A Superconducting X-Ray Spectrometer with a Tantalum Absorber and Lateral Trapping

M. C. Gaidis, S. Friedrich, K. Segall, D. E. Prober, A. E. Szymkowiak, and S. H. Moseley

Abstract— **We report the development of Nb-Ta-Al-Al_2O_3-Al superconducting tunnel junction structures for high energy resolution and high efficiency X-ray detection. These devices utilize a Ta X-ray absorber with superconductor "bandgap engineered" quasiparticle trapping to improve charge collection. Experimental results at 0.3 K are presented, showing energy resolution of 102 eV full-width-half-maximum for 6 keV X-rays. Collected charge is in excess of 5×10^6 electrons. The absorption efficiency is better than 35%. Devices thermally cycle with no change in characteristics.**

X-RAY DETECTORS with high energy resolution and single photon sensitivity are desired in the diverse fields of astronomy, physics, chemistry, materials science, biology, and medicine. To date, no single detector achieves both the desired energy resolution ($\Delta E/E \leq 10^{-3}$), single photon sensitivity, and the ability to form an imaging array. Superconducting detectors hold promise for realizing all these features. In this work we consider the detection of soft X-rays, of energy 0.2–10 keV, primarily for astrophysical observations.

An X-ray absorbed in a superconducting film breaks Cooper pairs, generating large numbers of quasiparticles. The number of quasiparticles created gives a measure of the deposited X-ray energy, and one can effectively count these quasiparticles if the absorbing film forms one electrode of a superconductor-insulator-superconductor (SIS) tunnel junction [1]. The subgap current in the SIS device will increase as the created quasiparticles tunnel out of the X-ray absorbing film. The number of quasiparticles produced in a Ta absorber is expected to be $(E_x/\Delta_{\mathrm{Ta}})$, multiplied by $\approx$0.6 to account [2][1] for losses to phonons; E_x is the photon energy and Δ_{Ta} is the energy gap in the Ta. This results in $\approx 5 \times 10^6$ quasiparticles for a 6 keV photon. Fluctuations in the number of created quasiparticles obey a Poisson distribution, giving a full-width-at-half-maximum (FWHM) of

$$\Delta E_{\mathrm{FWHM}} = 2.35\sqrt{E_x F \varepsilon} \tag{1}$$

where F is the Fano factor (≈ 0.2) [2], [3] and ε is the average ionizing energy required to create a single charge. Because of the small quasiparticle excitation energies in superconductors, the energy resolution theoretically can be better than 10 eV FWHM for 6 keV X-rays [2]. Such detectors can also offer high X-ray absorption efficiency, thus making them attractive for low flux X-ray astronomy observations. Existing "conventional" X-ray detectors either have insufficient energy resolution (e.g., semiconductor p-n junctions), or are impractical for use with low particle flux (e.g., dispersive detectors). Microcalorimeters offer the necessary energy resolution and single-photon efficiency, but typically exhibit slow response, present significant fabrication challenges for 2-D arrays, and require operation below 0.1 K [4]. Normal metal-insulator-superconductor tunnel junctions [5], [6] offer some advantages similar to SIS junctions, but, in theory, are not obviously superior at present.

Here we present results of X-ray detection with a superconducting absorber and separate SIS readout for the first time, using lateral trapping *and* only refractory materials that thermally cycle well. Tantalum is a nearly ideal absorber material. It has the shortest absorption depth of any superconductor with a convenient T_c [7]. It is a refractory material which thermally cycles well. Its electron-phonon coupling characteristics make it effective in converting X-ray energy to quasiparticles rather than to phonons [8]. In addition, the Ta bandgap is intermediate among common low-T_c superconductors, thus allowing superconductor bandgap engineering.

