser with a wavelength of 1550 nm (~0.8 eV). At this wavelength, the Si substrate is nearly transparent, and so the absorption should be much less. Figure 6.1e depicts an example of the model fit to an IR photon detection event. Note the relative heights of the slow and fast contributions is inverted from the blue laser case. Figure 6.1f shows histograms from three different attenuations of the IR laser. The $\delta E_{\rm FWHM}$ is plotted against average photon number for the IR data in figure 6.1d. The slope of this line is more shallow than the corresponding line for the blue laser data, indicating that a smaller fraction of the energy resolution is due to substrate events. The fact that both curves intersect at $\mu = 0$ is not surprising, as that point represents the best-case energy resolution in the absence of any broadening due to substrate absorption.

6.1.2 TES B: blocking substrate absorption with an in situ aperture

For TES B, the 20 \times 20 μ m² TES with a lithographed substrate shield, 10000 traces were taken at each of three different laser attenuations in the same manner as described for TES A. As before, the average and standard deviation of each dataset were calculated. For this TES, because of the substrate shield, the background signal was greatly reduced, and the standard deviation and the average were each pulse shapes with similar time-constants, which indicated that nearly all the measured pulse amplitude was due to direct photon absorption in the TES. The pulse area was calculated for each pulse and histograms were created of pulse area for each different attenuation. The histograms showed peaks that were Poisson distributed, and so an average was taken of pulses falling within the FWHM of the first (zero-photon) and second (single-photon) peaks for each attenuation. One of these pairs is depicted in figure 6.2b. The area of the single-photon pulse was used to normalize the x-axis of the pulse-area histograms to photon number, and the area of the zero-photon pulse was used to remove the x-axis offset of each histogram from zero. The resulting calibrated histograms are shown in figure 5.7 in the previous chapter. The energy collected in the single-photon average pulse was 0.92 eV, which gives an energy efficiency of about 35%. In other words, 35% of the energy from each photon absorbed results in TES electron heating.

Although TES B was a much better TES in the sense that it did an excellent job of cutting out the background signal and only admitted direct photon hits, TES B had a number of strange and unexpected attributes. The first, and most obvious, is the falling time constant of a photon pulse, which may be estimated from figure 6.2b to be about 150 μ s. Since TESs A and B were both fabricated by depositing a layer of ~16 nm thick Ti from the same evaporator and the intrinsic TES time constant should be independent of TES volume, one would expect they should have similar pulse shapes. The fact that the response of TES B is about 20 times slower than TES A is confusing, and suggests that either the thermal conductance of TES B is much smaller than that of TES A, or the heat capacity is much larger. Figure 6.2a shows the $I_{\rm b}/I_{\rm TES}$ curve for TES B, and gives the parasitic, normal, and operating resistances. The normal resistance for TES B is about five times larger than



Figure 6.2: The first panel shows the $I_{\rm b}/I_{\rm TES}$ curve for TES B and indicates the operating point. The second panel depicts the average zero-photon TES response, and the average single-photon TES response. The zero-photon response is from stray light hitting the sub-strate. The collected energy in the single photon pulse is 0.92 eV, which gives an efficiency $\eta = 0.35$.

that of TES A. This is also puzzling as both TESs are one square of evaporated Ti, and so should have the same resistance. Finally, the low critical current (~ 250 nA) suggests that the critical temperature (or the film quality) of TES B is also quite a bit lower than TES A. Gershenson et al. (2001) have shown that the electron-phonon coupling time in Ti can be greatly suppressed with increases in film disorder. Shen (2005) has measured anomalously large heat capacities in highly disordered gold films. It is possible that the nearly hundredfold increase in detector time constant is due to a combination of these two effects, but a precise microscopic explanation will have to remain a mystery.

Despite the uncertain physics, it seems clear that film disorder is the likely culprit, and it is almost certain that all of these confusing deviations from what was expected can be explained by one of the fabrication steps involved in making TES B. During the fabrication of the lithographed shield, the Ti film that made up TES B was coated in PMMA electronbeam resist and baked at 180° C. This caused the Ti to become very dirty (likely due to oxidation), which increased its resistivity. For TES devices constructed after TES B, care was taken to ensure that the bare Ti film would never be baked while in direct contact with PMMA. Unfortunately, TES B was ultimately destroyed in an incident involving highvoltage.



Figure 6.3: The left panel shows a histogram of pulse areas normalized to photon number from TES C. The right panel shows zero-photon and one-photon average pulse shapes made by averaging together traces that fell within the zero- and one-photon peaks of the histogram in the left panel.

6.1.3 TES C: blocking substrate absorption with a substrate mirror

TES C was designed to block the substrate from photon absorption and to avoid the complicated (and possibly damaging) fabrication steps required to create a lithographed shield. Instead of creating an aperture over TES C, the entire substrate was coated with aluminum, save for under the TES, and for a thin border around the TES, which electrically isolated it from the rest of the substrate. This aluminum coating was intended to act as a mirror, reflecting any incident light away from the substrate. Although not as successful as the lithographed shield used on TES B at shielding the substrate from incident light, the reflective coating reduces the background contribution to a point where it is well below the signal from the blue photons. Figure 6.3b shows the average signal recorded when zero photons were incident on the TES (dark blue), and also when a single photon was incident on the TES (light blue). The substrate signal is non-zero because the mirror-coating is not complete. There is an exposed area surrounding the TES pixel where light may be absorbed by the substrate.

In order to get the best possible estimate of the pulse area due to the direct photon hits, pulse areas were only recorded between 0 μ s and 1 μ s from the trigger. In this region, the direct TES hit signal to substrate signal is maximized. The histogram in figure 6.3a was created by binning these 1 μ s pulse areas, fitting the histogram to (5.2), and then normalizing the areas to photon number so that $x_s = 1$. Overall, the fit to (5.2) is good, however there is a region between the zero- and one- photon peaks, and also a region between the one- and two- photon peaks, where there are more counts than would be expected for Poisson distributed data. Identifying the cause of this excess signal is largely the subject of the next section.

6.2 Photon detection with TESs D, E, and F

TESs D, E, and F were made smaller than TES C to increase the amount of heating (and therefore the pulse height for a given energy input) and were constructed with builtin shields. The shield design was the same as that used for TES B, however a different fabrication process was used to ensure that the Ti TES surface was not contaminated by interaction with the electron-beam resist. TESs E and F were identical to TES D, but also had an additional thin layer ($\sim 20 \text{ nm}$) of sputtered metal added as a final step to the fabrication process. TES E was coated with gold, and TES F was coated with platinum. These two metals were chosen as they are both very resistant to corrosion, and have a high work function, both which are important when detecting triplet state excimers directly (see chapter 7). TES E will not be discussed in this section as the device was qualitatively similar to TES F (thin metal layer on top of a TES).

6.2.1 TES D: searching for the source of an extra unwanted signal

As discussed in the previous sections, a large amount of effort has gone in to designing a detector that allows photons to couple into the detector, but not into the substrate. From figures 6.2b and 6.3b, it is evident that neither a substrate shield nor a reflective substrate coating is entirely sufficient to keep energy out of the substrate; even when no photon is absorbed directly in the TES, some energy always couples in through the substrate. This substrate response is proportional to laser intensity as shown in figure 6.1d. In the analysis of TES C's photon response, it was noted that there was a population of pulses that were not well-described by a Poisson distribution. This population is also present in the results

from TES D as may be seen in figure 6.4. Figure 6.4a shows histograms of pulse areas taken at two different laser attenuations. Fits to (5.2) are not shown as neither histogram is welldescribed by Poisson statistics. Despite this, there are clear humps in each histogram that correspond to the absorption of integer numbers of photons. The question is, what is the cause of the population that appears between the zero- and one-photon peaks, apparent in both histograms? Figures 6.4c and 6.4d show the average pulse shape of events falling within the FWHM of the zero-photon peak (dashed gray), the one-photon peak (solid blue), and a region halfway in between the two (dot-dashed red). Figure 6.4b shows the same curves, but with the appropriate zero-photon (gray curve) subtracted. There are three conclusions to be made from these plots:

- 1. The substrate response scales with laser intensity, as was also discovered in the analysis of TES A.
- 2. The detector response is consistent across laser intensities; both of the datasets give the exact same response once the substrate contribution is accounted for.
- 3. Whatever is causing the so-called "half" photon pulses, it appears to result in a slower rise time than would be expected from a direct TES hit.

There are two good candidate explanations for these excess counts. The first possibility is that they arise from photons that are absorbed on the edge of the TES, very close the leads. As the energy from the photon is shared between the electrons in the TES, it is likely that, during the cascade from high energy, some energy from one of these edge events would escape the TES system into the leads, resulting in a pulse with a fraction of the energy expected from a single photon detection. This process should scale inversely with the size of the detector as the edge-length to surface-area ratio increases. The second possibility considers the fact that 15–20 nm thick titanium is not perfectly opaque to 2.6 eV light. In fact, it is about 20% transparent at 2.6 eV and at 15 eV (Johnson and Christy, 1974; Windt et al., 1988). In the event a photon transmits through the TES and is absorbed in the substrate very close to the boundary between TES and substrate, about half of the photon energy should couple into the TES, giving a response that would fall in between photon



Figure 6.4: TES D response to blue (2.6 eV) laser pulses at two different attenuations. See the text for discussion. The high-frequency oscillations apparent in the averaged pulse shapes is due to some undiscovered high-frequency noise source with a varying amplitude that occasionally triggered the oscilloscope.

numbers in the histogram. In each of these two cases, one would expect slightly different pulse shapes as compared with an ideal photon absorption event. For the edge-absorption case, the pulse should be slightly broadened, as some energy that escapes into the leads will diffuse back into the TES and become trapped, contributing to the signal at later times. For the second case, the near substrate absorptions, the pulse rise time might be noticeably slower. This is because if the initial photon absorption was in the substrate, then any energy transferral back into the TES must be through electron-phonon scattering, which operates on a much longer time scale than electron-electron interactions. From figure 6.4b it may be seen that the unwanted signal has both a slower rise-time, and a broader shape. It is thus not possible to decisively say which of the two proposed explanations is the primary contributor simply by analyzing the data from TES D.

6.2.2 TES F: considering photon absorptions near the TES edge

TES F was identical to TES D save for a thin layer of sputtered platinum that added as a final fabrication step. This additional metallic layer means that TES F is substantially more opaque than TES D, and an analysis of the TES F photon response helps to determine the source of the "half" photon events discussed in the analysis of TES D. The platinum layer was originally added to increase the work-function of the TES surface and ensure that the absorbing surface was as oxide-free as possible. However, it had the added benefit of increasing the opacity of TES F over TES D.

Figure 6.5a shows a histogram computed from 32 000 blue laser pulses. This was taken concurrently with the data shown in figure 6.4 dubbed "Less attenuated" and was processed in the same way. It is immediately clear that the data taken with TES F is much better quality than that taken by TES D; it is very nearly described by a fit to (5.2). There are still some events that occur in between the histogram peaks, but the majority of the counts are due to photons absorbed directly in the TES. Figure 6.5b shows the analogous pulses to those displayed in figure 6.4c for TES D. The one feature that is interesting to note is that unlike the TES D data, the "half"-photon pulse does not decay with the same characteristic shape as the one-photon pulse. For a period, the red curve actually rises above the blue curve. This is consistent with the hypothesis that once the platinum has been added, edge-



Figure 6.5: The upper left panel is a histogram of pulse areas, normalized to photon number; the offset due to substrate heating has not been removed. The upper right panel depicts average pulses corresponding to the average of pulses falling within the zero- and one-photon histogram peaks, as well as the region in between where the fit is near zero. The lower left panel shows the results of a calculation of the rate of quasiparticles re-entering the TES from the Al lead after a photon absorption event near the leads that resulted in some hot electrons diffusing into the lead. The lower right panel shows the integral of the lower left panel.

hits are the primary cause of the events that deviate from a Poisson distribution. If a photon is absorbed close enough to the leads, some energy from the photon will be converted into quasiparticles in the aluminum. These quasiparticles will diffuse along the aluminum, and some of them will reenter the TES. The quasiparticles that return to the TES will do so on a time-scale that depends on the diffusion constant and the quasiparticle lifetime in Al. Figure 6.5c shows the fractional quasiparticle arrival rate into the TES from the leads as a function of time, modeled in Mathematica (see appendix C for the code, and appendix A for a discussion of the diffusion model), for the case where a population of quasiparticles is created on the boundary of the TES and a long aluminum lead. Figure 6.5d gives the fraction of initial quasiparticle population injected into the TES over time. Values for the diffusion constant and quasiparticle lifetime of Al were taken from Wang et al. (2014), a work that measured the properties of aluminum evaporated from the same machine used to create the detectors for this experiment. The electron-electron scattering time in the Ti was set at 10 ns for the simulation. The time-scale of quasiparticles entering the TES from the leads, as calculated by this model, is consistent with the small increase in TES response seen at late times in the "half"-photon pulse.

