Optical/UV and X-Ray Microwave Kinetic Inductance Strip Detectors

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Abstract Microwave Kinetic Inductance Detectors (MKIDs) are superconducting detectors that sense the change in the surface impedance of a thin superconducting film when Cooper Pairs are broken by using a high quality factor resonant circuit. We are developing strip detectors that have aluminum MKID sensors on both ends of a rectangular tantalum strip. These devices can provide one dimensional spatial imaging with high quantum efficiency, energy resolution, and microsecond time resolution for single photons from the IR to the X-ray. We have demonstrated X-ray strip detectors with an energy resolution of 62 eV at 6 keV, and hope to improve this substantially. We will also report on our progress towards optical arrays for a planned camera for the Palomar 200″ telescope.

1 Introduction

A Microwave Kinetic Inductance Detector (MKID) [1, 5] is essentially a high-Q resonant circuit made out of either superconducting microwave transmission lines or a lumped element LC resonator. Photons or particles hitting an MKID break Cooper Pairs (creating free charge carriers called quasiparticles) which changes the surface impedance of the transmission line or inductive element. This causes the resonant frequency and quality factor to shift an amount proportional to the energy deposited by the photon or particle.

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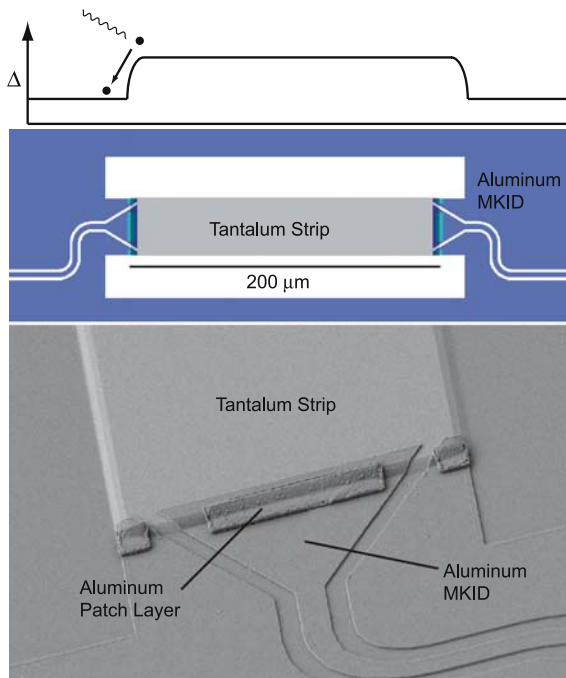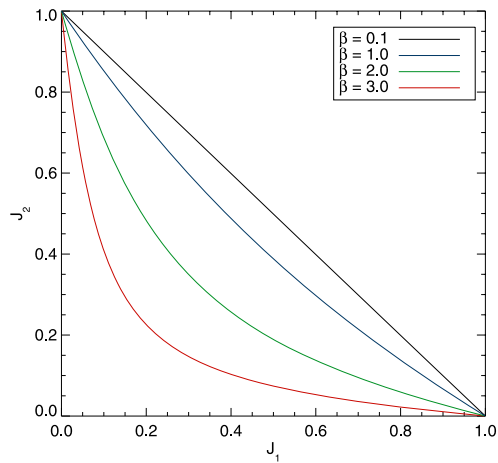e-mail: ben.mazin@jpl.nasa.gov

Fig. 1 (Color online) The *middle panel*, Fig. 1b contains a drawing of the central region of a MKID strip detector. A 200×35 μm, 600 nm thick tantalum strip (RRR = 22.6) is fabricated on R-plane sapphire and has MKIDs attached to both ends. The 3 μm center strip of the 200 nm thick aluminum (RRR = 9.5) CPW resonator that comprises the MKID is flared out where it contacts the tantalum strip to allow lateral trapping of quasiparticles. The *top panel*, Fig. 1a shows the superconducting gap Δ of the structure, including a quasiparticle diffusing into the aluminum MKID and being trapped by phonon emission. The *bottom panel*, Fig. 1c shows a SEM of the Al-Ta interface from the wafer tested in this paper. A patch of aluminum patterned with a liftoff process is used to bridge the Al-Ta interface to avert a step coverage problem. In this device the tantalum is nicely sloped and the aluminum resonator climbs smoothly over the step

