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Mitigation of position dependence in x-rays absorbers for Thermal Kinetic Inductance Detectors

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Abstract. The currently available microcalorimeter technologies are all affected by the difficulty of multiplexing large numbers of pixels (>1000). Microwave kinetic inductance detectors, on the other hand, are intrinsically highly multiplexible. We have recently shown that it is possible to use a superconducting resonator as a thermometer for a microcalorimeter (TKID). The moderate sensitivity of the resonator of a TKID requires a low heat capacity absorber (e.g. like Tantalum, Tin) in order to achieve sufficient signal to noise and absorption efficiency. These materials are often characterized by poor thermalization properties, which give rise to a position dependent response. In this work we introduce a new design solution based on a bilayer of Tantalum and Gold grown on a perforated SiN island that provides better thermalization properties and reduces the position dependence, while maintaining a small total heat capacity.

1. Introduction

Current microcalorimeter detectors, independent of their detection mechanism, require a fairly complex read-out system, which limits the scalability to big arrays. Microwave Kinetic Inductance Detectors (MKIDs) are attracting an increasing interest, due in part to the relative ease of multiplexing MKIDs. An array of MKIDs is readout by sending a comb of microwave frequencies matched to the resonators frequency past the resonators. Each resonator interacts with the comb signal at its designed frequency, changing the phase and amplitude of the input signal. The responsivity of MKIDs using phase readout is governed by several parameters according to $\mathrm{d}\theta/dN_{qp} \propto \alpha Q/V$ where $\mathrm{d}\theta/dN_{qp}$ is the phase change per change in quasiparticle density, α is the kinetic inductance fraction (i.e. the ratio between the kinetic inductance and the total inductance, kinetic plus magnetic inductance), V is the volume and Q is loaded quality factor [1]. This formula shows that in order to increase the responsivity, resonators with high Q, high α and small volumes are needed. These conditions put strong constraints on the material selection used for the resonator, especially in the case of detectors for x-rays where high-Z materials and big volumes are needed to achieve reasonable stopping powers. In our previous work [2] we introduced a new MKID concept, called a Thermal Kinetic Inductance Detector (TKID), where a superconducting resonator is used as a microcalorimeter, rather than as a non-equilibrium detector. The device consists of an absorber and the inductor of a superconducting resonator deposited on a SiN suspended membrane, which provides a weak thermal link to the bath. The thermalization of the photon in the absorber causes an increase in the temperature of the absorber itself and of the SiN membrane and inductor. As shown in Gao et al [3], the change in surface impedance of a superconductor due to an increase in temperature is nearly identical to the change due to an excess of quasiparticles. Consequently, by fabricating a resonator on the same SiN we were able to measure the temperature rise by examining the induced frequency shift and reduction in amplitude of a microwave signal transmitted past the resonator. In this design there is no electrical contact between the absorber and the resonator; the response of the resonator is purely due to the temperature evolution of the island and not to the injection of non-equilibrium quasiparticles.

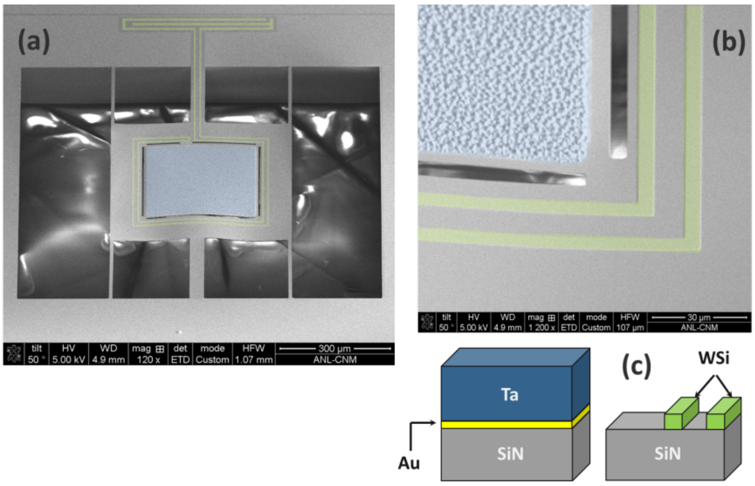

Figure 1. (a) SEM image of a representative device (Dev-H) in false colors; the resonator is green and the absorber is blue. **(b)** Detail of a corner of the absorber where showing the perforation in the SiN membrane.
(c) Schematic of the cross section of the device (not to scale).

