Measurement Of Quasiparticle Transport In Aluminum Films Using Tungsten Transition-Edge Sensors

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Quasiparticle (qp) transport dynamics have been studied experimentally by many groups\textsuperscript{1–3} using different materials, fabrication processes, and readout schemes. Quasiparticle transport in Al films plays an important role in the design specifications of Cryogenic Dark Matter Search (CDMS) detectors.\textsuperscript{4} These detectors utilize photolithographically patterned films of sputtered Al and W on both sides of high-purity, kg-scale, Ge and Si crystals. The superconducting Al and W films perform two roles simultaneously: some absorb phonon energy and others serve as ionization collection electrodes.

When a particle interacts with a CDMS detector, electron-hole pairs and phonons are created. Under typical operating conditions, a $\sim 1\, \text{V/cm}$ bias is used to drift the $e^-/h^+$ pairs through the bulk of the crystal so charge can be collected at the detector surfaces. At the same time, the thermal phonons produced by the event make their way to the detector surfaces where they can be absorbed in the Al film by breaking Cooper pairs, which create quasiparticles. Ideally, the quasiparticles diffuse randomly in the Al until they get trapped in the overlap region between the Al and W films, where the superconducting energy gap is smaller than in the Al film alone.\textsuperscript{5} This trapped energy gets absorbed by an attached W-transition-edge-sensors (TES), adding heat and providing the detector’s phonon signal for that event. We call these phonon sensors Quasiparticle-trap-assisted-Electrothermal-feedback Transition-edge-sensors (QETs).\textsuperscript{6}

The qp trapping length in CDMS Al films impacts overall detector energy performance. Here, we present results from a detailed study of energy collection and qp propagation in Al films coupled to W-TESs and describe an innovative model that explains QET pulse shapes and overall performance, and provides a way to measure qp trapping lengths in thin films and the energy transport efficiency from the qp energy to the TES electron system. Our measurements have benefited from a signal analysis approach based on template matching rather than pulse integration, which improves our energy resolution by a factor of two and yields better event reconstruction overall.\textsuperscript{7}

Test samples consisted of photolithographically patterned, 300 nm-thick Al and 40 nm-thick W films. Three Al film lengths were studied: 250 µm, 350 µm, and 500 µm. The metallization and process steps were identical to those used for CDMS detectors, including a 40 nm layer of amorphous Si (aSi) sputtered on each cleaned Si substrate just prior to metallization. Fig. 1(a) shows an image of one test device with a central 250 µm-wide × 350 µm-long Al phonon absorption film coupled to 250 µm × 250 µm W TESs (W-TES1 and W-TES2) at either end. A distributed

![FIG. 1. (a) SEM image of Al/W test device. The W–TESs at the ends of the Al film are 250 µm × 250 µm. The racetrack-shaped outer channel acts as a veto for substrate events. (b) Schematic side view (not to scale) where each W-TES overlaps the Al film. (c) Sample mount with $^{56}$Fe/NaCl x-ray fluorescence source. The test device is hidden behind a collimator plate.](http://dx.doi.org/10.1063/1.4899130)
a conventional voltage-biased TES circuitry setup, with the other. However, when the energy flux into a TES is sufficient to dominate the physics, and essentially cancel each other. In the low energy regime, the first two terms in the energy balance will increase sensor resistance and thus decrease the instantaneously.

\[ \Delta U = \Delta U_{\text{ext}} + \Delta U_{\text{joule}} + \Delta U_{e-ph} = 0, \]

where \( \Delta U_{\text{ext}} \) represents the deposited x-ray energy, \( \Delta U_{\text{joule}} \) corresponds to the Joule heating \( \sim V^2/R \) of the biased TES, and \( \Delta U_{e-ph} \) is an energy loss term arising from electron-phonon coupling within the TES. This latter term accounts for the thermal relaxation of the TES. It is relatively small when the TES is operated in the linear, non-saturated region of its \( R(T, I) \) curve and small energy inputs are considered. In general, event energy absorbed by a voltage-biased TES will increase sensor resistance and thus decrease the instantaneous energy loss from Joule heating. When in the linear, low energy regime, the first two terms in the energy balance equation dominate the physics, and essentially cancel each other. However, when the energy flux into a TES is sufficient to drive the TES fully normal, \( \Delta U_{e-ph} \) can be significant. Below, we show that by consistently including the \( \Delta U_{e-ph} \) term in our model we can more accurately reproduce the observed pulse shapes and energy distributions of W-TES events in both the non-saturated and saturated regimes.