Now that the unwanted signal has been tentatively identified as arising from photon hits in the TES that are close to the leads (at least for TESs E and F), it is interesting to estimate what fraction of the TES area gives "good" responses (all the available photon energy couples into the TES). The integral of the fit-curve in figure 6.5a is 0.85. Since the data histogram was normalized to an area of 1, this means that 15% of the data falls outside the fit, and may be attributed to edge-hits. The integral of the zero-photon Gaussian peak in the fit curve is 0.68, which means that for 68% of events, the TES had no photon incident upon it. The remaining 17% of events, then are "good" data in the sense that they correspond to the data that is described by the fit. If photon flux is uniformly incident on the TES, this analysis suggests that 47% of the photons absorbed in the TES are edge-hits. Since edge hits are adjacent to an edge, and TES F is 15 μ m long and symmetric in the width dimension, then it may be inferred that a photon absorption within 3.5 μ m of either lead may be classified as an unwanted edge-hit.

Finally, whether it is possible to easily remove the unwanted signals, regardless of origin,



Figure 6.6: The upper left panel shows a scatter plot of pulse width vs. photon number for TES F The upper right panel shows a plot of the density of points in the pulse width vs. photon number scatter plot; the region enclosed by the dashed lines corresponds to edge-hit events. The lower left panel shows a histogram of data with edge-hits removed. The lower right panel shows FWHM averages of pulses falling within zero- and one-photon peaks of the histogram.

must be addressed. Whether the unwanted events arise from photons transmitting through the TES and absorbing in the substrate (as discussed in the analysis of TES D), or from edge hits, they all have one thing in common: they have a repeatable pulse shape, and that shape is different from the pulse shape corresponding to "good" events. Figure 6.6a shows a plot of photon number vs. pulse width. The pulse widths were calculated by finding the pulse maximum in each trace, and then looking for two level crossings, at 30% of this maximum height, on either side of the pulse apex. For a purely exponential pulse, this width would very nearly correspond to the time constant, and one would expect that, for a dataset consisting of only "good" signals, the entire set would be tightly clustered along one horizontal line in this plot, and distributed in several clumps along the line corresponding to different photon number peaks. (The width variation in the zero-photon peak is very large—several orders of magnitude—as a byproduct of the algorithm trying to find a peak maximum that doesn't exist, and no importance should be attached to this variation.) Any extra signal with a wider pulse shape (edge-hits, or otherwise) should lie above the horizontal line corresponding to the wanted signal.

Each point in figure 6.6a corresponds to a single event; there are 32 000 data points. In regions where many points overlap, the scatter plot does not give a good sense of how many points are actually in that region. A better visualization of this data is shown in figure 6.6b where the density of points is calculated. The grid for calculating point density is 100×100 , giving a grid of 10 000 bins, and the color of each bin corresponds to the number of data-points falling within that bin on a log-scale. It is now easy to see where the zero-photon and one-photon maximums are located. Two dashed black lines have been overlaid on the density plot, and the region enclosed by them (up, and to the right) corresponds to events that have a pulse shape that is too wide to be considered a good event. Figure 6.6c shows a histogram of the data with these events removed, and the resulting fit to (5.2) is much improved. Figure 6.6d shows the zero- and one-photon average pulse calculated by averaging together the events falling within the FWHM of the respective histogram peaks. The total energy collected in the TES (less any substrate contribution) may be calculated from these two pulses, and is about 1.2 eV, which gives a device efficiency for TES F of $\eta = 0.46$.

6.3 Calibration algorithm

In all the analyses presented earlier in this chapter, much use was made of the fact that the exact timing of each laser pulse was known ahead of time. This made calculating pulse areas simple: integrate only the region of each trace corresponding to the known time of the photon pulse. The intended use of the TESs is to detect helium excimers and the processes used in this work to create helium excimers are stochastic; the arrival times can not be known a-priori. Instead, the trigger threshold is set to be just above the noise, and a trace is recorded whenever the oscilloscope detects a signal above the trigger. The trigger time (t = 0) is a measure of when the rising edge crosses the threshold, and its relationship with actual pulse arrival time will vary depending on the pulse height and the pulse rise-time.

During data collection, TESs D, E, and F were recorded simultaneously. The oscilloscope only has four channels (but does have an external trigger input) so a copy of each TES signal was sent to an external three channel comparator that was used to send the oscilloscope a trigger event when any one of the three TESs exceeded the trigger threshold. When the oscilloscope received a trigger from the comparator, it saved a 50 μ s time trace for each TES, starting 5 μ s before the trigger event (the oscilloscope can hold a buffer of data in order to provide a "pre-history").

In order to calibrate the detectors for measuring an unknown signal, the blue laser was used as a source, but instead of triggering on the laser, the above triggering scheme was used. The following algorithms were developed so that the exact same computer code used to calibrate the device response to blue laser photons would be used to measure the unknown signals. The parameters of the calibration algorithms were tuned on the known blue laser signal to provide the best results. The algorithm parameters were then fixed, and the calibration routine was applied to the unknown helium excimer signal.

Finally, there is one caveat to consider when applying the following algorithm: It only works if the incident signal flux of the unknown signal is small enough that the substrate contribution may be neglected. Compare, for instance, figure 6.4c with figure 6.4d. In the first, the one photon pulse contains a large contribution from the zero pulse. In the second, the zero pulse is small enough that it may be safely ignored. When collecting excimer data, the TES trigger rate is on the order of 1 Hz. This rate corresponds to a very low photon/excimer flux incident on the substrate and satisfies the above requirement.

6.3.1 Preprocessing algorithm applied to all traces

In previous sections it was determined that sometimes a TES signal arises not from a direct photon absorption, but from an edge-hit, or a photon that is absorbed in the substrate either below, or adjacent to, the TES. It was also shown that these unwanted signals may be excluded by applying a width threshold. This algorithm's primary goal is to accurately determine the pulse width. It applies different low-pass filters to the rising and falling edges in an attempt to reduce the noise as much as possible without affecting the intrinsic time constants associated with the two processes.

- Load trace, and remove any offset from zero by subtracting off the average of the first 200 points.
- Make two copies of the trace. Apply a 3 MHz filter to one copy (the fast copy), and a 500 kHz filter to the other copy (the slow copy).
- 3. Find the location of the maximum point in the fast copy (t_0) . If there is a pulse, this will be the location of the pulse maximum, and t_0 should be located very close to the trigger time. If there is no pulse, it will be the location of the largest noise spike, and t_0 will be a randomly chosen time in the trace. Set the **arrival time** to t_0 , and the **pulse height** to the maximum height.
- 4. From the maximum point, move back in time and find the location where the fast copy falls below 50% of the maximum value (t_1) . This is the rising edge.
- 5. From the maximum point, move forward in time, and find the location where the slow copy falls below 50% of the maximum value (t_2) . This is the falling edge.
- 6. Set the **pulse width** to $(t_2 t_1)$. Integrate the original unfiltered trace from t_1 to t_2 to define the **pulse area**.

Once this algorithm has been applied to every trace, there will be four datasets: pulse widths, pulse areas, pulse heights and arrival times.

6.3.2 Creating a model single photon pulse

Because the triggering scheme records each TES without regard to which TES experienced a pulse, it is necessary to throw away traces that don't contain a pulse (about two-thirds of the data for each TES). This algorithm accomplishes that, and also selects for good data using the width threshold. It is also reasonable to assume that sometimes a signal will be due to an external event like an electrical fluctuation. These events should be present in all three TESs, and that characteristic may be used to eliminate them.

- For each set of simultaneous traces, calculate the fraction of total pulse area across all three TESs according to: (TES pulse area)/(Sum of all three TES pulse areas). Select data where this fraction is greater than 0.7.
- 2. From the data that survives the previous step, make a histogram of arrival times. There should be a large peak near t = 0 corresponding to events that caused a trigger. Select data that falls within this peak.
- 3. From the data that survives the previous step, make a density plot of pulse widths vs. pulse areas, and use this plot to select a width threshold (τ_{max}) , keeping only the data below the threshold. This step can, in principle, be automated, but is easy to do manually and only needs to be done once.
- 4. Make a histogram of pulse areas from the data that survives the previous step. Average together the original unfiltered pulses in the FWHM of the single-photon peak, which should be clearly defined. This average is a good estimate of an ideal single photon response.
- 5. Fit the single-photon average pulse to an analytical function. In the case of this work, the best fit model was a pulse shape defined by one rising exponential and two falling exponentials. The resulting model is the best possible estimate of the detector response to a single photon.

The resulting model pulse may now be used as a calibration pulse. Any data processing algorithm that calculates an area may be also applied to the model pulse to return the "single-photon" area. The efficiency η may be calculated by dividing the model pulse area by the known photon energy (2.6 eV for the calibration laser used here).

6.3.3 Using the pulse model and the noise traces to build a better filter

Figure 7.1b shows a scatter plot of pulse heights vs. pulse areas for some helium excimer data, which were conditioned according to the preprocessing algorithm 6.3.1. There are

three clear clusterings of data: two of traces that contain signal, and one of traces that only contain noise. It is possible to use the noise traces, in conjunction with a model of the desired signal, to create a filter that maximizes signal-to-noise. The method is described in detail by Press et al. (2007), and the algorithm used in this work is given here.

- 1. Select only the noisy traces. Take a numerical Fourier Transform (FFT) of each trace, and then calculate the magnitude squared of the FFTd trace. This is the unscaled power spectrum (PS) of the noise in A^2 . Average all the noise PSs calculated this way to get the total best estimate for the noise power spectrum S_N .
- 2. Compute the model pulse's power spectrum $S_{\rm M}$ by taking the magnitude squared of the FFT of the pulse model.
- 3. A filter (f) is then created according to $f = S_M/(S_M + S_N)$. This filter is a filter in frequency space. It is near unity for frequencies where $S_M \gg S_N$, and close to zero for frequencies where $S_M \ll S_N$.
- 4. Apply the filter by taking the FFT of each trace, multiplying it by the filter, and then inverting the FFT. This could also be accomplished by converting the filter to the time domain and convolving it with each trace.
- 5. Filter the model pulse also, so that the effects of the filter on the pulse area may be worked out.

Once the entire dataset of traces has been filtered in this way, the preprocessing algorithm is then run again to determine better estimates for pulse width, height, area, and arrival time. Finally, the preprocessing algorithm is run on the filtered model pulse to get the pulse area that corresponds to a single photon. The efficiency η is the filtered model pulse area divided by the photon energy.

6.3.4 Processing algorithm for experimental data

1. Apply the algorithms described above to filter each pulse and then compute pulse area and pulse width from the filtered data. For the filter creation, a new S_N must be

calculated for each dataset as the noise contributions from each run might be different, but $S_{\rm M}$ comes from the intrinsic detector response and only needs to be calculated once.

- 2. Apply the first two steps of the algorithm from section 6.3.2 and then reject any remaining traces that have pulse widths greater than τ_{max} .
- 3. Multiply the pulse areas by the bias-voltage. The resulting number is the uncalibrated energy incident on the TES detector.

Once this algorithm has been applied to the unknown data, a histogram of incident energies may be made. The energy axis is then scaled by dividing by η (which must be calculated separately for each dataset as it depends on the filter used) and this corresponds to the spectrum of energy incident on the TES. This process is how all the spectra in chapter 7 were created.

