

Quasiparticle Trapping in Microwave Kinetic Inductance Strip Detectors

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Abstract. Microwave Kinetic Inductance Detectors (MKIDs) are thin-film, superconducting resonators, which are attractive for making large detector arrays due to their natural frequency domain multiplexing at GHz frequencies. For X-ray to IR wavelengths, MKIDs can provide high-resolution energy and timing information for each incoming photon. By fabricating strip detectors consisting of a rectangular absorber coupled to MKIDs at each end, high quantum efficiency and spatial resolution can be obtained. A similar geometry is being pursued for phonon sensing in a WIMP dark matter detector. Various materials have been tested including tantalum, tin, and aluminum for the absorbing strip, and aluminum, titanium, and aluminum manganese for the MKID. Initial Ta/Al X-ray devices have shown energy resolutions as good as 62 eV at 6 keV. A Ta/Al UV strip detector with an energy resolution of 0.8 eV at 4.9 eV has been demonstrated, but we find the coupling of the MKIDs to the absorbers is unreliable for these thinner devices. We report on progress probing the thicknesses at which the absorber/MKID coupling begins to degrade by using a resonator to inject quasiparticles directly into the absorber.

Keywords: Microwave kinetic inductance detectors, strip detectors, WIMP dark matter detectors, quasiparticle trapping

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INTRODUCTION

Microwave kinetic inductance detectors (MKIDs) are high-Q, superconducting resonators which respond to changes in the quasiparticle density in the superconductor through a change in surface impedance. We have demonstrated the detection of submillimeter, optical/UV, and X-ray photons using MKIDs [1–3]. For X-ray and optical/UV astronomy, we are pursuing spectrophotometer arrays based on a strip detector architecture [4, 5]. In a strip detector, photons are absorbed in a rectangular strip creating quasiparticles, which diffuse to either end of the strip where they are sensed by MKIDs. If the MKIDs are made of a lower gap material than the absorbing strip, the quasiparticles quickly emit a phonon and fall below the gap of the absorber, preventing diffusion out of the MKID. Since the response of the detector is proportional to the density of quasiparticles in the MKID, quasiparticle trapping allows for sensitive detectors while still maintaining large volume absorbers with high absorption efficiency.

Quasiparticle trapping is also used by the Cryogenic Dark Matter Search (CDMS) ZIP detectors for sensing athermal phonons produced by the interaction of Weakly Interacting Massive Particles (WIMPs) [6, 7]. The strip detector design described above for X-ray and

optical/UV astronomy can be adapted to a CDMS style phonon detector by running MKIDs along the edges of ~ 1 mm wide Al absorbers [8]. An MKID-based phonon detector would allow for finer pixellation of the phonon sensors as well as double-sided detector coverage due to their natural frequency domain multiplexing. Additionally, the cryogenic complexity of the readout electronics would be significantly reduced since the multiplexing would be performed by warm, largely commercial hardware [9].

STRIP DETECTORS

The geometry of the X-ray and optical/UV strip detectors is shown in Fig. 1a. The rectangular absorbing strip (typically made of Ta) is $30\text{ }\mu\text{m}$ wide and several hundred μm long. MKIDs (typically made of Al, AlMn, or Ti) are attached to both ends of the strip, with a $15\text{ }\mu\text{m}$ long triangular trapping region made of the same material as the MKID. When a photon is absorbed in the Ta strip, quasiparticles diffuse and are trapped in the MKIDs, changing the surface impedance of the resonator and causing a shift in the amplitude and phase of the microwave signal transmitted past the resonator. The sum of the response in each MKID is proportional to the total photon energy, and the ratio of the responses gives the location in the

