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Large-Area TKIDs for Charged Particle Detection

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Abstract Nuclear physics has long played a central role in our efforts to better understand the natural world. Several experiments are currently well positioned to improve limits in searches for physics Beyond the Standard Model (BSM). Many experiments in nuclear physics have traditionally used semiconductor or scintillation detectors for particle detection, yet these face fundamental performance limitations that greatly restrict the sensitivity achievable. A new detector paradigm for charged particle detection could potentially open up orders of magnitude improvement in sensitivity in searches for BSM physics. We are working to achieve this by adapting Thermal Kinetic Inductance Detectors (TKIDs) for external charged particle detection. These cryogenic detectors are used in X-ray and gamma spectroscopy as well as dark matter searches and have been shown to have photon energy resolutions on the order of tens of eV. They can be multiplexed to create large area detectors. Thus far, however, TKIDs have not yet been developed for external (non-embedded) charged particle detection. Creating a TKID with a sensitivity of 100s of eV or better suitable for external charged particle detection would significantly impact the next generation of nuclear experiments, allowing orders of magnitude improvements in sensitivity.

Keywords charged particle detection, microwave kinetic inductance detectors, neutron decay, quantum sensors

1 Introduction

Precision low energy nuclear physics experiments are increasingly critical to understanding fundamental symmetries and searches for physics Beyond the Standard Model (BSM). The lack of observation of new physics at the TeV mass scale at the Large Hadron Collider (LHC) suggests that further constraints on BSM physics may require a different approach such as precision measurements of fundamental symmetries [1, 2, 3]. These experiments are advantageous because, in many cases, they can access physics at the same or higher energy scale as those at the LHC. One such example, and a central motivation for the current work, is neutron beta decay. This decay is an ideal laboratory for precision BSM

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searches as it is the simplest example of the hadronic weak interaction and can be parameterized in terms of the electron and antineutrino energies and momenta [4]. By precisely measuring these correlation parameters, one can place competitive constraints on a wide range of BSM models[5, 6, 7].

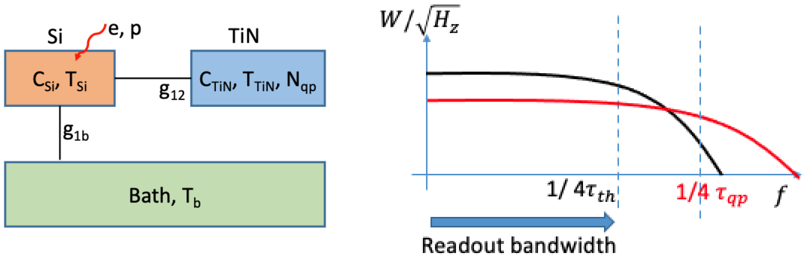
For many of these experiments, order of magnitude sensitivity gains occur only on the timescale of decades. This is, in part, due to the limitations of charged particle detection technology where the performance demands can be high. Take, for example, the case of neutron beta decay. The endpoint energy of the decay recoil proton is 751 eV — an energy range that is not easily resolved using current detector technologies. The state of the art in large-area pixelated semiconductor based detectors is the development of $\sim 100\ \mathrm{cm}^2$ active area pixelated silicon detectors for the UCNB and Nab experiments. These are a great stride in energy resolution (3 keV FWHM) and large area detection, but decay protons must still be accelerated by at least 15 kV to be distinguished from noise [8]. This creates several challenges - the acceleration requires potentially unstable high voltage systems, constrains experimental geometries and complicates time of flight measurements. Furthermore, the long lifetime of the neutron means that these experiments are often statistics limited and require guiding fields and detectors with large collection areas. The collection area of these detectors is about the limit of what can be achieved with a pixelated silicon detector scheme.

