Design of QET Phonon Sensors for the CDMS ZIP Detectors

T. Saab[a]*, R. M. Clarke[a], B. Cabrera[a], R. A. Abusaidi[a], R. Gaitskell[b]

[a] *Department of Physics, Stanford University, Stanford, Ca 94305, USA*
[b] *Center for Particle Astrophysics, University of California, Berkeley, CA 94720, USA*

ABSTRACT

The Cryogenic Dark Matter Search (CDMS) ZIP detectors utilize quasiparticle trapping as the mechanism for coupling the energy of a particle interaction in the Ge (or Si) absorber into a tungsten (W) transition edge sensor (TES). Consequently, the dynamics of quasiparticle propagation and loss significantly impact the energy collection and resolution of the detector. This paper describes the considerations necessary in optimizing the detector surface geometry in order to have maximal quasiparticle collection.

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1. INTRODUCTION

An interaction in the Ge (or Si) substrate of a CDMS ZIP (Z-dependent Ionization and Phonon) detector [1] deposits energy in the form of lattice phonons and ionized electron-hole pairs. The high energy, athermal phonons propagate to the crystal's surface whereupon they are absorbed by Quasiparticle-trap-assisted Electrothermal-feedback Transition edge sensors (QET). The QET consists of overlapping Al and W films. Since the detectors are operated in a dilution refrigerator at a temperature of $\sim 40\,\mathrm{mK}$ the Al film (fins) are superconducting, and phonons hitting the fins will break cooper pairs, creating quasiparticles which then diffuse and eventually reach the W/Al overlap region. Since the superconducting gap in the overlap region is smaller than in the Al film any quasiparticles entering that area become trapped and thus deposit their energy in the W transition edge sensor (TES). Consequently, the efficiency of each step in the process determines the final energy collection efficiency of the detector.

Previous designs of our detectors have $\geq$ 90% of the crystal surface covered with Al fins [2] (figure 1). However, due to the finite diffusion length of quasiparticles in the Al film ($\sim 180\,\mu$m) only a small fraction reaches and deposits their energy in the W TES. The solution we have proposed for coupling more of the phonon energy to the TES is to limit the dimensions of the Al fins to several quasiparticle diffusion lengths. The feasibility of this solution is based on the fact that phonons undergo very little down-conversion at the bare Ge (Si) surfaces. Consequently, they will reflect off of the crystal's surfaces until they are eventually absorbed in the Al fins, close to a W TES, allowing for the trapping of a larger fraction of the quasiparticles. Similarly, increasing the number of TESs allows for smaller Al fins, however, the total amount of W that can be used is restricted by two criteria [3] : (1) a minimum TES resistance is imposed by the L/R$_0$ of the SQUID readout circuit (R$_0$ is the operating resistance of the TES and L is the SQUID circuit inductance); and (2) the length of an individual TES element is limited by the requirement for superconducting/normal phase stability [4]. Together, these criteria limit the total number of TES elements that can be placed on the ZIP detector.

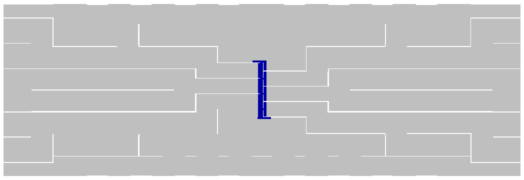

Figure 1. *Previous design of the CDMS ZIP QET.* $2352\times 770\,\mu\mathrm{m}^2$ *of Al collector fins funnel quasiparticles towards the* $250\times 2\,\mu\mathrm{m}^2$ *W TES at the center.*

2. LIMITS ON THE W TES

A lower bound on R$_0$ is set by the current readout circuit (shown in figure 2). The L/R$_0$ time constant is on the order of μs for $\mathrm{R}_0 \approx 0.1\Omega$, while the TES electrothermal feedback time constant is tens of μs. As R$_0$ decreases the two time constants become comparable, and when τ_{ETF} becomes less than $5.83\,\tau_{\mathrm{L/R}}$ the system can oscillate. The length of a TES element is limited by the phase stability criterion. If the TES exceeds a critical length $l^2 \propto T_c^{-3}$, where T$_c$ is the W superconducting transition temperature, regions of the element become fully superconducting thus reducing the resistance of the TES. Device fabrication constraints place a lower bound on both the width

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* contact person : tsaab@stanford.edu

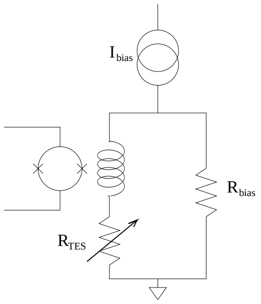

Figure 2. *TES current readout sensor. Any current variation in the TES will induce a change in magnetic flux through L, the input coil of a 100 squid array.*

of the TES elements and the W film thickness. The exposure and alignment resolution of the photolithography process limits the W element width to $\geq 1\mu$m while the ability to produce W film within an acceptable T_c range ($60 - 120\,$mK) limits the W film to a minimum thickness of ~ 350Å. Together, these constraints on the TES resistance and geometry dictate the maximum number of TES elements per detector channel.

3. OPTIMIZING THE AL FILMS

The phonons due to a particle interaction in the detector are created close to the Debye frequency. They subsequently undergo down conversion and isotope scattering at rates proportional to ν^5 and ν^4 respectively. The combination of down conversion and isotope scattering result in an overall quasidiffuse propagation of the phonons in which the phonons have a constant average speed around half the ballistic speed. Once the phonon frequencies drop below ~ 0.5THz (~ 0.7THz) for Ge (Si) the phonons are ballistic and isotopic scattering length becomes larger than the dimension of the crystal ($\sim$ 10 cm). A ballistic phonon incident upon the crystal surface undergoes reflection (specular or diffuse with similar probabilities). The probability for down converting during reflection is very small. Phonons incident on an Al film have a $\sim$ 30% chance of being absorbed. Consequently, the main factor determining the phonon lifetime in the substrate is the amount of Al on the detector surfaces.