Helium excimer detections

Chapter

THERE were two methods used in this experiment to create helium excimers. The first was to place a 22 Na gamma-ray source outside the cryostat at the same height as the superfluid chamber. Some fraction of the emitted gamma-rays pass through to the superfluid bath and Compton scatter off an electron, causing a chain reaction of events that ends in a cloud of both singlet and triplet excimers (Ito and Seidel, 2013). The second method is to immerse a sharp tungsten tip in the superfluid bath and hold it at a voltage above the electron emission threshold of the tip (~-1500 V in this experiment, although Guo et al. (2009) report lower voltages). The ejected electrons lose their energy by scattering in the superfluid bath, and the result is a cloud of excimers created near the tip. The first section of this chapter discusses the detection of excimers created via gamma-ray excitation, and the second discusses the detection of excimers created via electrons emitted from a sharp tip. All the spectra shown in this chapter were produced according to the algorithms described above in section 6.3.

One of the primary goals of this work was to detect (and differentiate between) both the triplet state excimers and the singlet state excimers. The signal arising from singlet decays should be straightforward to understand, as it ought to correspond directly to the allowable spectrum of UV light produced during relaxation. The mechanism by which the triplet state confers its energy to the TES is more nuanced, and is the subject of the final



Figure 7.1: The left panel shows the pulse heights vs. pulse areas of pulses recorded with TES D while an empty chamber was subject to a 22 Na gamma-ray source. The right panel shows the same, except in this case the chamber has been filled with superfluid helium.

section in this chapter.

7.1 Excimers created via gamma-ray excitation

²²Na is a positron emission source. Upon decay, it emits a positron and a 1.3 MeV gammaray. The positron quickly annihilates with an electron and produces a pair of counterpropagating 511 keV gamma-rays. Of the gamma-rays that pass through the cryostat shields and end up in the superfluid chamber, some fraction will Compton scatter in the helium and produce excimers, some will be absorbed in the silicon substrate that holds the detectors, and the rest will either pass through or be absorbed in the chamber walls (some will also be absorbed directly in the TES, but that is unlikely enough to be discounted as an observable population). Because the substrate is much larger (volume and surface area) than the TESs, it is expected that the majority of TES detection events will arise from gamma-ray absorptions in the substrate, which is the case. The substrate events are not interesting from the perspective of excimer detection and should be discarded. This is straightforward, as the pulse shape that results from a substrate hit has a much slower rise time (and fall time) compared with a direct energy absorption in the TES electron system. Figure 7.1 shows two scatter plots of pulse height vs. pulse area for events measured due to ²²Na irradiation. The events in the left panel were recorded with the chamber empty of helium, and the events in the right panel were recorded after helium was added. In both plots a population corresponding to large areas and large pulse heights may be observed; this is the substrate absorption signal. The noise (corresponding to traces without any signal) is also readily discernible as a blob in the lower left of each plot. In the plot corresponding to a chamber full of helium, a third population of much faster (larger height:area ratio), smaller area pulses may be observed. This population results from direct absorption of either excimers or photons in the TES.

It is interesting to estimate the expected number of excimer detections per minute and compare this to the actual event rate. The source used in this experiment had an activity of 100 μ Ci and was placed about 20 cm from the chamber; the chamber may be approximated by a sphere with a 2.5 cm radius. The source's rate of decay was 3.7 MHz and for each decay it emitted three photons (two 511 keV and one 1.3 MeV). The solid angle fraction presented by the chamber is ~ 4×10^{-3} , giving a flux of gamma-rays through the chamber of about 42 000 per second. Using data from Berger et al. (1998), the probability of a gamma-ray interacting with the He is about 0.05, giving about 2100 electron recoils per second. From Ito and Seidel (2013), a 364 keV recoil with an electron will produce ~ 10^4 singlets and ~ 2×10^4 triplets, which will propagate out spherically from the point of impact. The solid angle fraction of the detector is about 3×10^{-4} . Thus, the final back-of-the-envelope event rate calculation gives ~0.63 events per second (triplets and singlets combined). The measured rate was ~0.8 events per second and includes all the events due to gamma-rays absorbing in the Si substrate (estimated to be ~0.4 events per second).

7.1.1 Spectra from ²²Na irradiation

It is desirable to have a way to determine whether a given TES detection event is from a triplet excimer or from a singlet photon. The nature of the ²²Na decay (two counterpropagating gammas) means that it may be used as a trigger as well as a gamma-ray source. Figure 7.2 illustrates how this is possible. Every the time that the ²²Na emits a 511 keV gamma-ray towards the helium chamber, it will also emit an identical gamma-ray in the opposite direction. By placing a gamma-ray detector such that it covers an equal-



Figure 7.2: Experimental setup for coincidence measurement with 22 Na source. The PMT+NaI and the helium chamber are aligned relative to the radiation source such that the solid angles of illumination are matched. Any 511 keV gamma-ray that is incident on the chamber, will also produce a 511 keV gamma-ray that is incident on the PMT+NaI.

but-opposite solid angle as the helium chamber, one may determine when a gamma-ray is incident on the chamber by collecting its opposite number at the detector. The gamma ray detector in this experiment was a sodium-iodide (NaI) crystal coupled to a photo-multiplier tube (PMT). Incoming gamma-rays that pass through the NaI create scintillation light, which is detected by the PMT. For brevity the NaI+PMT combo will be shortened to just PMT for the remainder of this work. When a gamma-ray scatters in superfluid it creates a cloud of excimers that is roughly 2/3 triplet state and 1/3 singlet state (Ito and Seidel, 2013). The singlets convert to photons within a few ns, which may propagate out in any direction at the speed of light. Likewise, the triplets may also propagate in any direction, but do so at a slower rate. The speed of excimers (in the ballistic regime) has been measured by Zmeev et al. (2013b) to be ~ 2 m/s. In any case, the upper limit for excimer velocity in superfluid is set by the critical velocity for roton formation, which is $\sim 50 \text{ m/s}$ (McClintock et al., 1984). This delay means that any TES event which is coincident (within 250 ns) with a PMT signal must arise from the collection of a photon, or a triplet state excimer that was created within a distance of less than 12 μ m from the TES. The chamber is big enough that this small population of triplets will contribute fewer than one out of every fifty detection events and may thus be neglected.

The PMT is continuously monitored by the same oscilloscope that monitors the TESs. Whenever a TES triggers the oscilloscope, it collects 5 μ s of data before the trigger and



Figure 7.3: The upper left panel shows a histogram of the arrival time of PMT pulses. The sharp peak near zero indicates events that were coincident with detection events in TES D. Selecting only events in this peak ensures that only the singlet excimer population is sampled. The upper right panel shows spectra of all ²²Na events recorded by TES D (blue, solid) and coincident TES/PMT events (red, dashed). These spectra have been normalized such that each histogram has the same integral. The lower two panels show the same two spectra for TESs E and F, respectively. The vertical line on the center of the maximum bin in each spectrum is $\pm \sqrt{n}$ where n is the number of counts in that bin. The remaining error bars have been omitted for clarity.

45 μ s after the trigger. The start times of any pulses in the PMT trace are located in time, and their distance from the trigger time (t = 0) is recorded as a delay time. Figure 7.3a shows a histogram of delay times between TES events and PMT events for TES D. The large peak near zero delay is due to photon absorptions in the TES that were coincident with a gamma-ray detection in the PMT. Figure 7.3b shows two spectra from TES D. The solid blue curve is a spectrum of all the TES events due to irradiation by 22 Na. The dashed red curve shows a spectrum of just the coincident events (the events in the peak of the histogram in figure 7.3a), which arise from detecting singlet photons. The two curves have been scaled so that their integrals are equal. The large peak in the blue curve near 5 eV is interpreted as arising mostly from the detection of triplet state excimers, although it is clear that the photon signal also has a contribution in that energy range. The shape and location of these peaks will be discussed more in section 7.3. Figures 7.3c and 7.3d show the same spectra, but for TESs E and F, respectively. Although the overall shapes are different from the TES E spectra, all three plots have one thing in common: there is a low-energy peak that is reduced in size when the coincidence requirement is enforced. This suggests strongly that the lower-energy peak is mostly due to triplet state excimers.

7.1.2 Response to varying ³He concentration



Figure 7.4: Two spectra from TES D. One spectrum was taken with high-purity ⁴He (³He $< 10^{-12}$) and the other was taken after the pure helium was diluted with 10% commercial ⁴He (³He $< 10^{-8}$, estimated). Each spectrum contains roughly 20000 counts. The PMT coincidence technique was not used to make these spectra.

It has been reported by Zmeev et al. (2013b) that the addition of even a small amount of ³He present in the superfluid bath is sufficient to quench the triplet excimer signal. To see if it was possible to test this claim, the high-purity ⁴He superfluid bath in the experimental chamber was diluted with 10% commercial, unfiltered ⁴He, which contains trace amounts of ³He. Spectra were obtained (in the same manner as above, using a ²²Na source) and figure 7.4 shows the response of TES D for both the high-purity case and the 10% commercial case. It appears that in this experiment there is no real difference between the two cases. One reason why these results might differ from those of Zmeev et al. (2013b) is that in the latter case, the experiment measured the ballistic propagation of triplet-state excimers. If the ³He slowed down the triplets (via scattering) such that they arrived much later than the measurement time window, it would appear as if the signal had disappeared. In contrast, the present experiment just measures the energy spectrum of the excimer decays and the data collection window is essentially infinite from the perspective of excimer flight times. Another possible explanation is that the commercial helium used to "dirty" the superfluid in this experiment was actually more pure than estimated (³He < 10⁻⁸).

7.2 Excimers created via high electric field

This section discusses the response of the TESs to excimers created by applying a high voltage to a sharp tungsten tip. Figure 7.5 shows a plot of pulse heights vs. pulse areas for TES D, taken with the tip held below -1700 V. This plot is very similar to that of figure 7.1b, except there are no slow, large-area pulses, as there is no gamma-ray source in this experiment to produce substrate hits.

One advantage inherent in using a tip to create excimers is that the location of excimer creation is fixed within a small distance from the tip. This is in contrast to using a gammaray source, where the creation location is entirely random and may be any point inside the superfluid bath. In principle, this configuration allows for excimer time of flight experiments (Zmeev et al., 2013b) where the tip is pulsed and the time between voltage pulse and excimer detection is measured, but this measurement was not attempted in this work. One disadvantage inherent in using a sharp tip is that the tip will degrade over time, requiring


Figure 7.5: Pulse heights vs pulse areas for TES D response to excimers created with a sharp W tip held below -1700 V. The horizontal axis has not been calibrated to show absorbed energy, rather it shows raw pulse area (see section 6.3). The three dashed lines are lines of constant time-constant (steeper slope is a faster pulse) and serve to delineate the three major classes of signal event. The grouping labeled "Electrical noise" were caused by the TES triggering on an electrical glitch. The "Excimer signal" grouping is the desired signal due to excimer or photon absorption in the TES. The final grouping is due to either photons or excimers absorbed in or near the TES leads, or perhaps photons that transmit through the TES and are absorbed in the substrate. These two classes of events are discussed at length in sections 6.2.2 and 6.2.1 respectively.

an ever higher absolute voltage to maintain the same electron emission current. One way to mitigate this disadvantage is to place several sharp tips in parallel within the chamber. The sharpest one will emit until it is destroyed, and then the next sharpest will take over, and so on. Figure 3.6d shows a plot of current-voltage measurements for two different tips that were installed in parallel during the same run.

7.2.1 Response to varying tip voltage

The simplest experiment possible, once one has succeeded in producing excimers from a sharp tip, is to vary the tip voltage and record a spectrum at each voltage. This was done with a single tip, and the voltage was varied from -1700 V (the lowest absolute voltage at which a signal was observed) to -2000 V (the highest absolute voltage the electronics would admit). For each voltage, several thousand pulses were recorded each for TESs D, E, and F. Figure 7.6a shows spectra for the maximum and minimum absolute voltages recorded with TES D. Note that the same two primary peaks appear in these spectra as appear in the spectra shown in figure 7.3. The low energy peak has been associated primarily with

triplet state excimers and the higher energy peak with photon absorption from singlet state excimer decay. Figure 7.6b shows how these two peak areas vary with increasing absolute tip voltage: The triplet peak area decreases with increasing absolute tip voltage, while the singlet peak area increases. Zmeev et al. (2013a) found that a tip at high absolute voltage produces a turbulent vortex tangle as well as excimers. It is possible that increasing the absolute tip voltage increases the amount of turbulence, and thus the number of vortices, produced in the superfluid at the tip. Since triplet state excimers are efficiently trapped on vortices, increasing the tip to a higher absolute voltage would effectively reduce the number of triplet state excimers that reach the detector. Another possibility is that as the density of triplet state excimers in the vicinity of the needle increases, they become more likely to quench on each other through Penning ionization (Shaw, 1974; Adams, 2001), and eventually are converted to photons, which show up in the higher energy singlet peak. This process has a reaction rate of ~ 10^{-9} cm³/s, which limits the maximum possible triplet density (Keto et al., 1974).