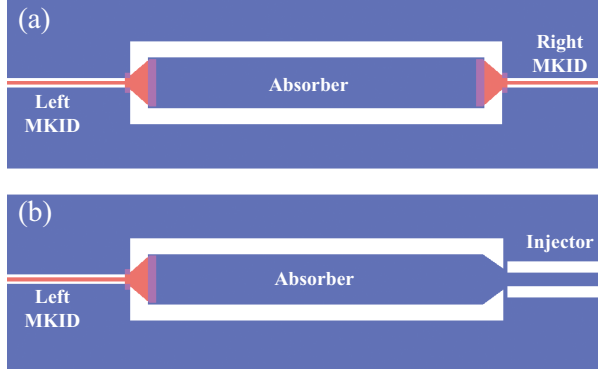


FIGURE 1. (Color online) (a) Geometry of the strip detector devices. The absorbing strip, shown in blue, is $30\ \mu\text{m}$ wide, and several hundred μm long. The MKIDs, shown in red, are attached to each end of the absorber. (b) Geometry of the quasiparticle injector. For the injector device, the right MKID in the strip detector design is replaced with a resonator made of the same material as the absorbing strip.

strip where the photon was absorbed.

We have demonstrated working strip detectors in both the X-ray and optical/UV. Fig. 2a shows the pulse heights in the left and right MKIDs for a Ta/Al strip detector illuminated by an ^{55}Fe X-ray source. The detector consisted of a $200\ \mu\text{m}$ long, $600\ \text{nm}$ thick Ta absorber coupled to $200\ \text{nm}$ thick Al MKIDs. The Mn K_α and K_β lines are both visible, with an energy resolution of $62\ \text{eV}$ at $6\ \text{keV}$, limited by noise from two-level systems (TLS) in amorphous dielectric layers on the resonator surfaces [10, 11]. We have demonstrated that this TLS noise can be reduced by scaling the capacitive section of the resonator to larger geometries [12], and are developing fabrication techniques to reduce the number of TLS present on the resonator surfaces. From an analysis of events at varying locations along the strips, we measure a Ta diffusion constant of $13.5 \pm 1.8\ \text{cm}^2/\text{s}$ and a quasiparticle lifetime in the Ta of $34.5 \pm 5.7\ \mu\text{s}$, leading to a diffusion length in the Ta of $l = \sqrt{D\tau} = 216 \pm 30\ \mu\text{m}$ [2].

Fig. 2b shows the pulse heights measured for an optical/UV strip detector with $100\ \mu\text{m}$ long, $60\ \text{nm}$ thick Ta absorbers and $20\ \text{nm}$ thick Al MKIDs, illuminated by $254\ \text{nm}$ UV photons. The responsivity for this device has been increased by a factor of ~ 1000 relative to the X-ray detector described above. By reducing the MKID thickness from $200\ \text{nm}$ to $20\ \text{nm}$, and the width from $3\ \mu\text{m}$ to $1\ \mu\text{m}$, the volume was reduced by a factor of 30 and the kinetic inductance fraction was increased from 0.03 to 0.75, giving the necessary increase in responsivity. The energy resolution for this device was $0.8\ \text{eV}$ at $4.9\ \text{eV}$. The diffusion length in the $60\ \text{nm}$ thick Ta was $\sim 60\ \mu\text{m}$, significantly shorter than for the $600\ \text{nm}$ films above.

We can reliably fabricate X-ray strip detectors (MKID thicknesses $\gtrsim 200\ \text{nm}$) which show the expected correla-

tion between pulse heights in the right and left MKIDs, indicating good transmission and trapping of quasiparticles from the absorber into the MKID. This trapping has been seen for both Ta and Sn absorbers with thicknesses between $150\ \text{nm}$ and $650\ \text{nm}$. However, when the same geometry is used for thin ($\sim 20\ \text{nm}$) MKIDs with optical/UV responsivities, each MKID shows large optical pulses, but a correlation between pulse heights in the left and right channel is rarely seen. Either the quasiparticles are not being transmitted through the Al/Ta interface in the thin devices, or they are diffusing out of the Al before they can become trapped. In the following section we present evidence that the quasiparticles are not being transmitted from the Ta absorbers into the Al MKIDs.