Fig. 2 shows the energy detected by each of the three W-TESs on a single test device exposed for ~48 h to our NaCl fluorescence source using the set-up shown in Fig. 1(c). The data were obtained with a 250 \( \mu \)m-long Al film device similar to that shown in Fig. 1(a). Event energies were determined using a non-linear optimal filter template fitting approach. As shown in Fig. 2, we observed four basic classes of events: (1) x-rays absorbed directly in W-TES1 or W-TES2, (2) x-rays absorbed in the central Al film, (3) x-rays absorbed in one of the four main W/Al overlap regions of the device (one at each end of both W-TES1 and W-TES2), and most commonly (4) x-rays absorbed in the Si substrate (large W-TES3 signal). The relative count rates observed for the various event types were consistent with the source-collimator geometry and the known penetration depths for 2.62 keV x-rays in Al (3.3 \( \mu \)m) and W (0.2 \( \mu \)m).

We scaled event energy measurements to the initial energy stored in qps after their number became constant, i.e., after the initial fast phonon decay modes were complete but before qps shed sub-gap phonons. In our experiments, a maximum of only 1.42 keV of the incident 2.62 keV Cl K\( \alpha \) x-ray energy was collected in W-TES1, even for a direct-hit x-ray in that sensor (see Fig. 2). This large energy deficit can be explained using an energy down-conversion model recently published by Kozorezov et al. Their model defines three stages of the energy down-conversion process following the absorption of an x-ray in a thin metal film. The most relevant to our experiments with W-TESs is stage II, where athermal phonon leakage into the substrate dominates the film’s energy loss to the substrate. Stage II can be subdivided into two main parts. In the first part, the mean energy of electronic excitations, \( \epsilon \), is below some threshold, \( E_1^\ast \), but much higher than the Debye energy: \( \Omega_D < \epsilon < E_1^\ast \). In this regime, energy loss to the substrate can be strongly dependent on event location in the film (i.e., proximity to the film-substrate boundary) and spectral peaks get broadened, but not typically shifted appreciably in energy.

The second part of stage II is characterized by \( \Omega_D > \epsilon > \Omega_1 \), where \( \Omega_1 \) is a low-energy threshold above which electron and hole relaxation by phonon emission is still important, but below which the dynamics is again dominated by electronic interactions. This portion of the energy cascade process turns out to be more important than expected for explaining the observed energy loss in TESs and other film-based devices. Applying Eqs. (7), (9), and (10) of Ref. 10 to our experimental conditions yields a predicted fractional energy loss in our W films of 49% for direct-hit x-ray events. In our experiments, we observe an actual energy loss of ~43% for these direct-hit events. One effect that can reduce this small discrepancy is the reabsorption of some high-energy escape phonons back into the W-TES from the substrate. In addition, using this energy down-conversion theory applied to our specific device geometry, x-ray events occurring in the W directly undergo more energy loss to the substrate than those occurring in the Al films (see below) resulting in a higher TES 3 signal for W.

We have developed a simple physical model that accurately describes the pulse shapes observed with our Al/W devices. We show in Fig. 3(a) one simulated pulse from this model superimposed on a raw pulse from a well-behaved device like the one shown in Fig. 1(a). We have also used this model to reproduce previously unexplained pulse shapes.
obtained with a device of similar design that was studied first in 1997 and then again in 2014. The same, unusual pulse shapes were observed in both data sets. The remarkable double-peak structure for that device is shown in Fig. 3(b). The pulses shown come from x-ray events occurring in the central Al film.