Figures 7.6c and 7.6d show the same spectra as figure 7.6a, except for TESs E and F, which were coated with a thin layer of platinum and gold, respectively. Although the peak height shift is not as pronounced in these spectra, there is still a shift in peak area from the low-energy peak to the high-energy peak with increasing absolute voltage, which is in line with the hypotheses made above regarding the relationship of vortex creation (or Penning ionization) to tip voltage.

7.3 Discussion

The previous sections in this chapter have presented several spectra, and made claims as to what the different peaks in the spectra represent (i.e., one is the triplet peak, etc). There are three outstanding questions that immediately ask for resolution.

- 1. Why is the triplet peak at such a low energy if the excimer binding energy is $\sim 15 \text{ eV}$?
- 2. Why do the spectrum shapes differ between detectors if they are detecting the same signal?



Figure 7.6: The upper left panel shows spectra from TES D taken at tip voltages of -1700 V and -2000 V. For clarity, the absolute value of the voltage is shown. The upper right panel shows the area of each of the two visible peaks as a function of absolute tip voltage. The dashed lines are fits to guide the eye, not a theoretical prediction. The bottom two panels show histograms for TESS E and F.

3. Why is the peak that appears to be associated with singlet decays at a lower energy than expected, especially in TES D?

This section will address these three questions, starting with the last.

7.3.1 UV photon coupling to TESs

Figure 7.7 shows a spectrum of the helium scintillation light produced due to passing highenergy electrons through a liquid helium bath, taken by Stockton et al. (1970). This measurement was taken by placing a grating spectrometer at the top of a cryostat with a line-of-sight view of the helium bath. Electrons were passed through the bath, and some scintillation light (from decaying singlet excimers) reached the spectrometer. The primary feature of this spectrum is a peak centered at 15.5 eV, with a cutoff near 20 eV, which is due to the opacity of liquid helium above about 20 eV. The clear question here is why the TES D spectra shown earlier in this chapter, which are claimed to be due to singlet excimer decays, do not peak at 15.5 eV. Instead, they peak somewhat lower, at about 10 eV. The spectra from TESs E and F appears to be centered closer to 12 eV, with cutoffs much closer to 20 eV (although the cutoffs are not as sharp as expected).



Figure 7.7: Scintillation spectrum from electron-bombarded helium. Reprinted figure with permission from M. Stockton, J. W. Keto, and W. A. Fitzimmons, Physical Review Letters, 24, 654, March 1974. Copyright (1974) by the American Physical Society.

This calls in to question the calibrations of the TESs, and whether they are valid at photon energies that are different from the 2.65 eV used to make the initial calibration. To test this, a separate calibration was done with near-IR photons at 0.8 eV, and the calibration (fraction of energy absorbed) was identical. This indicates that the detector energy efficiency (η) is constant with energy up to at least 2.65 eV. Unfortunately, it was not possible to do a TES calibration with a larger energy due to a general dearth of pulsed monochromatic UV sources. There is no reason why the TES should be as efficient at higher photon energies. When the TES absorbs a photon, it is all initially absorbed in one high-energy photo-electron. That photo-electron shares its energy with other electrons, as well as with phonons, as it relaxes to the Fermi surface. If the strength of the electronphonon coupling depends on energy, then it is entirely possible to suppose that the efficiency of the detector should as well. Bezuglyi and Shklovskii (1997) suggest that a thin film TES's electron temperature immediately after a photon absorption should be described by $E_{\rm phot} = V\gamma/2(T_{\rm TES}^2 - T_{\rm bath}^2)$. In the limit of $(T_{\rm TES} - T_{\rm bath}) \ll T_{\rm bath}$, this reduces to $E_{\rm phot} = V\gamma T_{\rm bath}(T_{\rm TES} - T_{\rm bath})$ or, more familiarly, $E_{\rm phot} = C_{\rm e}\Delta T_{\rm TES}$. However, at larger input energies, the TES electron temperature rises like the square-root of the photon energy. In this case, treating the detector temperature as linear with regards to photon energy will result in an underestimate of the true photon energy. As an example, for $E_{\rm phot} = 15$ eV, $T_{\rm bath} = 100$ mK, $V = 1 \ \mu {\rm m}^3$, and $\gamma = 304 \ {\rm J/K^2m^3}$, the above equation predicts a measured energy of 13.4 eV, or about a 12% discrepancy.

At higher photon energies (larger than the work function of the TES), the photo-electric effect also may play a role. When an electron is removed from the TES via the photoelectric effect, the resulting hole is filled by an electron at the Fermi-surface, and the energy difference is read out as a pulse on the oscilloscope. This means that, in addition to a peak around 15.5 eV, a TES that measures UV light should also have some peaks at lower energies that correspond to the TES band structure within several eVs of the Fermi level. Oxidized titanium has a large peak in the density of states that is 5 eV below the Fermi level (Eastman, 1972; Hanson et al., 1981; Hagström et al., 1977). This is one possible explanation for why, in figure 7.3, even after using the PMT to window exclusively on the photon signal, there are still many counts near 5 eV.

The spectra from TESs E and F are closer to what is expected at high energies in the sense that the cutoff is closer to that expected from figure 7.7. One possible reason for this is that the extra layer of metal present on these two TESs helps keep the efficiency more constant at higher energies, as any high-energy phonons created during the initial photo-electron's scattering process will have a higher probability of being reabsorbed into the electron system thanks to the larger total detector volume.

7.3.2 Triplet excimer coupling to TES

Figure 7.8 depicts the manner in which a triplet excimer couples its energy to the TES. This has been generalized from the method in which a single excited He atom couples to a surface presented by Harada et al. (1997). There are four main steps:

1. When the excimer gets physically close to the TES surface, the excited electron res-

onantly tunnels into the empty states above the Fermi level. This electron scatters down to the Fermi surface, releasing an energy $(E_1 - E_F)$ into the TES. For this to happen, the work function of the TES surface must be greater than $E_v - E_1$. E_1 is somewhat dependent on the proximity of the excimer to the surface, and increases as this distance decreases.

- 2. An electron from within the TESs Fermi sea fills the empty state at the ground level of the helium atom, leaving a hole in the TES Fermi sea.
- 3. An electron from within the Fermi sea gains the energy released in the previous step $(E_3 E_g)$ through an Auger process. This may be enough energy to cause the electron to escape the TES.
- 4. Finally, electrons from the Fermi surface drop down to fill the holes left in the previous two steps. These two energies are $E_{\rm F} E_3$ and $E_{\rm F} E_2$. If the Auger electron from the previous step remains within the TES, it will deposit the rest of its energy, $(E_3 E_g) (E_{\rm F} E_2)$, in the TES as it relaxes to the Fermi level.

In this process, $E_1 - E_F$ is always deposited in the TES. For Ti, this energy is very nearly zero. For Au and Pt, it should be about 2–3 eV, as these metals have larger work-functions than Ti. There appears to be a peak near 2–3 eV in both figure 7.3c and figure 7.3d that is reduced in size when the triplet signal is suppressed by enforcing PMT coincidence. The two electrons from steps 2 and 3 can come from any filled state in the TES, and so the density of states plays a large part in determining E_2 and E_3 . There is also no reason why E_2 should be larger than E_3 . This process effectively maps out the density of states near the Fermi level, and is nearly the inverse of a technique called atomic/molecular deexcitation spectroscopy (Trioni et al., 2005; Harada et al., 1997). In that process the Auger electron is collected when it escapes from the surface, where in this case, the TES collects the energy that does not escape.

This process gives some insight into the spectra shown in this chapter and allows one to make some educated guesses as to what the various peaks all mean. The following statements are this author's best hypotheses as to what is happening, but a more careful



Figure 7.8: The left panel shows the triplet state excimer on the right of the dashed line (one He atom in the ground state, and one in an excited state) and the TES on the left of the dashed line. The horizontal axis is distance, and the vertical axis is energy. $E_{\rm v}$ is the vacuum energy and $E_{\rm F}$ is the Fermi energy the gradient region depicts a non-uniform density of states below the Fermi level. $E_1 - E_{\rm g}$ is the excimer energy and is about 15 eV. E_1 is roughly 4 eV below $E_{\rm v}$, but shifts upwards as the excimer approaches the surface. The right panel shows the processes involved in the excimer quenching on the detector (blue arrows), numbered in order of occurrence 1: the excited electron tunnels into a free state in the TES, and relaxes to the Fermi surface. 2: An electron from the TES Fermi sea fills the empty ground state of the helium molecule, and the molecule splits into two atoms. 3: An Auger electron is promoted from within the TES Fermi sea, and has energy $E_3 - E_{\rm g}$. Finally, electrons relax from the Fermi surface to fill the two empty states in the TES (this is not pictured).

study with higher energy resolution is required to make any definitive statements.

Discussion of TES D spectra

Oxidized titanium (and TES D is certainly oxidized as it was exposed to air for several days prior to installation) has peaks in the density of states near 2 eV and 5 eV below the Fermi level (Eastman, 1972; Hanson et al., 1981; Hagström et al., 1977). This means that when the Auger electron escapes, there should be peaks in the spectrum at 4 (2 + 2), 7 (2 + 5, 5+2), and 10 (5+5) eV, and when the Auger is reabsorbed there will be a peak near 15 eV as in that case, the total energy of the excimer is deposited in the TES. The blue curve from figure 7.3b has a broad peak at 4 eV that shifts to a narrower peak at 5 eV when the PMT coincidence is applied (red curve). This is the expected behavior as the dominant physics for the low energy-peak on the red curve should be the photo-electric effect as discussed above in section 7.3.1.

Discussion of TES E spectra

The density of states of platinum has a sharp narrow peak within an eV of the Fermi level, but then is relatively constant below 1 eV (Harada et al., 1997; Baptist and Chauvet, 2000). This explains the lack of any real structure in the TES E spectra depicted in figure 7.3c save for the small peak near 2 eV, which is likely due to the fact that $E_1 \approx 2$ eV for platinum. This peak is strongly reduced when PMT coincidence is enforced, as expected.

Discussion of TES F spectra

The density of states of gold has a large peak near 3 eV below the Fermi level (Krolikowski and Spicer, 1970; Smith, 1971), which should give rise to a peak in the blue curve of figure 7.3d at 6 eV (3 + 3). There does appear to be a small bump in the spectrum near 6 eV, but that could also be due to statistical variation. The large peak near 3 eV is due to triplet excimers, as may be seen by the corresponding reduction of that peak in the red curve. The most plausible origin of this peak is that, like platinum, E_1 is about 2 eV for gold and so the spectrum is peaked at low energy.

Discussion of TES count rate differences

It is clear from the sizes of the error bars on the blue curves in figure 7.3 that the TES D spectrum contains many more counts than the spectra collected by either TES E or TES F. The reason for this is unknown. The fact that both TES E and F experienced the same dearth of detection events when exposed to the same excimer flux suggests that the surface chemistry is responsible; gold and platinum both have similar surface properties. For now this will have to remain an open question.

Next steps



S HORTLY before the writing of this dissertation, the experiment was decommissioned and is, at the time of this writing, bound for the University of California, Berkeley. In the hopes that it may be eventually recommissioned, here are presented a number of things that could be done differently (and better). With a better system would come increased capabilities to answer questions, and so a list of future science goals is also presented.

8.1 Engineering improvements for version 2

This section breaks down the list of improvements that ought to be made to any future version of this experiment by sub-system.

8.1.1 Electronics

Low-voltage signal electronics

There were three main issues encountered with the signal electronics.

1. The original detector design (discussed in appendix A) called for a two-pixel TES coupled to an aluminum absorber that also acted as a shared ground. Unfortunately, the bias current sources provided with the SQUID system that was purchased for this

experiment was not able to provide two independent current biases when two of the SQUID chips were sharing a ground.

- 2. There was no way to attach external instruments to the SQUID/TES system. It would have been helpful to be able to measure the complex impedance of the TESs as a function of a frequency, but there were no ports for applying an external signal to the TES.
- 3. The TES was very sensitive to any small currents on the ground lines. Turning the room lights on/off, connecting a new instrument, rolling a large metal object near the cryostat, or even using a noisy switched-mode computer power supply were all enough to introduce fluctuations in the TES output that were several times larger than the photon signal.