We have demonstrated the detection of submillimeter, optical/UV, and X-ray photons with MKIDs. In this paper we will detail our efforts to build large arrays of MKIDs for X-ray and Optical/UV astronomy. The basis of our work is the tantalum/aluminum strip detector [2, 7]. In this structure, shown in Fig. 1, photons are absorbed in a tantalum absorbing strip. The quasiparticles created by the photon diffuse from the absorption site until they reach the ends of the strip. At the ends they enter a lower gap aluminum trapping bar that is also the center strip of a 1/2-wave coplanar waveguide (CPW) MKID. In this bar they quickly emit a phonon and relax to the gap energy of aluminum, preventing their return to the tantalum absorber. The change in the surface impedance caused by the excess quasiparticles modifies probe signals sent down the feedline. The modified signal is measured for both MKIDs. The signals are summed to provide the total photon energy, and the position is available by taking the ratio of the signals. This can be represented as a scatter plot (Fig. 3). Following Kraus [4] we can write an expression for the fraction of the total created quasiparticles J_0 that reach the end of the strip $J(x_0) = J_0 \frac{\sinh(\beta x_0/L)}{\sinh(\beta)}$ where x_0 is the distance away from the end of the strip that the photon hit, and L is the length of the

Fig. 2 (Color online) The effect of loss in a strip detector. The *x*-axis and *y*-axis show the normalized amount of quasiparticles that reach the ends of the strip for a given photon absorbtion position for various loss factors β. For example, an X-ray event in the center of a strip with $\beta = 3$ will deliver 20% of the total quasiparticles to each end of the strip. The remaining 60% will be lost to recombination

strip. The parameter β is related to the diffusion constant D, quasiparticle recombination time τ_{qp}, and the length of the strip L by $\beta = L/\sqrt{D\tau_{qp}}$.

2 X-ray Detectors

We have fabricated X-ray strip detectors with a 600 nm thick tantalum absorber and 200 nm thick aluminum MKIDs, as shown in Fig. 1c. A scatter plot of events generated by illuminating the device in Fig. 1b with an ^{55}Fe X-ray source yields Fig. 3. The Mn K_α and K_β lines from the ^{55}Fe source are clearly visible. Analysis of this data yields an energy resolution of 66 eV at 6 keV, which is approximately the same as the value we expect from noise measurements. By modeling photon events from various locations along the strip we measure a tantalum diffusion constant of 13.5 ± 1.8 cm^2/sec and a tantalum quasiparticle lifetime of 34.5 ± 5.7 μs. These parameters allow us to calculate the tantalum diffusion length $l_{Ta} = \sqrt{D_{Ta}\tau_{Ta}} = 216 \pm 30$ μm. For more details see [2, 7].

The X-ray detectors shown here are limited by the poor quality of the sapphire used as a substrate. We believe we are getting excess phase noise from two-level systems (TLS) in the dielectric [3]. We have measured similar devices on higher quality sapphire that should improve our energy resolution to 12 eV with the same geometry detector. Higher quality substrates, optimizing the resonator geometry, using an amplitude readout, and using different superconductors may improve this further.

3 Optical/UV Detectors

While the extremely interesting X-ray astronomy [2] delivered with X-ray MKIDs is only available with a space-based telescope, optical/UV detectors provide exciting science opportunities from the ground and from space [6, 9, 10].