The key elements of our physical model are shown in Fig. 4. In the model, physical weak links (i.e., multiple filamentary attachments) between the W and Al films are used to mimic the step-coverage impedance where the 40 nm-thick W film overlaps the 300 nm-thick Al film below it, as the W transitions down to the substrate where it operates as a TES (see Fig. 1(b)). We refer to these film transition regions as “waterfall” regions based on their appearance in SEM images. In our test devices, the W/Al overlap region (Fig. 1(b)) is excellent along the top surface of the Al but is filamentary along the steep Al sidewalls. Our model treats the added impedance of the waterfall region as a necked-down weak W link that acts effectively as a small Joule heater providing constant power even when the W-TES itself is in its superconducting transition. This impedance alters the superconducting temperature and critical current of the TES in predictable ways. Additionally, instead of treating the W-TES as a lumped element, in our model, each TES square is divided into ten equal-width strips parallel to the W/Al overlap region. The heat capacity of each strip is assumed to be the same as all others. The Wiedemann-Franz Law is then used to provide constant power even when the W-TES itself is in its superconducting mode.

Our waterfall model works well. For example, it yields the first decay-time in the raw data pulse shown in Fig. 3(a). It also correctly predicts the second distinct decay-time that corresponds to the time ($\tau_{cd}$) needed for the TES to cool back to its equilibrium state. Lastly, the model explains the double-peaked pulses observed with our older devices from 1997—the odd pulse shapes we now know resulted from poor film connectivity between each W-TES and its corresponding Al bias line at the end away from the main Al absorber (see Fig. 4). We have shown that the poor connectivity between the TES and the Al x-ray absorber film is due to sputtering geometry. The subset of devices that exhibited the odd pulse shape shown in Fig. 3(b) were found to have poor connectivity at the wiring side of the TES, caused by mask misalignment and etch problems during fabrication. A detailed description of this model and its use in pulse shape simulations is discussed in Ref. 7.

After selecting Al direct-hit events (dark blue in Fig. 2) using the method described in Ref. 12, we modeled qp transport in the Al film using a 1D diffusion equation with a linear loss term

$$\frac{\partial n}{\partial t} = D_{Al} \frac{\partial^2 n}{\partial x^2} - \frac{n}{\tau_{AI}} + s,$$

where $n = n(x, t)$ is the linear number density of qps, $D_{Al}$ is the diffusivity of qps, and $\tau_{AI}$ is the qp trapping time. The source term $s = q \delta(x - x_0) \delta(t - t_0)$ represents the rate of qp density creation. The rates for qp absorption into W-TES1 and W-TES2, symbolized by $I_1$ and $I_2$, respectively, were modeled by the linear relations

$$I_1 = n_1 v_1, \quad I_2 = n_2 v_2,$$

where the coefficient $v_1(v_2)$ has units of length/time, and $n_1$ ($n_2$) is the qp number density at the W/Al boundary closest to W-TES1 (W-TES2). This 1D approach is sufficient because the qps are reflected at the edges of the Al, and the mean free path is smaller than the width of the film, making diffusion along the two axes independent.

Equation (2) can be solved analytically to find the fraction $F_1(F_2)$ of qp generated by an event that is absorbed in W-TES1(W-TES2)

$$F_1 = \frac{\Lambda_d \left( \frac{1 + 2x_2}{\Lambda_d} \right)}{\Lambda_d (\lambda_1 + \lambda_2) \cos \left( \frac{1}{\Lambda_d} \right) + \left( \Lambda_d^2 + \lambda_1 \lambda_2 \right) \sinh \left( \frac{1}{\Lambda_d} \right)},$$