All three of these problems are easily remedied, and only require some careful planning when wiring up the electronics for the first time. First, each twisted pair/triplet should have its own shield (either a braided stainless steel sheath or a solid thin-walled stainless steel capillary). At each stage of the cryostat, all the output lines should be filtered heavily with non-dissipative low-pass filters at the desired bandwidth. The input lines should have current dividers at each cryostat stage to reduce the input fluctuations by several orders of magnitude. Care should be taken, however, not to attenuate so much that the input current source is incapable of biasing the TES. Second, instead of using the built-in current sources, the input lines should instead be wired to general input ports at the cryostat bulkhead. This would allow one to connect anything from a current source to a spectrum analyzer to the TES, and would make it easy to take measurements of the complex impedance as well as the $I_{\rm b}/I_{\rm TES}$ curves. Finally, it is now clear that there was really no need to mount the SQUID amplifiers in the same chamber as the TES. Originally this was done to minimize the parasitic resistance (see figure 2.2). A better design would have had each SQUID amplifier in its own niobium shield, mounted outside the chamber on the cryostat baseplate.

High-voltage tip electronics

The main difficulty with the HV system was figuring out a way to create a high-voltage pulse that was short ($\sim \mu s$) and did not produce any electrical noise that would be picked up by the TES. This was never properly solved. The answer is probably to spend some money and just buy a system engineered for exactly this. They exist, but are expensive. Attempts to build one from scratch were only marginally successful; it produced a short high-voltage pulse, but also produced so much electronic noise that it completely overwhelmed the TES.

The HV system was also slightly more complicated than was necessary, as it included a grid at a negative high-voltage to keep electrons from the tip from impacting the TES. However, by the time they reach the TES the energy contained in any electrons is below the noise floor of the detector. During this experiment, there was no observed difference in signal whether the high-voltage grid was on or off.

8.1.2 LHe chamber

The chamber discussed in chapter 3 has several flaws that a new chamber design could address.

- 1. The chamber is very large. It takes 100 L of helium gas at standard temperature and pressure to fill it up completely with superfluid helium. The condensation process takes a very long time, and the more helium required to fill the chamber, the more potential there is for an ice block in the filling capillary.
- 2. Opening and closing the chamber was a laborious process due to the large number of screws required to seal the flange. It was also very difficult to access the tungsten needles, which needed to be changed after every cool-down. The more difficult a subsystem is to access, the more likely it will be broken whenever maintenance is required.
- 3. There were far too many electrical lines going into the chamber. As discussed above, the choice to mount the SQUIDs inside the chamber was not a particularly good one and raised the number of required DC feedthroughs into the chamber from 6 to 24.

An extra 25-pin connector was also added for auxiliary wiring. This connector was never used, and could have been eliminated.

- 4. The lack of a film-burner meant that a small injection capillary had to be used for helium filling in order to minimize the heat leak from the superfluid film. Because such a small capillary was prone to ice blockages, a secondary plumbing line had to be added to the chamber to evacuate it sufficiently fast in the event of either a rapid unscheduled warm up or a capillary ice blockage. This secondary plumbing line, while necessary (it was required more than once), could be eliminated by incorporating a film burner and using a larger injection line. If a supplier could be found, this simplification would be well worth any added cost. One possible option would be to salvage a still unit off of a decommissioned dilution refrigerator (or convince a cryostat company to sell a stand-alone still), as the film burner is typically incorporated into the still.
- 5. The "high voltage" feedthroughs used were actually RF feedthroughs and were only good to about 1800 V. It would have been much better to use true high-voltage feedthroughs (and would have saved the hassle of having to replace them).

The solution to most of the above issues is simple: redesign the chamber to be cylindrical with a circular flange on each end. One flange could hold the detectors along with two DC feedthroughs per TES (as mentioned above, the SQUIDs would be outside the chamber in this implementation). The other flange could hold all the tungsten needle hardware, the fiber-optic feedthrough, and the helium injection port. Either flange could be mounted with no more than six bolts and would be easily removable for maintenance. Furthermore, only the system requiring maintenance would have to be removed. The overall volume of helium required to fill such a chamber could be reduced by a factor of at least two or three without any special consideration, and perhaps even farther with a careful approach to design.

8.1.3 TES

Although the TESs used in this work were sufficient to detect individual excimers, there are a few improvements that could make them much better.

- The TESs could be much thicker. The TESs were 16 nm thick evaporated Ti. As mentioned in chapter 6, they were ~20% transparent to both blue light and UV light. A thicker TES would allow for more complete absorption of signal in the detector.
- 2. The TESs could be longer. A longer TES (length between leads) would be less susceptible to edge-hits (where the photon is absorbed near enough to the lead that it loses some fraction of the signal to the lead). In chapter 6 it was estimated that an area of about 3 μ m from the leads shouldn't be used as a detection area as energy deposited in that zone may be lost. A narrow, but long detector would minimize the effect of edge-hits. Increasing length and thickness is also going to decrease sensitivity, as the amount of TES heating is proportional to the TES volume, through the heat capacity, and so there is some limit to how long is reasonable. Another way to reduce the edge hit effect would be to use a superconductor with a larger T_c (like Nb) for the leads, which would increase the depth of the hot electron trap. This would come at the expense of a more complicated fabrication procedure.
- 3. It might be interesting to consider suspending the TESs above the Si substrate (this could be accomplished with a Xe₂F etch prior to the aluminum etch that exposes the TES). This would reduce any substrate absorptions and would likely clean the signal up quite a bit. This is, however, at odds with the above recommendation to make the TES longer (longer things are harder to suspend), but would be relatively easy to try. The robustness of a suspended thin film is not known, but could also prove to be an issue.

8.2 Future science goals

Here is a short list of immediate goals that should be the first priority for a future TES-based excimer detection experiment.

• Acquire a narrow-band pulsed light source in the vacuum UV (or as high energy as possible) and look at calibrations over a wide spectrum. This will help determine whether the efficiency of the TES is constant, or depends on input energy.

- It would be interesting to look at more surface materials than just gold or platinum to get a better idea of what is happening with the excimer coupling, especially with regards to the count rate.
- A careful look at spectra at a range of different bath temperatures would be very interesting for both for the tip data and the ²²Na data.
- Using an alpha source mounted very near the TES would change the ratio of singlet:triplet excimers produced and would also increase the count rate to the point where it should be possible to see coincident singlets and triplets that arise from the same scattering event. This would make it possible to determine excimer time-of-flight as well.
- A low-noise fast HV pulse generator would make time-of-flight measurements using the tungsten tip possible, and would make it feasible to actually start studying quantum turbulence.
- Getting the two-pixel device working would significantly increase the detector collection area. There is no reason why this concept should not work, however, the aluminum absorber should probably be deposited via evaporation, not sputtering, in order to realize long quasiparticle lifetimes and a large diffusion constant.

8.3 Concluding remarks

This experiment was designed as a proof of concept to show that

- 1. It is possible to detect individual He_2^* excimers directly within a superfluid bath.
- 2. It is possible to differentiate between the triplet and singlet state excimers.
- 3. It is possible to have a detector that is easily scalable to large surface area.

On the first count the experiment was very successful; the detection of individual excimers has been conclusively demonstrated. Indeed, this work is the first demonstration of calorimetric detection of individual He^{*}₂ excimers. On the second count of differentiating between excimer states, the success level was somewhat mixed. It appears that each excimer state has a characteristic spectrum (that also depends strongly on the TES surface material), but the singlet and triplet spectra overlap in energy to such an extent that it is only possible to fully differentiate between the two states in aggregate. Perfect real-time tagging of individual detection events has not been accomplished. On the third count, there was no demonstration of detector scalability, but this was not due to any intrinsic limitations of the detector design. In fact, the success of the single pixel TESs suggests that a scalable detector based on an aluminum absorber should work as designed.

Finally, there is a considerable amount of uncertainty as to the physics behind the unique spectrum shapes presented in chapter 7. A hypothesis has been put forward that appeals to the photoelectric effect, the surface chemistry of the TES, and the unknown high-energy electron-phonon coupling of the TES, but it is not at all rigorous. A full understanding is not possible within the limits of the current data, and a new set of experiments and devices is required to arrive at a satisfactory explanation of the results presented here.

TES absorber diffusion math



MAGINE a long superconducting absorber of superconducting gap energy (Δ) with TES detectors at each end. If the TES is biased on the transition, then its superconducting energy gap is zero, and any quasiparticles at the boundary of the absorber and the TES will scatter into the lower-energy region of the TES. In the event of a photon incident on the absorber, the photon will break a Cooper pair and create two excited quasiparticles. As these quasiparticles relax, they will break more Cooper pairs, exciting more quasiparticles above the gap, until all the quasiparticles have energy Δ . These quasiparticles will then diffuse along the absorber until they reach one of the two TES detectors, where they will relax down to the Fermi levels of the TESs and will effectively become trapped. They will share their energy with the electron systems of the two TESs, which will result in a pulse in each TES. The following analysis solves for the total number of quasiparticles collected by each of the two detectors as a function of excitation location along the absorber. In sections A.1 and A.2 the lossless 1-D case is treated. Section A.3 deals with the addition of loss in the absorber. Section A.4 considers the 2-D case and shows that if the boundaries not connected to the TESs exhibit specular reflection, the problem reduces to the 1-D problem. Finally, in the last section, section A.5, the addition of a finite trapping length (the distance a quasiparticle must travel into the TES to become trapped) in the TES is considered and the result is the conclusion of this appendix. These solutions may also be used to estimate the number of quasiparticles that end up in the TES when a photon is absorbed in/near the TES leads for the case where the TES lead is a superconductor with a higher T_c than the TES material.

This problem is well studied already in the context of superconducting tunnel junction (STJ) detectors and the solution has been presented in multiple works (Loidl et al., 2001; Li, 2003). However, although these works provide the final expression given in (A.34), none of them (even in aggregate) provide all the steps for arriving at the solution. The full solution is thus presented here.

A.1 Diffusion equation

In 1-D, the relevant equation for describing the number-density of quasiparticles as a function of time and position is the lossless diffusion equation:

$$\frac{\partial}{\partial t}\Phi_{\rm qp}(x,t) = \frac{\partial}{\partial x} \left(D(x)\frac{\partial}{\partial x}\Phi_{\rm qp}(x,t) \right) \tag{A.1}$$

If the superconducting absorber is homogeneous along its length, then D(x) = D and the above becomes:

$$\frac{\partial}{\partial t}\Phi_{\mathbf{qp}}(x,t) = D\frac{\partial^2}{\partial x^2}\Phi_{\mathbf{qp}}(x,t) \tag{A.2}$$

If one assumes that Φ_{qp} is separable in both time and space¹, then $\Phi qp(x,t) = X(x)T(t)$. This may be substituted into (A.2) and rearranged to get:

$$\frac{\dot{T}(t)}{T(t)} = D \frac{X''(x)}{X(x)}$$
 (A.3)

The only way that the above equation is valid for all t and all x is if both sides equal some constant value k. Now the partial differential equation (A.2) has reduced to two ordinary

^{1.} The proof of separability is straightforward: If one is able to separate it, then it is separable. If it is not separable, then it will be impossible to arrive at a separated expression such as (A.3).

differential equations:

$$X''(x) = \frac{k}{D}X(x) \tag{A.4}$$

$$\dot{T}(t) = kT(t) \tag{A.5}$$

The solutions to each of these equations are trivial, but depend of the value of the constant k, which can be positive, negative, or zero. In order to fix the constant, one must consider the boundary conditions. Let the 1-D wire be centered at x = 0 with length L. As the quasiparticles diffuse to the end of the wire, they are trapped in the TES and disappear from the wire; at the ends of the wires, the quasiparticle density must be zero:

$$X(\pm \frac{L}{2}) = 0 \tag{A.6}$$

If one considers the solution to (A.4) in light of this boundary condition, there is only one range of k that gives meaningful results: k < 0. In light of this, redefine $k \to -k^2$ where now k > 0, and rewrite (A.4) and (A.5) as:

$$X''(x) = \frac{-k^2}{D}X(x)$$
 (A.7)

$$\dot{T}(t) = -k^2 T(t) \tag{A.8}$$

and the solutions to these equations are:

$$X(x) = Ae^{i\frac{k}{\sqrt{D}}} + Be^{-i\frac{k}{\sqrt{D}}}$$
(A.9)

$$T(t) = Ce^{-k^2t} + Ee^{k^2t} (A.10)$$

Application of the boundary conditions to (A.9) fixes the value of k to be:

$$k = \frac{m\pi\sqrt{D}}{L} \tag{A.11}$$

where m = 0,1,2, etc... Substituting this back into (A.9) gives A = B for odd values of m, and A = -B for even values of m. For each m, let $A = A_m$. The constant E in (A.10) may be eliminated by requiring T(t) to be bounded as $t \to \infty$. Absorbing C into A_m , putting it all together, and summing over all m gives:

$$\Phi_{\rm qp}(x,t) = \sum_{m=0}^{\infty} A_m \left(e^{i\frac{m\pi x}{L}} - (-1)^m e^{-i\frac{m\pi x}{L}} \right) e^{-(\frac{m\pi}{L})^2 Dt}$$
(A.12)