QUASIPARTICLE INJECTORS

Fig. 1b shows a modification to the strip detector geometry which allows the direct creation of quasiparticles by microwave power at one end of the strip. These “quasiparticle injectors” can be used to create quasiparticles which can be sensed by MKIDs at thicknesses between those needed for optical/UV and X-ray detectors, allowing us to study the thickness at which the quasiparticle transmission and trapping begins to break down. The injector consists of a resonator made from the same material as the absorber shorted to the right side of the strip. When the injector is driven at its resonant frequency (or one of its harmonics), power is dissipated in the injector, creating quasiparticles above the gap in the absorber. These quasiparticles can then diffuse across the strip and be trapped in a lower gap MKID attached to the left side of the strip.

There are two possible regimes for injecting quasiparticles into the strip. When the length of the microwave pulse is much longer than the quasiparticle lifetime and diffusion time, a steady state is reached where the quasiparticle creation rate, $\Gamma_c = \eta_{inj} P^{SS} / \Delta_{abs}$, equals the decay rate, $\Gamma_d = N_{abs} / \tau_{abs} + N_{MKID} / \tau_{MKID}$, where η_{inj} is the efficiency for the microwave power to create quasiparticles, P^{SS} is the steady state microwave power, Δ_{abs} is the energy gap in the absorber, and N_{abs}/τ_{abs} and N_{MKID}/τ_{MKID} are the steady state number of quasiparticles and lifetime in the absorber/MKID. In this regime, a response will be seen in the MKID as long as there is quasiparticle transmission from the absorber to the MKID, even if there is no trapping, since enough quasiparticles will be created to fill the strip and MKID with a uniform density.

When the length of the microwave pulse is much shorter than the diffusion time, the quasiparticle density does not reach a steady state, and the amount of signal seen in the MKID depends strongly on the trapping efficiency. For a short pulse, the number of quasiparticles