2. Device and Measurements

The TKID device consists of three main components: a superconducting resonator, an x-ray absorber, and a SiN membrane. A false color SEM image of a finished device is shown in Figure 1(a) with the absorber blue and the resonator green. All of the devices described here use a 100 nm thick WSi_2 film patterned into a lumped element resonator as the thermometer. The inductor portion of the resonator extends onto the SiN membrane while the capacitor remains on the bulk substrate. The SiN membrane that serves as the weak thermal link is 500 nm thick and patterned into an island to further decrease thermal conductance between the absorber and substrate. Given the sensitivity of our resonators ($Im[\alpha] = -Q_i \times (T/L) \times (dL/dT) \sim 50$), a low heat capacity absorber is needed. Consequently, we used a superconducting material (Tantalum) as the basis for our tests of the absorber. We have looked at two design solutions: pure superconducting absorber (500 nm of Tantalum, 300 × 300 μm lateral dimensions, from this moment Dev-S) and a hybrid bilayer of a superconductor over a normal metal (500 nm of Ta over 25 nm of Au, 200 × 200 μm lateral, from this moment Dev-H). In addition, the SiN between the absorber and the resonator has been perforated in Dev-H to further decouple the absorber from the resonator. All the devices have been characterized in an ADR cryostat with 6 keV photons from an uncollimated Fe-55 radioactive source, following the procedure described in [2].

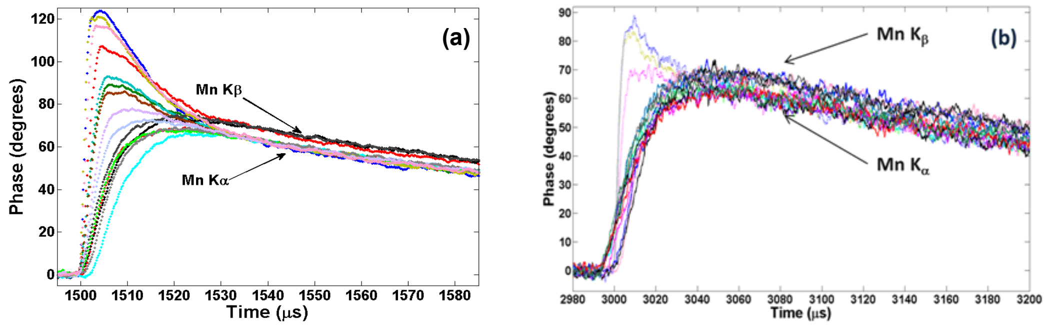

Figure 2. (a) Pulses from Dev-S under illumination with a Fe-55 source. (b) Pulses from Dev-H under illumination with a Fe-55 source.

Figure 2(a) shows a series of phase pulses from Dev-S when illuminated with photons. Clearly the rise time of the pulses is extremely variable, ranging from a few μs up to ~ 10-15 μs, giving rise to very different pulse heights and pulse shapes. After ~30 μs all the pulses collapse on two lines, corresponding to the K_{α} and K_{β} emission lines of the source. Applying a matched filter to the data, based on a template generated by averaging tens of pulses we have obtained a distribution of pulse heights. Fitting the rise time of each pulse and plotting the distribution of the rise times as a function of the pulse height, as in figure 3(a), a clear correlation can be seen. This is a strong indication of a position dependent response, where events closer to the edge of the absorber generate bigger pulses with a faster rise time. Due to poor thermalization in the absorber, the photon energy is initially confined to a limited area of the absorber, resulting in a larger pulse. Because this pulse is closer to the resonator, the heat arrives at the resonator sooner than for a photon absorbed in the middle of the absorber. Conversely, for events toward the center of the absorber the heat is forced to flow through the entire volume of the absorber; consequently the effective heat capacity will be higher, giving rise to smaller pulses and slower rise times. A similar effect has been seen in other microcalorimeters that used superconducting absorbers, with the effect particularly evident in Ta [4]. This dependence can strongly affect the energy resolution of the detector: collapsing the distribution in figure 3(a) on the x-axes the spread in phase is wide, with overlapping between the two emission lines. One way to improve the resolution could be by rejecting all the pulses with a rise time faster than 10 μs, at the cost of strongly reduced detection efficiency. The application of a low pass filter to the data could mitigate the problem, but this will reduce the usable bandwidth of the pulse.