Further progress appears possible with quantum cryogenic sensors, as thermal noise is highly suppressed at sub-1 K temperatures. In particular, two types of cryogenic sensors promise improved sensitivity and array scalability: the superconducting transition-edge sensor (TES) and the microwave kinetic inductance detector (MKID). A TES, the more mature detector, measures the energy deposited by incident radiation on a small thermally isolated island. The island carries a thin metal film that is biased to the transition between the superconducting and normal-metal states, and acts as a thermometer by converting the heat into a change of resistance of the material. The resulting change of current is measured by a SQUID magnetometer [9]. In contrast, MKIDs use the nonzero kinetic inductance of a superconductor when an AC current is applied. A deposition of energy from particle impact on the superconductor with enough energy to break a Cooper pair creates an excess of quasiparticles, which changes the impedance of the material. By creating a resonant circuit with this impedance, the energy absorption becomes a frequency measurement. Individual detector channels can be tuned to different resonance frequencies and can be multiplexed on the order of kilo-pixels[10]. MKIDs have not yet been explored for external charged particle detection, as most applications have focused on photon detection with energies from the far-infrared to gamma[11, 12, 13].

Current TES and MKID designs are not ideal for neutron beta decay applications as the films are too thin to fully stop $\sim 1\,\mathrm{MeV}$ electrons and have nonuniform position response. Instead, we are exploring a subset of MKIDs — thermal kinetic inductance detectors (TKIDs). TKIDs differ from MKIDs in that the kinetic inductance change is a function of temperature, rather than a direct breaking of Cooper pairs from incident radiation[14]. To ensure that all energy is deposited thermally, a TKID detector circuit is lithographed onto a Si absorber that is thick enough to fully stop and absorb the incoming radiation and create a distributed thermal change across the superconducting film. This absorber thickness can be tuned for different particle types and dynamic ranges. We will refer to a TKID optimized for this purpose as a charged particle TKID (CP-TKID).

2 Prototype Design

Beyond the expected improvements in energy resolution, there are a few important considerations for creating a CP-TKID that is appropriate for low energy charged particle de-



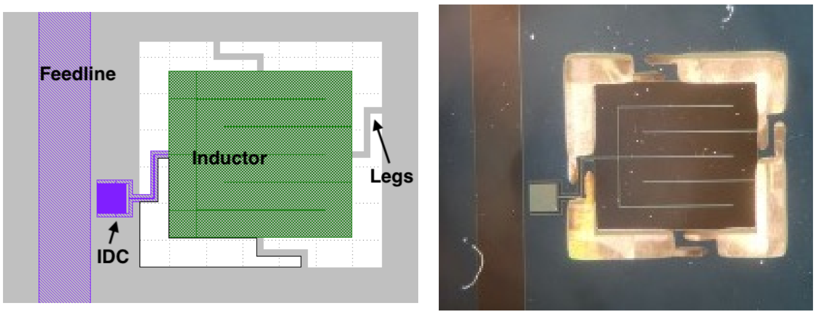
(a) (b)

Fig. 1: 1a) CP-TKID thermal model. The island consists of a phonon system in Si absorber and a quasiparticle system in TiN. We assume $\tau_{th} \gg \tau_{qp}$ ($g_{12} \gg g_{1b}$), so that the two systems are thermalized to a common island temperature $T = T_{Si} = T_{TiN}$. In addition, the Si absorber has much larger specific heat than the sensing TiN film (Si absorber is mm-thick while the TiN film is 200 nm thick), $C \approx C_{\mathrm{si}} \gg C_{TiN}$. 1b) Power spectra of the thermal and generation-recombination (GR) noise contributions. The thermal (GR) noise has a Lorentzian profile that can be simplified as a uniform distribution of total noise power in an effective noise bandwidth of $1/4\tau_{th}$.

tection. The first is that the detector must be thick enough to fully stop the incoming charged particles. The second is that our detector should be able to scale in active area to accommodate the statistics requirements of an experiment. If we use a generalized neutron beta decay experiment as an example, the silicon thickness should be on the order of millimeters to stop the decay electrons and the total active area should approach 1 m^2 to achieve reasonable coverage. This requires a pixel size of about 1 cm^2 if we assume a multiplexing factor of 10^4. These dimensional requirements dictate the development of TKIDs with a significantly larger silicon volume than the traditional TKIDs which have thicknesses on the scale of µm and surface areas on the scale of mm^2. This increase in volume has an important impact on the energy resolution of the device, since now the silicon dominates the thermal response and concerns over spatial variation become more significant. We are exploring this regime with our initial prototype designs.