Adapting our strip detectors for the optical requires boosting their responsivity by a 1000×, although the final signal to noise requirements are significantly lower.
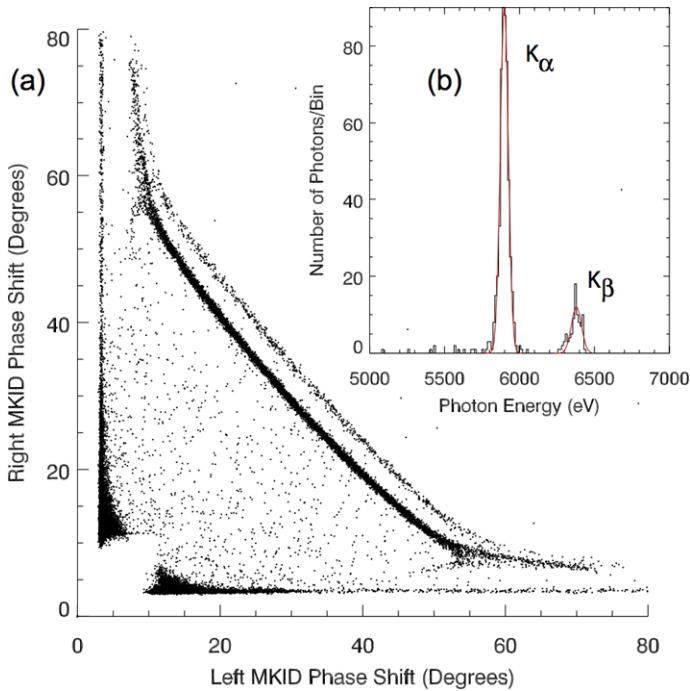
Fig. 3 (Color online) The optimally filtered maximum phase pulse height in degrees observed in an aluminum MKIDs attached to a 200 μm tantalum strip is shown in Fig. 3a. The pulse height in the left MKID is shown on the x-axis, while the right MKID is shown on the y-axis. The Mn K_α and K_β lines from the [55]Fe source are clearly visible. This data is fit to determine the diffusion length, and this is used to compute the energy spectrum shown in the inset, Fig. 3b. We calculate a FWHM energy width $\delta E = 62$ eV at 5.899 keV when we restrict our data to all pulses that show greater than 22 degrees of phase shift in both MKIDs

This can be achieved by making the aluminum MKIDs thinner (20 nm vs. 200 nm), smaller (1 μm wide vs. 3 μm wide), and increasing the quality factor Q by a factor of 3 or more.

In order to stack the strips detectors closer together and ensure a electrically contiguous ground plane, we have developed a new coupling system that uses a microstrip feedline and coupler. We use standard CPW bond pads, but use a CPW to microstrip transition structure to move to a 2 μm wide microstrip feedline as shown in Fig. 4a. The coupling structure uses parallel lines in the center strip of a CPW resonator as shown in Fig. 4b. This feedline and coupler structure has performed well in actual devices.

Our optical/UV test devices contain 50 strips, each with a width of 20 μm and lengths varying from 100–800 μm. The strips have 2 μm gaps between them, allowing a filling factor of 90%. They are fabricated in a seven layer process. First the tantalum absorber is deposited and patterned with sloped edges as described in [7]. A SiO$_2$ layer is deposited and pattered as a protection layer for the tantalum absorber. Aluminum is then deposited over the wafer and patterned into the last ~ 100 μm of the resonator's center strip. The niobium ground plane is deposited and etched in
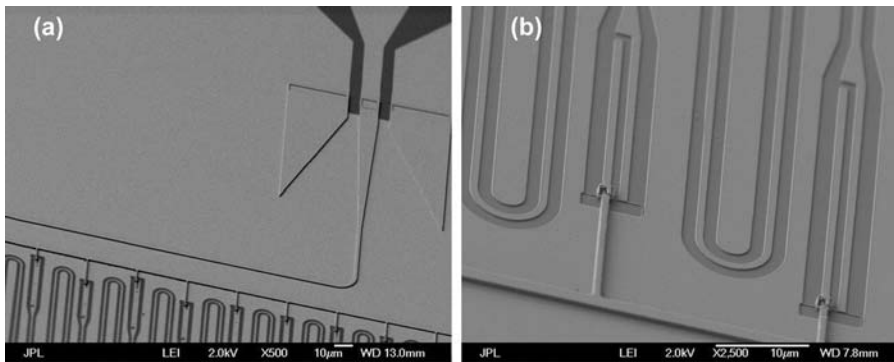
Fig. 4 Panel (**a**) shows the CPW to microstrip transition structure in the top right corner. A 2 μm wide microstrip feedline exits the structure and is connected to the coupling structure shown in Panel (**b**) if each resonator
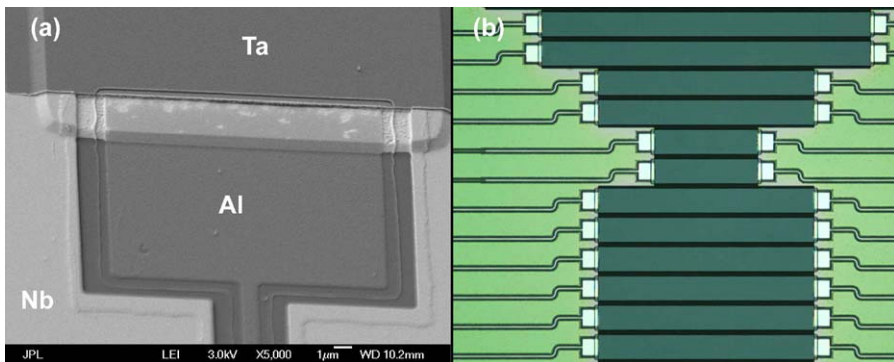