One may now use Fourier's trick² Multiplying both sides of (A.12) by the complex conjugate of the summand and integrating over the length of the wire gives:

$$A_m = \frac{1}{2L} \int_{-\frac{L}{2}}^{\frac{L}{2}} \Phi_{\rm qp}(x,t=0) \left(e^{i\frac{m\pi x}{L}} - (-1)^m e^{-i\frac{m\pi x}{L}} \right) dx \tag{A.13}$$

All that now remains is to specify the distribution of quasiparticles at time t = 0 and solve for the coefficients A_m . A photon that is absorbed in the wire will initially produce a large quantity of quasiparticles in the immediate vicinity of the absorption. This distribution is well described by a delta function: $\Phi_{qp}(x,0) = N_{qp}\delta(x-x_0)$, where N_{qp} is the number of quasiparticles excited by the photon. Substituting this into (A.13) and then subsequently into (A.12) gives (after some algebra):

$$\Phi_{\rm qp}(x,t) = \frac{N_{\rm qp}}{L} \sum_{m=0}^{\infty} \left[\cos\left(\frac{m\pi(x-x_0)}{L}\right) - (-1)^m \cos\left(\frac{m\pi(x+x_0)}{L}\right) \right] e^{-(\frac{m\pi}{L})^2 Dt} \quad (A.14)$$

^{2.} Fourier's trick assumes that the summand constitutes a complete set of orthogonal functions on the interval $\{-L/2, L/2\}$. The proof for this case is outside the scope of this text, but not difficult, and is available in nearly any textbook on mathematical methods.

A.2 Solving for the number of quasiparticles in the TES detector

In the previous section the quasiparticle number density as a function of time and position was calculated, given some initial excitation of quasiparticles at x_0 . What is more interesting is determining the number of quasiparticles that end up in each detector after an excitation. Since the quasiparticles that reach the ends of the absorber are trapped into the TESs, the change in quasiparticle density at either end of the wire is proportional to the rate at which quasiparticles get trapped as a function of time $(J_{N_{\pm}})$. Another way of saying this is that the number current $(J_{N_{\pm}})$ is proportional to the gradient of the number density along the wire, with the diffusion constant playing the analog of conductivity as the constant of proportionality.

$$J_{N_{\pm}}(t) = D \left| \frac{d}{dx} \Phi_{\rm qp}(x = \pm \frac{L}{2}, t) \right| \tag{A.15}$$

In the above equation, the absolute value signs account for the fact that the change in number at the ends may be negative (i.e., the number current has a direction and only the magnitude is important). The plus sign denotes the TES at x = L/2 and the minus sign denotes the TES at x = -L/2. Evaluating this gives:

$$J_{N_{\pm}}(t) = \frac{DN_{\rm qp}}{L^2} \left| \sum_{m=0}^{\infty} m\pi \left[\sin\left(\frac{\pm m\pi}{2} - \frac{m\pi x_0}{L}\right) - (-1)^m \sin\left(\frac{\pm m\pi}{2} + \frac{m\pi x_0}{L}\right) \right] e^{-(\frac{m\pi}{L})^2 Dt} \right|$$
(A.16)

Finally, this expression may be integrated from the absorption of the photon at time t = 0 to $t \to \infty$ to get the total number of quasiparticles deposited in the TES detector a long time after an absorption event:

$$N_{\pm} = N_{\rm qp} \left| \sum_{m=0}^{\infty} \frac{1}{m\pi} \left[\sin\left(\frac{\pm m\pi}{2} - \frac{m\pi x_0}{L}\right) - (-1)^m \sin\left(\frac{\pm m\pi}{2} + \frac{m\pi x_0}{L}\right) \right] \right|$$
(A.17)

The infinite sum is analytic on the interval $-L/2 \le x \le L/2$ and reduces to³:

$$N_{\pm} = N_{\rm qp} \left(\frac{1}{2} \pm \frac{x_0}{L}\right) \tag{A.18}$$

A.3 Adding loss in the superconducting absorber

The addition of a loss mechanism in the superconducting absorber is straightforward, and consists of adding a loss term to (A.2):

$$\frac{\partial}{\partial t}\Phi_{\rm qp}(x,t) = D\frac{\partial^2}{\partial x^2}\Phi_{\rm qp}(x,t) - \gamma\Phi_{\rm qp}(x,t) \tag{A.19}$$

Here, $\gamma = 1/\tau$ where τ is the time constant of all the combined loss mechanisms $(1/\tau = 1/\tau_1 + 1/\tau_2 + ...)$. Equation A.7 is unchanged, and (A.8) becomes:

$$\dot{T}(t) = -(k^2 + \gamma)T(t) \tag{A.20}$$

This is straightforward to propagate through the previous analysis, and (A.17) becomes:

$$N_{\pm} = N_{\rm qp} \left| \sum_{m=0}^{\infty} \frac{m\pi}{m^2 \pi^2 + \frac{L^2}{D\tau}} \left[\sin\left(\frac{\pm m\pi}{2} - \frac{m\pi x_0}{L}\right) - (-1)^m \sin\left(\frac{\pm m\pi}{2} + \frac{m\pi x_0}{L}\right) \right] \right|$$
(A.21)

In the limit $\tau \to \infty$ this reduces to the lossless case. The infinite sum is analytic, and evaluates to⁴:

$$N_{\pm} = N_{\rm qp} \frac{\sinh\left(\frac{L}{\sqrt{D\tau}} \left(\frac{1}{2} \pm \frac{x_0}{L}\right)\right)}{\sinh\left(\frac{L}{\sqrt{D\tau}}\right)} \tag{A.22}$$

^{3.} I.S. Gradshteyn and I.M. Ryzhik, "Table of integrals, series, and products; corrected and enlarged edition," pp. 38, Sec. 1.441, Eqs. 1 and 3, Academic Press Inc. San Diego, 1980.

^{4.} I.S. Gradshteyn and I.M. Ryzhik, "Table of integrals, series, and products; corrected and enlarged edition," pp. 40, Sec. 1.445, Eqs. 1 and 4, Academic Press Inc. San Diego, 1980.

A.4 The 2-D case

If some width (W) is given to the superconducting wire so that it becomes a superconducting slab, one may calculate the effect on the collection of quasiparticles by the TES detectors at either end of the slab. This analysis assumes that the TES detectors are in contact with the entirety of each edge of the slab. The coordinate system is chosen such that center of the slab is at (0,0). In this case, (A.19) becomes:

$$\frac{\partial}{\partial t}\Phi_{\rm qp}(\vec{x},t) = D\nabla^2 \Phi_{\rm qp}(\vec{x},t) - \gamma \Phi_{\rm qp}(\vec{x},t) \tag{A.23}$$

Note that now $\Phi_{qp}(\vec{x},t)$ has units of per-length squared. Separation of variables gives:

$$\frac{\dot{T}(t)}{T(t)} = D\left(\frac{X''(x)}{X(x)} + \frac{Y''(y)}{Y(y)}\right) - \gamma \tag{A.24}$$

The X(x) solution remains the same as in the previous case. The T(x) solution is modified slightly by replacing $(m/L)^2$ with $(m/L)^2 + (n/W)^2$. At the top and bottom of the absorber (where there are no detectors) the quasiparticle number should remain constant (no quasiparticles escape; they all reflect). This is written as:

$$\frac{d}{dy}\Phi(x,y=\pm\frac{W}{2},t)=0 \tag{A.25}$$

Application of these conditions to Y(y) gives:

$$Y(y) = A_n \left(e^{i\frac{n\pi y}{W}} + (-1)^m e^{-i\frac{n\pi y}{W}} \right)$$
(A.26)

Combining this with (A.12) gives:

$$\Phi_{\rm qp}(\vec{x},t) = \sum_{m,n=0}^{\infty} A_m \left(e^{i\frac{m\pi x}{L}} - (-1)^m e^{-i\frac{m\pi x}{L}} \right) \dots$$
$$\dots A_n \left(e^{i\frac{n\pi y}{W}} + (-1)^n e^{-i\frac{n\pi y}{W}} \right) e^{-(\pi^2 D \left(\frac{m^2}{L^2} + \frac{n^2}{W^2}\right) + \gamma)t} \quad (A.27)$$

If the initial quasiparticle distribution is $N_{qp}\delta(x - x_0, y - y_0)$ then the coefficients may be determined and the final 2-D solution (with loss) becomes:

$$\Phi_{qp}(\vec{x},t) = \frac{N_{qp}}{2LW} \sum_{m,n=0}^{\infty} \left[\cos\left(\frac{m\pi(x-x_0)}{L}\right) - (-1)^m \cos\left(\frac{m\pi(x+x_0)}{L}\right) \right] \dots$$

$$\dots \left[\cos\left(\frac{n\pi(y-y_0)}{W}\right) + (-1)^n \cos\left(\frac{n\pi(y+y_0)}{W}\right) \right] e^{-(\pi^2 D\left(\frac{m^2}{L^2} + \frac{n^2}{W^2}\right) + \gamma)t}$$
(A.28)

If one now integrates over y from -W/2 to W/2, it becomes clear that the only term in the sum over n to survive is the n = 0 term. This integral returns a constant of 2W and the equation becomes:

$$\Phi_{\rm qp}(x,t) = \frac{N_{\rm qp}}{L} \sum_{m=0}^{\infty} \left[\cos\left(\frac{m\pi(x-x_0)}{L}\right) - (-1)^m \cos\left(\frac{m\pi(x+x_0)}{L}\right) \right] e^{-(\pi^2 D \frac{m^2}{L^2} + \gamma)t}$$
(A.29)

This is identical to the 1-D case with loss and one may immediately write down the number of quasiparticles that become trapped in each TES as:

$$N_{\pm} = N_{\rm qp} \frac{\sinh\left(\frac{L}{\sqrt{D\tau}} \left(\frac{1}{2} \pm \frac{x_0}{L}\right)\right)}{\sinh\left(\frac{L}{\sqrt{D\tau}}\right)} \tag{A.30}$$

It is worth noting that although the number of quasiparticles entering the TES detectors in the 2-D case is identical to the 1-D case for a given length (L), the actual density of the quasiparticles in the TES detectors goes like 1/W. Care must be taken to ensure that there are adequate quasiparticles relaxing into the TES to heat it up enough to give a signal.

A.5 Adding the effects of finite trapping time to the 1-D case

In the case where the quasiparticle trapping in the TES is not perfect, the boundary conditions at the ends change from $\Phi_{qp}(\pm L/2, t) = 0$ to:

$$\mp \frac{1}{l_{\text{trap}}} \Phi_{qp} \left(\pm \frac{L}{2}, t \right) = \frac{\partial}{\partial x} \Phi_{qp} \left(\pm \frac{L}{2}, t \right)$$
(A.31)

where $l_{\text{trap}} = \sqrt{D\tau_{\text{trap}}}$ is the length a quasiparticle must diffuse through the TES before it scatters down into the trapping region. This boundary condition describes an exponential decay of quasiparticle density into the TES starting at the boundary, rather than a sharp step-function to zero. If this length is long, some fraction of the quasiparticles reenter the absorber before relaxing into the trap.