2.1 Energy Resolution Calculations

To estimate the energy resolution of a CP-TKID, we first consider the effect of the silicon absorber volume on the thermodynamic behavior. Fig. 1 shows a thermal model of the CP-TKID. The thermal island consists of a phonon dominated system in a Si absorber and a quasiparticle system in TiN. Energy is initially deposited primarily in the Si absorber and the two systems quickly thermalize on a time scale of τ_{qp} by the quasiparticle generation-recombination process. The island temperature will then decay to the bath temperature with a thermal time constant of $\tau_{th} = C/G$, where C is the island specific heat and G is the thermal conductance of the legs ($G = g_{1b}$ in Figure 1). Since $C_{Si} >> C_{TiN}$, total specific heat of the system can be approximated as simply the specific heat of the silicon, $C_{tot} = C_{Si} + C_{TiN} \approx C_{Si}$. This allows us to write the thermal rms energy resolution as a function of bath temperature, T_b, giving $\sigma_E^{th} = \sqrt{k_B T_b^2 C_{Si}}$ (where the Gaussian FWHM $= 2.355\sigma_E^{th}$). As for the quasiparticle system in the superconductor, the time averaged total number of quasiparticle is $N_{qp}(T) = 2N_0 V_{TiN} \sqrt{2\pi k_B T \Delta} e^{-\frac{\Delta}{k_B T}}$ where V_{TiN} is the superconductor volume, Δ is the superconductor gap, k_B is Boltzmann's constant, N_0 is the electron



(a) CP-TKID design (b) Fabricated CP-TKID

Fig. 2: A single CP-TKID pixel prototype design with parameters as listed in Tab. 1.

density of state, and T is the thermalized island temperature [15]. The deposited energy δE will raise the temperature of the island by some $\delta T = \delta E/C_{Si}$. After the system thermalizes, the superconductor quasiparticle system will see a change in energy, $\delta E_{qp} = C_{TiN}\delta T$ where C_{TiN} is the specific heat of the superconductor. Then the change in energy can be written as the change in quasiparticle population, where $\delta E_{qp} = C_{TiN}\delta T = \Delta\delta N_{qp}$.

This allows us to derive the generation-recombination noise contribution to the rms energy resolution from $\sigma_E^{gr} = \Delta\frac{C_{Si}}{C_{TiN}}\sigma_{N_{qp}}$. The fluctuation of the quasiparticle population follows Poisson statistics as $\sigma_{N_{qp}} = \sqrt{N_{qp}}$ and the rate of quasiparticle general recombination (τ_{qp}) has a bandwidth of $1/4\tau_{qp}$ [16]. By limiting the readout bandwidth to match the thermal bandwidth $BW = 1/4\tau_{th} \ll 1/4\tau_{qp}$, we pick up an enhancement factor of $\sqrt{\tau_{qp}/\tau_{th}}$. This suggests that σ_E^{gr} can be suppressed by reducing the quasiparticle recombination time, as seen in Equation 1.

$$\sigma_E^{gr} = \Delta\frac{C_{Si}}{C_{TiN}}\sqrt{\frac{\tau_{qp}}{\tau_{th}}}\sqrt{N_{qp}} \tag{1}$$

There are a few nuances to this signal model. A key point is that we are designing a true TKID wherein our pulse signal decay primarily depends on the thermal decay of the silicon island rather than the quasiparticle lifetime as in conventional MKIDs. By purposefully designing our thermal decay such that $\tau_{th} >> \tau_{qp}$, we have our σ_E^{gr} depend only on the relationship between the quasiparticle lifetime and the thermal decay. Furthermore, since the majority of the signal information is contained within the thermal tail of the response, the effect of any athermal phonon behavior will be constrained to the initial rise of the pulse. We plan to study the effect of this initial athermal response on the energy resolution as part of our detector characterization.