Fig. 5 (Color online) Panel (**a**) shows the trapping bar that traps quasiparticles at the end of the strips. Care must be taken in this area, and in this device some pitting and corrosion of the 20 nm aluminum film is evident. The various materials used in the construction are labeled in this figure. Panel (**b**) shows an optical micrograph of part of the array of 50 strips that comprise our test device

several key places. Next, a SiO_2 microstrip dielectric layer is deposited and etched to make vias. This is followed by the niobium microstrip wiring layer. After the wiring layer is deposited the niobium ground plane layer is etched again to define the slots of the CPW resonators. It is important that this step is done near the end as we have found that reactive ion etches done after the slots are etched tends to degrade the quality of the resonators. As a final step a plasma etch removes any exposed SiO_2 in order to eliminate the possibility it may contribute dielectric noise.

This device is very complex, and several of the steps can interact with each other in unexpected ways. We believe we have most of the problems solved and are currently testing a very promising strip detector.

Despite fabrication difficulties we have illuminated the individual resonators with 254 nm UV photons and seen excellent results. Figure 6 shows the pulse recorded when a photon hits the center aluminum strip of one of our resonators. The signal to noise of this event is as high as expected for thin devices on a high quality sapphire
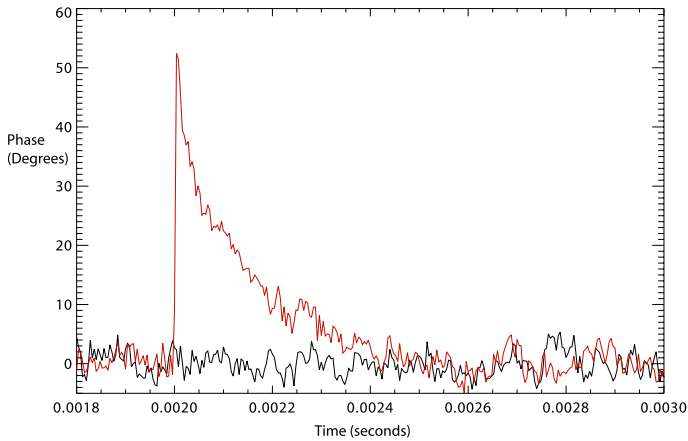
Fig. 6 (Color online) The response of a optical/UV MKID to 254 nm photon illumination is show in *red*. The *black line* is the response of a nearby resonator. This UV photon was most likely absorbed directly in the aluminum center strip, not in the tantalum absorber

substrate, and shows that we have the required sensitivity to make a scientifically interesting detector with no additional changes to the methods or materials.

4 Conclusions

Optical/UV/X-ray MKIDs are excellent candidates for large arrays for the future ground and space based missions. The designs presented here can provide very high fill factors in one dimension—for example, an optical/UV array with 1024×20 pixels would be very straightforward to fabricate with this style device. The size of the MKIDs compared with the pixels means that full 2-d arrays will have poor fill factors without the use of complex optics to slice up the focal plane. In the longer term, MKID arrays using microstrip MKIDs with thin-film dielectrics should allow us build near 100% fill factor megapixel scale imagers in the optical/UV. These arrays, coupled with the rapid development of digital readout techniques [8], allow us to contemplate extremely large arrays for the next generation of astronomical imaging spectrophotometers.

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