Unfortunately, it is not possible to write $\Phi_{qp}(x,t)$ as an analytic series solution in this case because the eigenvalues of the $X_n(x)$ are described by a transcendental equation. It is still possible to find an analytic solution for $N_{\pm}(x_0)$ however, by converting the differential equation for $\Phi_{qp}(x,t)$ to a differential equation for $N_{\pm}(x_0)$. This is achieved by integrating (A.19) once in time, and once in space, and then differentiating twice with respect to x_0 . Finally, one uses the fact that N_{\pm} equals the time integral of (A.16) to arrive at:

$$\frac{1}{D\tau}N_{\pm}(x_0) = \frac{\partial^2}{\partial x_0^2}N_{\pm}(x_0) \tag{A.32}$$

with boundary conditions:

$$N_{+}\left(\frac{-L}{2}\right) = l_{\text{trap}}\frac{\partial}{\partial x_{0}}N_{+}\left(\frac{-L}{2}\right)$$

$$N_{+}\left(\frac{L}{2}\right) = N_{0} - l_{\text{trap}}\frac{\partial}{\partial x_{0}}N_{+}\left(\frac{L}{2}\right)$$

$$N_{-}\left(\frac{L}{2}\right) = -l_{\text{trap}}\frac{\partial}{\partial x_{0}}N_{-}\left(\frac{L}{2}\right)$$

$$N_{-}\left(\frac{-L}{2}\right) = N_{0} + l_{\text{trap}}\frac{\partial}{\partial x_{0}}N_{-}\left(\frac{-L}{2}\right)$$
(A.33)



Figure A.1: Curve of number of counts in each detector for realistic values of α and β . $D = 18 \text{ cm}^2/\text{s}$, $\tau = 1 \text{ ms}$, and $\tau_{\text{trap}} = 100 \text{ ns}$ Wang et al. (2014). The different colored curves represent different length absorbers, as indicated in the legend.

This evaluates to (after a lot of algebra):

$$N_{\pm} = N_0 \frac{\sinh(\alpha \left(\frac{1}{2} \pm \frac{x_0}{L}\right)) + \beta \cosh(\alpha \left(\frac{1}{2} \pm \frac{x_0}{L}\right))}{(1 + \beta^2) \sinh \alpha + 2\beta \cosh \alpha}$$
(A.34)

with $\alpha = L/\sqrt{D\tau}$ and $\beta = \sqrt{\tau_{\rm trap}/\tau}$.

A parametric plot of N_+ and N_- may be made by treating x_0 as a parameter and sweeping it from -L/2 to L/2. Figure A.1 shows this parametric plot for a number of different absorber lengths (L) with realistic values of α and β for an electron-beam evaporated Al film.

Plumbing circuits



The following diagrams depict the plumbing network used to fill the chamber with helium. Every possible mode of operation is depicted, and the route the He gas takes during each mode is highlighted in blue. Note that there are two inputs to the He fill keg. One input is a thin pipe that extends to the back of the keg. This allows for pulling helium from the back of the keg while replacing it at the front, thereby causing the gas in the keg to circulate.

The first diagram depicts the electrical connectivity of the network. It was desirable to keep as much of the plumbing network as possible electrically separated from the rest of the experiment. This was accomplished with the use of plastic flange clamps and plastic O-ring holders between the stainless steel bellows at certain key points. The components sharing an electrical ground with the cryostat are highlighted in orange-red.



















Computer code

MATHEMATICA was chosen for solving differential equations because it has a builtin engine that chooses the best method for solving a particular problem. It also outputs very nice plots with minimal effort. Data analysis was all handled in Igor Pro, but that code is not listed here, as all the relevant algorithms are described in the text.

Appendix

C.1 TES differential equations

Solving the TES equations is fairly straightforward with one small exception: when the TES switches to, or from, the super-current branch of the $I_{\rm b}/I_{\rm TES}$ curve, it experiences a very sharp cusp. Since the derivative of this cusp is discontinuous, the standard numerical solver can get hung up. Luckily, the solution to the equations in the super-current region is amenable to a simple analytic expression. This means one only needs to run the numerical solver in the region to the right of the cusp.

The algorithm for the code is straightforward:

1. Start at I = 0, T = 0 and run the solver until the derivative starts to change. This location will be the cusp of the increasing current branch.

2. Start at the end (maximum current), calculate I and T for the fully normal situation, and work backwards until I gets close to the super-current branch. 3. Plot the solution as a piecewise function by stitching together the two solutions from steps 1 and 2.

In order to apply a bias current, a simple linear ramp function was used that ramps from zero to one in one second. This is more than slow enough to avoid any strangeness from either the L/R time or the C/G time.

For the plots where one parameter was swept, the algorithm above was simply repeated in a loop, and the resulting traces were combined in the same plot. The base parameters, which are defined in the code, are given also in table C.1.

Table C.1: Parameter values corresponding to the numerical models, taken from the code in this appendix.

Parameter	Value	Parameter	Value	Parameter	Value
Width	$10 \ \mu m$	γ	$304 \mathrm{~J/m^3 K^2}$	L	5 nH
Length	$15~\mu{ m m}$	Σ_{e-ph}	$3.25 imes 10^8 \ \mathrm{W/m^3 K^n}$	α_I	60
Thickness	$15 \ \mathrm{nm}$	n	5.9	β_I	1
$R_{ m N}$	$48.6 \ \Omega$	T _c	430 mK	$E_{ m phot}$	2.6 eV
$R_{ m s}$	$200 \text{ m}\Omega$	$T_{\rm b}$	122 mK	η	0.4
$R_{ m p}$	$5~\mathrm{m}\Omega$	Ic	130 µA	I _b	18 µA

Mathematica code

This code calculates an $I_{\rm b}/I_{\rm TES}$ curve given a certain set of input parameters. It also calculates and plots TES temperature, power, and voltage.

```
1 (*Import some dependancies*)
2 Needs["DifferentialEquations 'NDSolveProblems '"];
3 Needs["DifferentialEquations 'NDSolveUtilities '"];
4 Needs["DifferentialEquations 'InterpolatingFunctionAnatomy '"];
5 Needs["GUIKit '"];
6
7 (*Detector Properties*)
8 gamma=304; (*Specific heat of TES in J/(m^3 K^2)*)
9 V=(15*^-6)*(10*^-6)*15*^-9; (*Volume of TES in cubic meters *)
10 Tc=0.43; (*Critical temperature in Kelvin *)
```

```
11 dTc=0.01; (*Width of the transition in Kelvin *)
12 Rn=48.6; (*Normal-state resistance of TES in Ohms *)
13 sigma=3.25*^8; (*e-ph coupling constant for Ti in W/(m^3K^5) *)
14 n=5.9; (*Thermal conductivity exponent*)
15 Tb=0.122; (*Operating Temperature of fridge in Kelvin *)
16 Ic=130*^-6;(*Critical current*)
17
18 (*Circuit Properties*)
19 Rs=0.2; (*Shunt resistor in Ohms*)
20 L=5*^-9; (*Input inductor in Henries*)
21 Rp=0.005; (*Parasitic resistance in Ohms *)
22 IbMax=100*^-6;(*Maximum value of bias current in Amps*)
23 (*Model of resistive transition*)
24 Rw[Temp_, Is_]:=
25 (Rn/2)*(1 + Tanh[(Temp - Tc*(1 - Re[(Is/Ic)^(2/3)]))/(dTc/(2*Log10[3]))]);
26
27 (*Heat Capacity*)
28 Cw[Temp_]:=V*gamma*Temp;
29
30 (*Make sure nothing is using these variable names*)
31 Clear [Is, Temp];
32
33 (*Calculate the boundary conditions at current=IbMax*)
34 IsMax = (IbMax*Rs)/(Rp + Rn + Rs);
35 TMax = ((IsMax^2*Rn)/(V*sigma) + Tb^n)^(1/n);
36
37 (*Set up the direction the bias current will ramp*)
38 IbUp[t_]:=IbMax*(t);
39 IbDown[t_]:=IbMax*(1-t);
40
41 (*Define the differential equations*)
42 eqnElecUp =
43 Rs*(IbUp[t] - Is[t]) ==
44 Is[t]*(Rp + Rw[Temp[t], Is[t]]) - L*D[Is[t], t];
45
46 eqnElecDown =
```

```
47 Rs*(IbDown[t] - Is[t]) ==
4* Is[t]*(Rp + Rw[Temp[t], Is[t]]) - L*D[Is[t], t];
40
50 eqnHeat =
51 Cw[Temp[t]]*D[Temp[t], t] ==
52 Is[t]<sup>2</sup>*Rw[Temp[t], Is[t]] - V*sigma*(Temp[t]<sup>n</sup> - Tb<sup>n</sup>);
53
54 (*Set the boundary conditions*)
55 (*For ramping down*)
56 eqnBC1Down=Temp[0]==TMax;
57 eqnBC2Down=Is[0]==IsMax;
58
59 (*For ramping up*)
60 eqnBC1Up=Temp[0]==Tb;
61 eqnBC2Up=Is[0]==0;
62
63 (*Define the super-current and normal-current branches*)
64 supercurrent[Ib_]:=Rs*Ib/(Rs+Rp);
65 normalcurrent[Ib_]:=Rs*Ib/(Rs+Rp+Rn);
66
67 (*Ramp up bias current, stop when derivative crosses zero*)
68 solUp=NDSolve[
69 {eqnElecUp, eqnHeat, eqnBC1Up, eqnBC2Up}, {Temp, Is}, {t,0,1},
70 Method ->{
71 "EventLocator",
72 "Event"->D[Is[t],t],
73 EventAction:>Throw[tUp=t;IsUp=Is[t]; TempUp=Temp[t];,"StopIntegration"]
74 },
75 SolveDelayed->True, (*This helps handle discontinuities*)
76 MaxStepSize ->0.001
77 ];
78
79 (*Ramp the bias current down from IbMax*)
so (*Stop when TES current gets close to supercurrent*)
81 solDown=NDSolve[
82 {eqnElecDown, eqnHeat, eqnBC1Down, eqnBC2Down}, {Temp, Is}, {t, 0, 1},
```
```
83 Method ->{
84 "EventLocator",
85 "Event"->Is[t]-0.9*supercurrent[IbDown[t]], EventAction:>Throw[tDown=t;
      IsDown=Is[t]; TempDown=Temp[t];,"StopIntegration"]
86 },
87 SolveDelayed ->True,
88 MaxStepSize ->0.001
89 ];
90 (*Make Some Plots*)
91 GraphicsGrid[{{
92 Show[
93 (*Plot the supercurrent branch up*)
94 ParametricPlot[
95 {1*^6*IbUp[t],
96 If [t<tUp, {1*^6*Is[t]/.solUp}, {1*^6*Is[1-t]/.solDown}]
97 },{t,0,1},
98 PlotStyle ->{Arrowheads [{0,0.02,0,0.02,0,0}], Blue}
99 ]/.Line->Arrow ,
100
101 (*Plot the branch of the curve from IbMax back down to the cusp*)
102 ParametricPlot[
103 {1*^6*IbDown[t],
104 If [t<tDown, {1*^6*Is[t]/.solDown}, 1*^6*supercurrent[IbDown[t]]]</pre>
105 },{t,0,1},
106 PlotStyle ->{Arrowheads [{0,0,0.02,0}], Blue}
107 ]/.Line->Arrow,
108
109 (*Plot the current a resistor of R=Rn would have*)
110 ParametricPlot[
111 {1*^6*IbUp[t],
112 1*^6* normalcurrent[IbUp[t]]
113 },{t,0,1},
114 PlotStyle ->{Gray, Dashed, Lighter}
115 ],
116
117 (*Attributes for the overall Ib/Is plot*)
```

```
118 PlotRange ->{{0,1*^6*IbMax},{0,1*^6*0.75*supercurrent[IbUp[tUp]]}},
119 AspectRatio ->0.5,
120 PlotRangePadding->None,
121 ImageSize ->Large,
122 Frame ->True.
123 FrameLabel ->{"Bias Current (ÎijA)", "Sensor Current (ÎijA)"},
124 FrameStyle ->Directive [16]
125 ],
126
127 (*Plot the resulting TES temperature*)
128 ParametricPlot[
129 {1*^6*IbDown[t],
130 If [t<tDown, {1*^3*Temp[t]/.solDown}, 1*^3*Tb]
i31 },{t,0,1},
132 PlotRange ->{{0, IbMax*1*^6}, {0, 1*^3*TMax}},
133 AspectRatio ->0.5,
134 PlotRangePadding->None,
135 Frame->True,
136 FrameLabel ->{"Bias Current (ÎijA)","TES Temperature (mK)"},
137 FrameStyle ->Directive [16]
138 ]
139 },{
140
141 (*Plot the TES Joule Power*)
142 ParametricPlot[
143 {1*^6*IbDown[t],
144 If [t<tDown,1*^12*Is[t]^2*Rw[Temp[t],Is[t]]/.solDown,0]
145 },{t,0,1},
146 AspectRatio ->0.5,
147 PlotRange ->All,
148 PlotRangePadding->None,
149 Frame->True,
150 FrameLabel ->{"Bias Current (ÎijA)", "TES Joule Power (pW)"},
151 FrameStyle ->Directive [16]
152 ],
153 (*Plot the TES Voltage*)
```

```
154 ParametricPlot[
155 {1*^6*IbDown[t],
156 If[t<tDown,1*^6*Is[t]*Rw[Temp[t],Is[t]]/.solDown,0]
157 },{t,0,1},
158 AspectRatio->0.5,
159 PlotRange->All,
160 PlotRangePadding->None,
161 Frame->True,
162 FrameLabel->{"Bias Current (ÎijA)","TES Voltage (ÎijV)"},
163 FrameStyle->Directive[16]
164 ]
165 }}]
```

C.2 Diffusion equation

For a discussion on the solution to the diffusion equation as it relates to TESs, see appendix A.