2.2 Initial Design

In adapting the TKID technology to charged particle detection, we first need to validate that we can create a resonant superconducting circuit with a suitable quality factor (i.e. the ratio of stored to dissipated energy) in our desired detector geometry. We have designed the resonator quality factor and resonance frequency of our prototype such that the ring time of the detector is on the order of a microsecond ($\tau_{ring} = Q_r/\pi f_r \approx 1\,\mu s$, see Table 1), which is significantly shorter than the signal decay time expected from the island heat capacity and leg conductance, $\tau_{th} = C/G \approx 90\,\mu s$. We scaled up previous x-ray detector designs to a 5 mm x 5 mm inductor surface area for initial testing, with a goal of pushing this to a 10 mm

Table 1: Key TKID Design Parameters

Parameter	Symbol	CP-TKID Design
Si island area		5 mm $\times$ 5 mm
Si island thickness		1.5 mm
TiN layer thickness		200 nm
Bath temperature	T_b	100 mK
Silicon specific heat	C_{Si}	1.5e8 eV/K
TiN specific heat	C_{TiN}	1.8e6 eV/K
# of Si legs		4
Si legs dimension		200 μm $\times$ 2 mm
Thermal time constant	τ_{th}	90 μs
qp recombination time	τ_{qp}	50 μs
IDC area		1 mm $\times$ 1 mm
Resonance frequency	f_r	1.3 GHz
Resonator quality factor	Q_r	5000
Energy resolution-thermal	σ_E^{th}	26.6 eV
Energy resolution-gr	σ_E^{gr}	185.8 eV
Total energy resolution	σ_E	187.7 eV

Material parameters for TiN: $T_c = 700$ mK, electron density of state $N_0 = 3.9 \times 10^{10}$ eV$^{-1}\mu$m^{-3}[21].

x 10 mm active area. Similarly, we are initially using 1.5 mm thick silicon but the final goal is to use a 2 mm thick silicon wafer. Since the silicon dominates the thermal response at this scale, the island surface area and thickness are the only parameters required to estimate σ_E^{th}. The rest of our design focuses on shrinking the noise contribution from quasiparticle general recombination.

There are several ways we can attempt to reduce σ_E^{gr} in our design. First, we want to minimize the factor C_{Si}/C_{TiN} in Equation 1 by maximizing the thickness of the superconducting layer and thereby increasing the superconductor specific heat. As C_{TiN} and N_{qp} both scale linearly with V_{TiN}, we can see that an increase in superconducting volume will reduce our σ_E^{gr} by a factor of $\sqrt{V_{TiN}}$. We chose a 200 nm thick TiN for the initial prototype, as that thickness has been reliably fabricated with uniform T_C for previous TKID designs. We then need to carefully select an appropriate T_C for our superconductor. A lower T_C will lead to a smaller Δ, but it will also increase τ_{qp} and decrease the quality factor, Q. The choice of 700 mK is a optimization between gap, recombination time and the desired operation temperate of 100mK. Finally, we must reduce the ratio $\sqrt{\tau_{qp}/\tau_{th}}$. This can be done by either increasing τ_{th} by designing longer legs or by independently shortening the τ_{qp} by introducing impurities in the superconducting film by tuning the film deposition process[17] . A previous measurement of a 20 nm TiN film gave a quasiparticle recombination time of 50 µs. We assume that fabrication of our 200 nm superconductor results in a similar lifetime, as the thicker film has a similar granularity, which governs the quasiparticle lifetime. The result of these prototype design parameter calculations can be seen in Table 1.