$$F_2 = \frac{\Lambda_d \left( \frac{1 - 2x_2}{\Lambda_d} \right)}{\Lambda_d (\lambda_1 + \lambda_2) \cos \left( \frac{1}{\Lambda_d} \right) + \left( \Lambda_d^2 + \lambda_1 \lambda_2 \right) \sinh \left( \frac{1}{\Lambda_d} \right)}.$$
The dimensionless variable $\Lambda_d \equiv L_d/L$ depends on the characteristic diffusion length $L_d = \sqrt{D_{Al} \tau_{Al}}$ of the Al film, and the term $\zeta \equiv x_0/L$ depends on the qP source location, $x_0$, measured from the center of the Al film. $L$ is the length of the Al film. The dimensionless parameters $\lambda_1$ and $\lambda_2$ are defined by the relation, $\lambda_i \equiv L_i/L$, where $L_i = D_{Al} \tau_i$ ($i = 1, 2$) is a characteristic qP absorption parameter with units of length that varies inversely with the efficiency for coupling qP into each W-TES. In general the W-TESs would have slightly different qP absorption capabilities, hence $\lambda_1 \neq \lambda_2$. However, if one assumes the same absorption capability for the two TESs, Eqs. (4) and (5) can be further simplified to

$$L_{d,1} = \frac{1}{C_{15}} \left( 1 + \frac{1}{C_{16}} \right) \frac{1}{C_{24}} L_{d,2}$$

Fig. 5 shows a maximum likelihood fit of this diffusion model to x-ray data for a 350 $\mu$m-long Al film. The fit yields estimates for three important parameters: the characteristic qP diffusion length, $L_{d,1}$, the qP absorption into W-TESs, $L_{d,1}(L_{d,2})$, and an energy scaling factor, $\xi_{d,1}$. The scaling factor corresponds to the deposited energy before position dependent qP trapping and sub-gap phonon losses have occurred as energy is absorbed into the two W-TESs. Applying Eq. (2) to our data yields $L_{d,1} \sim 130$ $\mu$m for three Al film lengths studied: 250 $\mu$m, 350 $\mu$m, and 500 $\mu$m. For small values of $L_{d,1}$, the band of Al direct-hit events shown in Fig. 5 would extend towards the energy axes. In our data, $L_{d,1} \approx L_{d,2} \approx 100$ $\mu$m, and we observe gaps between the end points of the Al direct-hit band and the energy axes. Summing the two W-TES energies and reconstructing position yields the inset of Fig. 5. Note that individual values of $D_{Al}$ and $\tau_{Al}$ cannot be determined using Eq. (2) alone. In the next paper, we will determine $D_{Al}$ and $\tau_{Al}$ separately using TES time-delay data and different thickness Al films.

Fig. 6 shows the reconstructed energy vs. position data of Fig. 5 using the parameters from our diffusion model fit. The scaling factor obtained from the model yields a total event energy of 2.3 keV rather than the expected 2.62 keV.

This $\sim 10\%$ discrepancy is consistent with known energy down-conversion mechanisms. The $5\%$ variation in reconstructed energies shown in Fig. 6 can be understood using a model that includes the latter stages ($\epsilon < 3 \Delta$) of the energy down-conversion cascade and simulates qP trapping in terms of a percolation threshold (below which qps are trapped by local variations in the gap). Electronic and environmental noise sources in lab currently limit our energy resolution for $\sim 6$ keV x-rays to $\sim 100$ eV FWHM for events in the Al film and 50 eV for W-TES “direct-hit” events.

The results presented here for x-rays interacting with Al films coupled to W-TESs are useful for optimizing CDMS detector performance, which improves for large Al film qP diffusion lengths and well-coupled Al and W films at all W-TES interfaces. The response function of a TES relates closely to its critical current. For the CDMS array of $\sim 2.5$ $\mu$m wide TESs in parallel, connections to the ends of the TESs are typically $\sim 33$ $\mu$m wide. For our test devices, the Al and W films have equal width. Thus, our test devices are $\sim 13$ times more sensitive to critical current issues due to filamentary “waterfalls” than comparably fabricated CDMS QETs. These studies also allow us to monitor the fabrication integrity and catch defect levels that do impact CDMS detector performance.