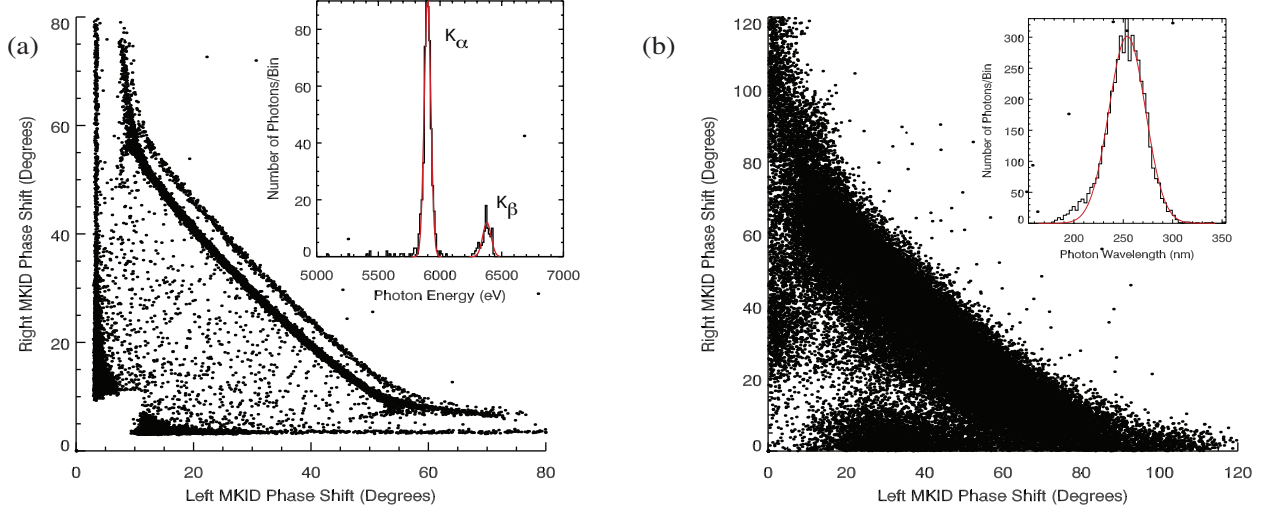


FIGURE 2. (a) Optimally filtered pulse heights for 200 nm thick Al MKIDs attached to a 200 μm long Ta strip, illuminated by an ^{55}Fe X-ray source. The inset shows the energy spectrum for events with greater than 20 degrees of phase shift in both MKIDs. (b) Optimally filtered pulse heights for 20 nm thick Al MKIDs attached to a 100 μm long Ta strip, illuminated by 254 nm UV photons. The inset shows the energy spectrum for events with greater than 20 degrees of phase shift in both MKIDs.

created is $N_{\text{pulse}} = \eta_{\text{inj}} P_{\text{pulse}} T_{\text{pulse}} / \Delta_{\text{abs}}$, where P_{pulse} and T_{pulse} are the microwave power and duration of the pulse. The number of quasiparticles in the MKID is $N_{\text{MKID}}^{\text{pulse}} = \eta_{\text{trap}} N_{\text{pulse}}$, where η_{trap} is the quasiparticle trapping efficiency.

Initial results from Al/Ta injector devices indicate that quasiparticles are not being transmitted from the Ta to the Al for the optical/UV devices. When driving the injectors in the steady state regime described above, a quasiparticle response was seen for X-ray devices with 320 nm thick Al and 160 nm thick Ta. However, for optical/UV devices with 25 nm thick Al and 70 nm thick Ta, no quasiparticle response was seen when driving the injector. Devices at intermediate thicknesses will be studied to determine the diffusion length in the Ta and trapping probability as a function of thickness.

In contrast to the Al/Ta devices, we have seen quasiparticle transmission from the absorber to the MKID in optical/UV AlMn/Al devices. These devices consisted of a single layer, 60 nm thick Al film patterned into the standard strip detector geometry. The trapping region was then selectively implanted with 4.8×10^{14} Mn ions/cm² at 20 keV using a photoresist implant mask, lowering the superconducting transition temperature of the implanted region to 500 mK [13]. It was found that the implant also lowered the internal Q s of the resonators to $\sim 2 \times 10^4$, but that annealing the devices in vacuum for 60 minutes at 300 C after the implant increased the internal Q s to $\sim 4 \times 10^5$. In addition, the T_c was increased to 720 mK after annealing, consistent with results from cosputtered AlMn devices [14], where the Mn concentration is constant with depth in the film. Unlike the Ta/Al strip detec-

tors, where the vacuum is broken between the deposition of the Ta and Al, this design eliminates the interface between the absorber and MKID.

Fig. 3 shows the pulse response in the left MKID when driving the injectors for the AlMn/Al device. From fits to the pulse response, we find the diffusion constant, $D_{\text{Al}} = 19.8 \pm 5.3 \text{ cm}^2/\text{s}$, and lifetime, $\tau_{\text{AlMn}} = 130.1 \pm 4.4 \mu\text{s}$. The measured lifetime in the AlMn is similar to lifetimes previously measured for 60 nm Al films, so we assume $\tau_{\text{Al}} \approx \tau_{\text{AlMn}}$ and calculate a diffusion length in the Al, $l = 507.5 \pm 68.5 \mu\text{m}$.

From the ratio of the steady state response to the pulse response, we can estimate the trapping efficiency, η_{trap} . In the limit of good diffusion and poor trapping, the steady state density of quasiparticles is constant throughout the absorber and MKID, so the quasiparticle decay rate becomes $\Gamma_d = N_{\text{abs}}/\tau_{\text{abs}} + N_{\text{MKID}}/\tau_{\text{MKID}} = (N_{\text{MKID}}/\tau_{\text{MKID}})(1 + V_{\text{abs}}/V_{\text{MKID}})$, where we have assumed $\tau_{\text{MKID}} \approx \tau_{\text{abs}} \approx 100 \mu\text{s}$ as above. The ratio of volumes for the absorber and MKID for this device is $V_{\text{abs}}/V_{\text{MKID}} = 9.6$. Since both the steady state and pulse response depend on quasiparticle creation efficiency, we can take the ratio of the steady state and pulse response to eliminate η_{inj} and obtain the trapping efficiency:

$$\eta_{\text{trap}} = \left(1 + \frac{V_{\text{abs}}}{V_{\text{MKID}}}\right)^{-1} \frac{P^{\text{SS}} \tau_{\text{MKID}}}{P_{\text{pulse}} T_{\text{pulse}}} \frac{\delta\theta^{\text{pulse}}}{\delta\theta^{\text{SS}}} \quad (1)$$

where the phase response $\delta\theta$ is proportional to the number of quasiparticles in the MKID, N_{MKID} . For the 200 μm strip, the steady state phase response was $\delta\theta^{\text{SS}} = 0.15 \text{ rad}$ at a microwave drive power of -81 dBm, and the pulse response was $\delta\theta^{\text{pulse}} = 0.09 \text{ rad}$ for a 5 μs pulse

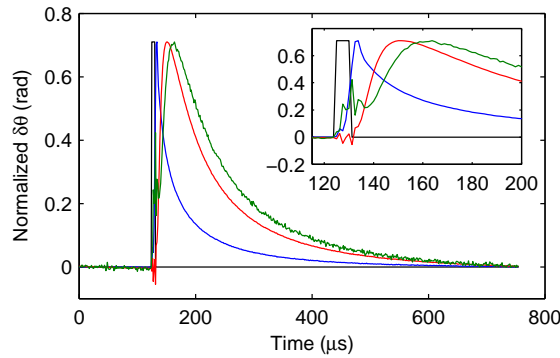


FIGURE 3. (Color online) Phase response of the left MKID for several different strip lengths when the corresponding injector was driven at its 3rd harmonic at a feedline power of -61 dBm. The inset shows an enlarged version of the rising edges of the pulses. The microwave pulse is a 5 μ s long square wave, shown in black. When the MKID is driven at its own 3rd harmonic, there is a fast pulse (blue) which peaks within a ring-up time after the pulse is turned off. When the injector at the opposite side of the strip is driven at its 3rd harmonic, a slow rise time is seen. The response for the MKID attached to a 200 μ m strip (red) peaks ~ 15 μ s earlier than for the 400 μ m strip (green), due to the longer diffusion time in the 400 μ m strip. All pulses are normalized to the pulse height for the 200 μ m strip. The transient oscillations visible immediately after the microwave power is switched off are due to the readout electronics and not the response of the resonators.

at -69 dBm. From this response, we determine the trapping efficiency, $\eta_{trap} = 0.07$. When illuminating this device with 254 nm UV photons, we measured 60 degree pulses for events directly absorbed in the AIMn section. The rms phase noise was measured to be ~ 8 degrees. By enlarging the trapping region, implanting to a higher dose to lower the AIMn T_c to 500 mK, and using sapphire substrates with lower TLS noise, we should easily be able to observe correlated pulses for strip events for these devices.

CONCLUSIONS

Due to their inherent frequency domain multiplexing, optical/UV and X-ray MKID strip detectors are natural candidates for fabricating large detector arrays. We can reliably fabricate X-ray strip detectors with energy resolutions ~ 60 eV, with substantial improvement possible through the reduction of two-level systems coupled to the resonator. In thinner devices sensitive to optical/UV photons, the transmission of quasiparticles from the Ta absorber to MKID is unreliable. We are investigating the thicknesses at which this transmission begins to break down by using resonators to inject quasiparticles directly into the absorber. Single layer implanted AIMn devices

have shown good transmission of quasiparticles at optical thicknesses, and reliable AIMn/Al optical strip detectors should be achievable with only minor modifications to the Mn concentration and trapping geometry of the devices tested to date.

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