The quasiparticle diffusion length in the 150 nm thick Al films has been measured to be $180\,\mu$m, and is limited by the film thickness. Consequently, we turned to using 300 nm thick Al for the new devices where we expect the diffusion length to be a factor of $\sqrt{2}$ as large. ZIP detectors of the previous design had $\geq 90\%$ Al surface coverage on the QET side. The charge collection electrode on the side opposite the QET is also made from Al in the form of a grid pattern with $20\,\mu$m pitch and a 20% filling fraction as a compromise between the desire for a uniform electrical field at the surface and a minimal amount of uninstrumented phonon absorber (dead area). Simulations of quasiparticle diffusion for that geometry indicate that only 6.4% of quasiparticles are collected. This is in close agreement with the results obtained in [1]. For the new design, the QET side has a 5.6% dead area due to features such as alignment marks and voltage rails. However, with the ability to photolithographically define features as small as $1\,\mu$m (compared to $2\,\mu$m in the previous design) we have the freedom to double the number of TES elements without changing the sensor's R_0.

By limiting the width of the Al fins to $50\,\mu$m the trapping of magnetic field, which can limit the quasiparticle diffusion length, is minimized. In addition, the diffusion takes on a more one dimensional nature. For the sensor geometry shown in figure 3, calculations of quasiparticle collection efficiency as a function of Al fin length and number of TES elements have been performed. These result in figure 4.

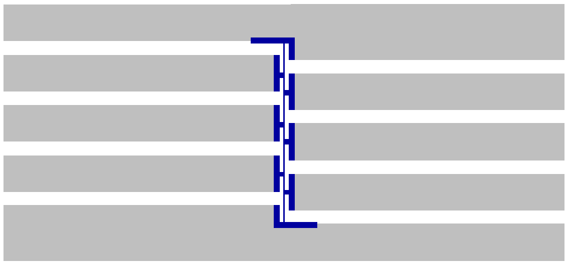

Figure 3. *Geometry of a single TES element with Al quasiparticle collection fins. The Al fins are $380\,\mu$m long and $50\,\mu$m wide.*

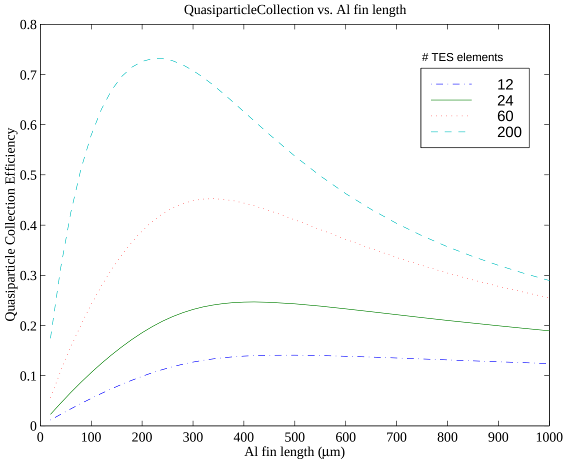

Figure 4. *One dimensional diffusion calculation of quasiparticle collection efficiency as a function of Al fin length and number of W elements per 5 mm^2 area.*

The maximum efficiency of the 24 element curve is slightly less than 25% for an Al fin length of $420\,\mu$m. For this configuration, the fraction of area covered with active quasiparticle collection fins is 22.6%. The efficiency near the peak is slowly varying and for an Al fin length of 380 μm, the length chosen for the current ZIP detector, it is reduced only by a tenth of a percent. From figure 4 it can also be seen that quasiparticle collection efficiency is a strong function of the number of TES elements per unit area. The sharp decline in efficiency for Al fin lengths less than $\sim 200\,\mu$m is due to phonon loss in the dead areas on the detector surface. If the limits on the TES R_0 are relaxed, by using a two stage SQUID read out scheme with low input inductance L and a fully superconducting front end circuit [5], then it can be seen (as in the 60 and 200 TES curves in figure 4) that there is still some efficiency to be gained, however, at about 200 TES elements the area of the Al becomes 100% before the curve peaks. In other words the efficiency becomes a monotonically increasing function of fin length and the gains in collection efficiency become very minimal.

For the 24 TES geometry the phonons will, on average, visit the surface of the ZIP detector over 7.4 times before they are attenuated by a factor of $1/e$. Given the speed of ballistic phonons in Ge is 1cm/μs that means that phonons created at a given time will be absorbed on a time scale of is 15μs. However, as seen in [1] the quasidiffuse process of phonon propagation leads to phonon lifetimes (before they thermalize below the 2Δ of Al) of hundreds of μs. Therefore the pulse shape will be determined by phonon dynamics in the absorber as well as the phonon interactions with the surfaces.

4. CONCLUSION

Optimizing the area of the quasiparticle collection fins can lead to a factor four increased signal, thus reducing the energy threshold of the ZIP. The optimized design of the ZIP TES and collection fin geometry, shown in figure 3), was recently used to fabricate new ZIP detectors. We will run those devices soon to determine the effectiveness of the newly designed QETs.

5. ACKNOWLEDGMENTS

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REFERENCES

[1] J. Hellmig *et al.* these proceedings.
[2] R. M. Clarke *et al.* these proceedings.
[3] S. Nam. PhD thesis, Stanford University, 1998.
[4] B. Cabrera. these proceedings.
[5] S. Nam *et al.* these proceedings.