A simple model fit to our data matches the observed pulse shapes well, and correctly determines the energy of direct-hit events in W-TESs. Our results are consistent with phonon and qP energy down-conversion physics. In the simple diffusion model used here, losses to sub-gap phonons and qP trapping were combined into a single, generic term. A more detailed study that includes percolation threshold effects from spatial variations in the superconducting gap of our Al films will be reported soon. We are also using SEM and FIB imaging to modify fabrication recipes and improve connectivity at the Al/W interfaces.

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1M. Loidl, S. Cooper, O. Meier, F. Pröbst, G. Sáfrán, W. Seidel, M. Sisti, L. Stodolsky, and S. Uchaikin, *Nucl. Instrum. Methods Phys. Res., Sect. A* 465, 440–446 (2001).

2J. Martin, S. Lemke, R. Gross, R. P. Huebener, P. Videler, N. Rando, T. Peacock, P. Verhoeve, and F. A. Jansen, *Nucl. Instrum. Methods Phys. Res., Sect. A* 370, 88–90 (1996).

3C. Bailey, J. Adams, S. Bandler, J. Chervenak, M. Eckart, A. Ewin, F. Finkbeiner, R. Kelley, C. Kilbourne, F. Porter, J. Sadleir, S. Smith, and M. Sultana, *J. Low Temp. Phys.* 167(3–4), 236 (2012).

4Z. Ahmed, D. S. Akerib, S. Arrenberg, C. N. Bailey, D. Balakishiyeva, L. Baudis, D. A. Bauer, P. L. Brink, T. Bruch, R. Bunker et al., *Phys. Rev. Lett.* 106, 131302 (2011).

5N. E. Booth, *Appl. Phys. Lett.* 50, 293 (1987).

6K. D. Irwin, S. W. Nam, B. Cabrera, B. Chugg, and B. A. Young, *Rev. Sci. Instrum.* 66, 5322 (1995).

7B. Shank, J. J. Yen, B. Cabrera, J. M. Kreikebaum, R. Moffatt, P. Redl, B. A. Young, P. L. Brink, M. Cherry, and A. Tomada, “Nonlinear Optimal Filter Technique For Analyzing Energy Depositions In TES Sensors Driven Into Saturation,” AIP Adv. (submitted).

8S. M. Seltzer, *Radiat. Res.* 136, 147 (1993).

9T. Guruswamy, D. J. Goldie, and S. Withington, *Supercond. Sci. Technol.* 27, 055012 (2014).

10A. G. Kozorezov, C. J. Lambert, S. R. Bandler, M. A. Balvin, S. E. Busch, P. N. Nagler, J. P. Porst, S. J. Smith, T. R. Stevenson, and J. E. Sadleir, *Phys. Rev. B* 87, 104504 (2013).

11M. Pyle, P. L. Brink, B. Cabrera, J. P. Castle, P. Colling, C. L. Chang, J. Cooley, T. Lipus, R. W. Ogburn, and B. A. Young, *Nucl. Instrum. Methods Phys. Res., Sect. A* 559, 405 (2006).

12J. J. Yen, B. A. Young, B. Cabrera, P. L. Brink, M. Cherry, R. Moffatt, M. Pyle, P. Redl, A. Tomada, and E. C. Tortorici, *J. Low Temp. Phys.* 176, 168–175, (2014).

13J. M. Kreikebaum, B. A. Young, B. Cabrera, P. L. Brink, M. Cherry, A. Tomada, and J. J. Yen, “Growth Of a-b Phase W Thin Films Over Steep Al Topography In A Confocal Sputtering Machine,” J. Vac. Sci. Technol. B (submitted).

14B. Cabrera, J. J. Yen, B. Shank, B. A. Young, P. L. Brink, M. Cherry, J. M. Kreikebaum, R. Moffatt, P. Redl, R. Mahapatra, R. Harris, and A. Tomada, “Quasiparticle transport in superconducting aluminum thin films – comparing experiment to theory” (unpublished).