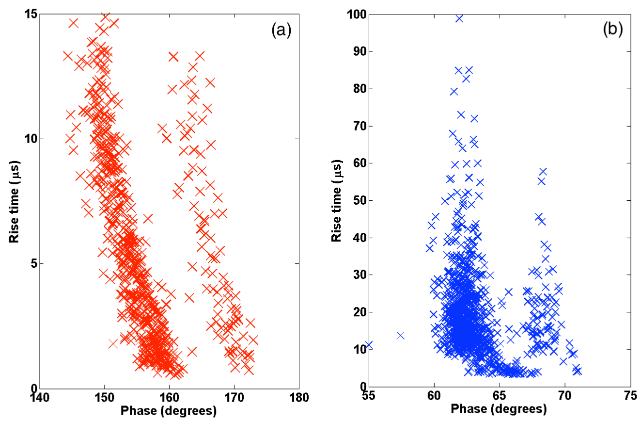

Figure 3. Pulse rise time as a function of pulse height for (a) Dev-S and (b) Dev-H.

We have begun exploring ways to mitigate this position dependence. In this paper, we present a hybrid device (Dev-H) that incorporates a thin layer of Au underneath a thick Ta absorber. Additionally, this structure is grown on a SiN island with perforations between the absorber and the resonator. A SEM picture of such device is shown in figure 1(a). In figure 1(b) is the detail of the device, where the perforation is clearly visible. The detail is schematically depicted in figure 1(c). An example of the pulses from this device is shown in figure 2(b). The vast majority of the pulses are characterized by a longer rise time (~ 10-30 μs) with respect to Dev-S. This is due to the reduced thermal conductance between the absorber and the resonator due to the perforation of the SiN membrane. The pulses have nearly identical rise time and shape (in the limit of the noise), indicating much less position dependence. In this device the gold underlayer helps with the thermalization of the Ta absorber. A role is also played by the perforation of the membrane, which, by reducing the thermal conductance between the absorber and the resonator, confines the heat in the absorber longer, allowing its uniform thermalization before the temperature rise is sensed by the resonator. To distinguish between the two effects a device with an absorber of Ta only on a perforated island is needed; this will be subject of future studies. A few fast rising pulses are still present, even if in very low number. Those are probably due to photon absorptions in the SiN membrane, close to the resonator. Even in this case two emission lines of the source are visible.

Plotting the rise time as function of the pulse height (figure 3(b)) the points align on two vertical straight lines, showing no relationship between the rise time and pulse height. The different rise times are actually an artifact of the poor quality of the fit, due to the relatively high level of noise in this device. The distribution in figure 3(b) indicates that the response of the device is independent of the absorption position in the Ta. Collapsing the data on the x-axes, it is possible to generate a histogram of the pulse height distribution. Fitting two Gaussian functions on the histogram a resolution of $\Delta E \sim$ 130 eV has been obtained, without having to reject the vast majority of the pulses (i.e., limited to rise times greater than 8 μs).

3. Conclusions

In this work we have analyzed two different kinds of absorbers for TKIDs. A low heat capacity absorber is needed, given the sensitivity of the resonator. Although a superconducting absorber (Ta) has a low enough heat capacity, the poor thermalization properties generate a position dependent response, which ruins the resolution of the detector. Consequently, we have introduced a new design of our TKID for x-rays based on a hybrid Ta/Au absorber, deposited on a perforated SiN island. This solution kept the total heat capacity low but improved the thermalization properties, reducing the position dependence.

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