3 Initial Fabrication and Characterization

The Si island and legs were fabricated by the Deep Reactive-Ion Etching (DRIE) process. As noted above, for this initial design we are targeting a superconductor with a T_C of approximately 700 mK and a 200 nm thickness. We use proximitized TiN/Ti/TiN multi-

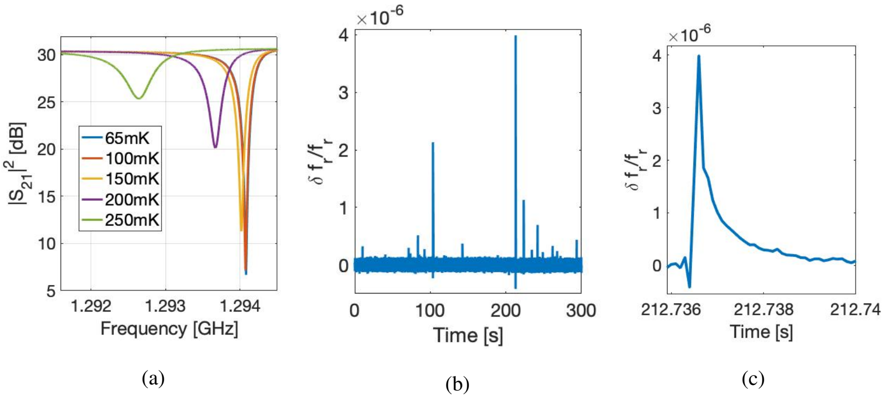


Fig. 3: Initial results from first CP-TKID prototype. 3a, the forward transmission $|S_{21}|^2$ as a function of frequency, shows resonance peaks at 5 different bath temperatures. We measured a resonator Q-factor of 5e3. 3b is the $\delta f_r/f_r$ for a set of 5 minutes run time at 65 mK. The observed peaks are from incident cosmic rays striking the detector, and 3c is an expanded view around the largest peak. A rough fit of the peak gives a decay time of $\sim 0.1\,\mathrm{ms}$.

layer films, which use the superconducting proximity effect to tune the critical temperature [18]. These superconducting films have demonstrated large kinetic inductance (and penetration depth), high-Q and tunable T_c. They have been previously used in near-infrared photon counting MKIDs (showing excellent single-photon sensitivity) and in large arrays of MKIDs for sub-millimeter astronomy [11, 18].

For our initial testing, we cooled our prototype in an adiabatic demagnetization refrigerator (ADR) to a bath temperature of 65 mK and measured the system transmission using a vector network analyzer. We measured the TKID frequency shift using the standard homedyne readout system [19] . The initial cool down focused on tracking resonance behavior of the CP-TKID circuit as a function of bath temperature, as shown in Figure 3a. We find resonance near 1.3 GHz and measure the fabricated T_C to be approximately 850 mK, both near our design goals as seen in Table 1. Figure 3b shows five minutes of continuous readout of the circuit response at a bath temperature of 65 mK, showing some clear pulse structure which is expanded in Figure 3c. As we did not use an external photon or particle source, we attribute these pulses to cosmic ray events.

The results from this initial run are preliminary but quite promising, as they demonstrate that a functional TKID is possible at this scale. We have just begun to test this prototype with a series of external sources. This will allow us to extract energy resolution and thermal decay times. With a known total effective heat capacitance of our material (C_{Si}) and a measured τ_{th}, we can extract the heat conductivity G and fully characterize the thermal response of our prototype. Initially we are utilizing a controlled X-ray source to perform this characterization as well as a series of tests exploring the linearity and position sensitivity of the detector response. We will then repeat these measurements using electrons from one or more monoenergetic electron capture sources such as ^{57}Co and ^{109}Cd to determine the response to charged particle detection.

The datasets generated during the current study are available from the corresponding author on reasonable request.

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