Mathematica code

This code calculates the quasiparticle dynamics associated with a photon hit right at the edge of the TES and the Al lead.

```
1 (*Set up some model parameters*)
2 A = 1800; (*Diffusion constant in micron^2/s*)
3 tauLoss = 1000; (*quasiparticle lifetime in microseconds*)
4 length = 200; (*length of aluminum lead -- anything long will do*)
5 sigma = 2; (*diameter of the initial quasiparticle cloud in microns*)
6 lTrap = 0.1; (*Trapping length in TES in um*)
7
8
9 (*Set up the diffusion equation*)
10 eqnDiff = Derivative[1, 0][u][t, x] - A*Derivative[0, 2][u][t, x] + u[t, x]/
tauLoss == 0;
11
12 (*Set some boundary conditions at either end of the aluminum*)
```

```
13 eqnBC1 = Derivative[0, 1][u][t, -length/2] == (1/lTrap)*u[t, -length/2];
14 eqnBC2 = Derivative[0, 1][u][t, length/2] == (-lTrap^(-1))*u[t, length/2];
15
16 (*Set up the initial quasiparticle distribution as a gaussian*)
17 eqnInit = u[0, x] == (1/(Sqrt[2*Pi]*sigma))*Exp[-((x - x0)^2/(2*sigma^2))];
18
19 (*How long to run the simulation for in us*)
20 \text{ tend} = 50;
21
22 (*Solve the equations, but leave the location of the distribution as a
      parameter*)
23 sol = ParametricNDSolve[{eqnDiff, eqnBC1, eqnBC2, eqnInit}, u, {t, 0, 10}, {
      x, -length/2, length/2, x0,
      MaxStepSize -> 0.1];
24
25
26 (*Plot the rate of quasiparticles entering into the TES for a hit on the
      edge. x0=0*)
27
28 plt = Plot[{
29 Evaluate [A*(1/1Trap)*u[0] [t, length/2] /. sol]
30 }, {t, 0, 10},
31
32 Frame -> True,
   FrameLabel -> {"Time (Îijs)", "Quasiparticle Rate"},
33
34 FrameStyle -> Directive[18],
35 ImageSize -> Large,
   PlotRange -> All
36
37 ]
38
39
_{40} (*Calculate the total quasiparticles injected in the TES vs time*)
41 int=Integrate[{(A/lTrap)*u[0][t, length/2] /. sol}, t];
42
43 plt2 = Plot[
44 int, {t, 0, 10},
45
```

```
46 Frame -> True,
47 FrameLabel -> {"Time (Îijs)", "Quasiparticles absorbed in TES"},
48 FrameStyle -> Directive[18],
49 ImageSize -> Large,
50 PlotRange -> All
51 ]
```

Fabrication recipes



A LL of the fabrication was done at Yale University. Electron-beam lithography was accomplished with the Raith EBPG 5000+ at the Yale Institute for Nanoscience and Quantum Engineering. Wet processing and metal deposition was done at the Yale Clean Room.

D.1 Wafer cleaning

The wafer is sonicated for 2 minutes each in N-methyl-2-pyrrolidone (NMP), acetone, and methanol, and then blow-dried with dry nitrogen.

D.2 Single layer resist

The wafer is spun with a 4% solution of 950k polymethyl methacrylate (PMMA) in anisole (A4) at 2500 rpm for 60 s. It is then baked on a hotplate for 5 min at 180° C. This results in a layer of PMMA that is about 200 nm thick.



Figure D.1: This photograph shows the lift-off process in action during the fabrication of TESs D, E, and F (and six other TESs that were not measured). The beaker is full of NMP, and the detachment of the Ti/Al bilayer is clearly visible.

D.3 Bilayer resist

The wafer is spun first with a 13% solution of copolymer (MMA) in ethyl-lactate (EL13) at 3500 rpm for 60 s. It is then baked on a hotplate for 90 s at 180 C. Then a layer of A4 is spun on top as described above. This results in a resist stack that is 200 nm of A4 on about 600 nm of EL13. EL13 is more sensitive than A4 to electron current, and will develop a slightly larger area than A4. This results in a resist stack where the A4 overhangs the EL13 somewhat and provides for a cleaner lift-off process. Figure D.1 shows an example of lift-off, where the metal film may be seen floating above the patterned devices in a jar of solvent.

D.4 Copper evaporation

The wafer is loaded into the Plassys deposition system and pumped down to a base pressure $< 5 \times 10^{-7}$ Torr. A so-called Ti-sweep is performed where Ti is evaporated onto the shutter

to getter impurities and reduce the pressure by a factor of two. Then a 5 nm layer of Ti is evaporated at 0.5 nm/s to provide an adhesion layer for the Cu. Finally, 400 nm of Cu are evaporated at 1 nm/s.

D.5 Ti/Al bilayer evaporation

The wafer is loaded into the Plassys and pumped down to a base pressure $< 1 \times 10^{-7}$ Torr. A Ti-sweep (as described above) is performed, and then the wafer is cleaned with an Anatech hollow cathode ion gun at 250 V and 160 mA in a 3.5:1 Ar:O₂ mixture at 0.2 mTorr. Then 15 nm of Ti is evaporated at 0.5 nm/s, immediately followed by 300 nm of Al at 1 nm/s.

D.6 Lift-off

After metal is deposited on a patterned PMMA mask, the PMMA mask is removed by soaking the wafer in hot NMP for three hours at 90 C and then sonicating for 60 s. See figure D.1 for a photograph of this process step.

D.7 Al etching

Etching of Al is performed by immersion in Microposit MF-312, a tetra-methyl-amoniumhydroxide-based photoresist developer. The etch rate depends on both temperature and MF-312 freshness, and so is monitored under a microscope to determine completion. Typical etch time for 300 nm of Al is 3–5 minutes. It is important to sonicate the wafer during etch as gas bubbles will form at the Al surface during etch, and if not released, will act as an etch-barrier.

D.8 Cu etching

Etching of the 50 nm Cu shield is performed by immersion in a heated, aerated bath of 1:4 ammonium persulfate and water for about 10 seconds (a small aquarium aerator and heater are ideal for the purpose).

D.9 Electron beam lithography: writing and developing

D.9.1 Beam current and dose

All e-beam lithography is performed on a Raith EBPG 5000+. It is a 100 keV system capable of providing beam currents of several hundred nA. For the resists described above, spun on a Si substrate, a beam current of 50–150 nA is used for an electric charge dose of 700 μ C/cm². The fact that pattern centers naturally receive a higher dose than pattern edges is nullified through an automatic routine that estimates the actual dose at each point in the pattern required to achieve an effective dose of 700 μ C/cm².

D.9.2 Developing E-beam resist

After writing, the wafer is developed by immersion in a 3:1 isopropanol:water solution kept at 7 C. The wafer is immersed for 2 min. The wafer is sonicated for the last 30 s of development.

Sources of noise and interference

Appendix

DEALLY, the experiment would be housed in a perfect Faraday cage to prevent electromagnetic (EM) interference, installed in a basement on a concrete slab connected directly to bedrock to prevent vibrations, and connected to a magical set of noise-free instruments and computers powered by clean linear power supplies. In this experimental utopia, the nearest other scientist is miles away in her own perfect Faraday cage, and the measurement noise floor is limited only by the intrinsic noise of the TES detectors. This is an unlikely scenario. The experiment discussed in this dissertation shared a room with three qubitbased experiments, each with a large collection of RF generators, synchronization clocks, computer controllers, and resourceful graduate students who use narrow bandpass filters to pretend they live in a clean EM environment. Furthermore, the building the experiment is in has an interesting (euphemism for maddening) electrical wiring configuration that somehow manages to couple building utilities and experiments together in a variety of unintelligible ways that introduce interference covering the spectrum from a few mHz to a few kHz. The computers used all contain highly-efficient switched mode power supplies that broadcast loudly in and around the AM radio band, and the SQUID amplifiers used to read out the TES are so sensitive to current that rolling a large ungrounded helium dewar across the floor can induce a measurable current spike. Interference can be dealt with in one of four ways: Remove the source; filter out the source; fix the ground-loop that picks up the source; or ignore the source. The following short sections discuss how these methods were applied to the majority of interference sources encountered in this work. An excellent reference for mitigating noise and interference issues is Ott (2009), which was consulted heavily throughout the operation of this work.

E.1 Computers (and other electronics)

By far the noisiest piece of equipment in the lab is the common switch-mode computer power supply. This supply switches on and off at hundreds of kHz and is a modern marvel of efficiency. It is also very loud! The ~ 100 kHz signal it creates is broadcast out into the room by anything resembling an antenna, most often by the power cord that plugs into the wall and by any USB cables. The best way to deal with this solution is to buy an old linear power supply or make a battery supply and use that for the computer. These can be hard to find however, and annoying to mate to modern motherboard connectors. A good alternative is to get a large ferrite toroid and wrap the power supply cord around it as many times as possible. The toroid should be as close to the end of the cord that plugs into the computer as possible. Smaller toroids may be used for USB cables in the same manner. This effectively puts a large inductor in series with the antenna/power cord and attenuates the noisy signal. If possible, the computer should also be plugged into a completely separate electrical panel than the one used for the oscilloscope or other readout instruments. Otherwise, the circuit ground in the wall can inject the noisy power-supply signal right back into the readout. Figure E.1 shows an example of how to set this up. Another good option is to use a battery-powered laptop computer as the measurement computer. Laptops are, from an unwanted noise perspective, very quiet!

Switch-mode power supplies are found in nearly every piece of modern electronics, so it's possible that more than just the computer may interfere with an experiment. In addition to the computer, the network switches and routers in the lab were also found to emit a fair bit of unwanted signal. Happily, Ethernet cables can be quite long and still function well, so the solution here is to just move the offending piece of electronics far away.

The static DC power supplies that were integrated into the high-voltage setup were also



Figure E.1: Computer power cord wrapped around ferrite donut core for noise mitigation.

switched mode DC-DC power supplies. They take a supply of 18 V and output between 0 V and 1000 V based on some control voltage. These small low-power supplies injected a large amount of 100 kHz signal into the ground lines, which translated into a small oscillating current through the SQUID. To combat this, a number of different filters were added to the outputs and inputs of these supplies. Those filters are fully described in Crane Aerospace (2006). The final filtered supply worked very well, but unfortunately did not output a high enough voltage.

E.2 Overhead lights

Modern, efficient LED lighting can also be a source of unwanted interference, as most LED lamps have a switched-mode power supply. Either buy low-noise LED lighting (specifically designed for quiet EM environments), use less noisy fluorescents, or stick with incandescent bulbs, which are the quietest of all!

E.3 Vibrations

The mechanical resonant frequency of the dilution refrigerator is between 9-10 Hz. Any vibration source (from the pulse-tube cryocooler to the building's HVAC system) is enough to excite this resonance. In practice, this interference source manifested as a small square-wave type signal every 100 ms or so that contains frequency components as high as 300 Hz. A 1 kHz high-pass filter takes care of this problem from an electrical standpoint, but to really solve the problem (and keep the cryostat temperature from responding to vibrations) vibrational isolators should be installed on the cryostat.

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