Our SIS detector design is shown in Fig. 1. It makes use of superconductor bandgap engineering to control the flow of quasiparticles in the device. The wiring contact to the Ta absorber ($\Delta \approx 700$ μeV) is formed with the higher bandgap Nb ($\Delta \approx 1500$ μeV) to prevent quasiparticle diffusion away from the tunnel junction [9], [10]. The Nb lead is narrow and thin. The Ta edges are sloped to ensure good step coverage. An Al film ($\Delta \approx 180$ μeV) forms a quasiparticle trap [11] on the opposite end of the Ta absorber. The trap is positioned off the absorber to utilize *lateral* quasiparticle trapping. Quasiparticle inelastic scattering [10], and hence quasiparticle trapping, should occur much faster in the Al trap region which does not overlap the Ta, as this region's gap is not increased by the proximity effect of the Ta. The tunnel barrier is Al oxide. The

Manuscript received May 15, 1995; revised January 23, 1996. This work was supported by NASA under Grant NAG 5-1244. The work of M. C. Gaidis was supported by a Graduate Fellowship, CT High Technology, and ATT Fellowships. The work of K. Segall was supported by a Graduate Fellowship.

M. C. Gaidis, S. Friedrich, K. Segall, and D. E. Prober are with the Department of Applied Physics, Yale University, New Haven, CT 06520-8284 USA.

A. E. Szymkowiak and S. H. Moseley are with NASA Goddard Space Flight Center, Greenbelt, MD 20771 USA.

Publisher Item Identifier S 1051-8223(96)03121-1.

[1] Kurakado finds that in Sn about 60% of the X-ray energy is converted into quasiparticles. In Ta, which has a comparable gap and comparable electron-phonon coupling, one expects a similar number (A. Zehnder, private communication).

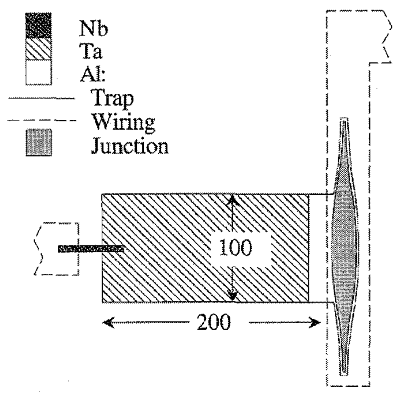

Fig. 1. Schematic of device layout. Dimensions are in micrometers. The Al trap overlaps the Ta absorber by 10 μm.

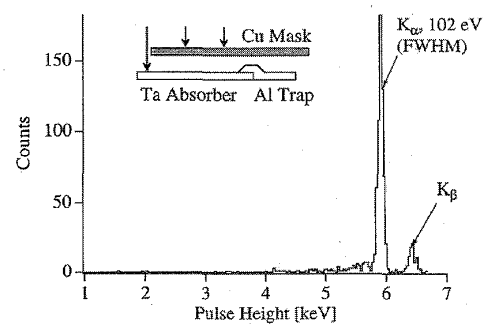

Fig. 2. X-ray spectrum, device A; $T = 0.30$ K. Exposed area of absorber is 20×100 μm^2.

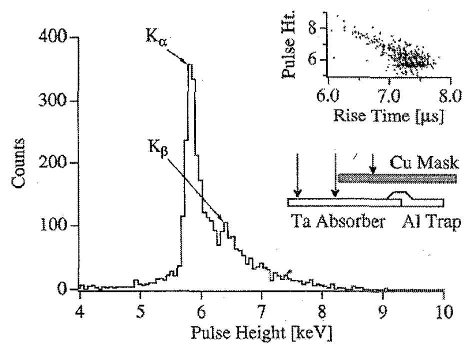

Fig. 3. X-ray spectrum, device B; $T = 0.30$ K. Exposed area of absorber is 100×100 μm^2. Higher energy pulses have shorter rise time, as shown in the inset. These higher energy pulses result from absorptions nearer the trap.

devices have been thermally cycled over many months without any changes. The junction is formed in trilayer fashion with the Al trap and a thin Al counterelectrode. The thick Al wiring layer contacts the counterelectrode and enhances quasiparticle outdiffusion to reduce backtunneling from the counterelectrode [13]–[16]. The Si substrate is coated with 3000 Å of wet-grown thermal oxide (amorphous) to reduce the phonon signal from X-ray absorption events in the substrate. The film parameters are as follows: Ta absorber: 8000 Å ($R_{300\text{K}}/R_{10\text{K}} \approx 20$); Nb wiring: 1500 Å; Al trap: 2000 Å ($R_{300\text{K}}/R_{10\text{K}} \approx 8$); SiO junction isolation: 1500 Å; Al counterelectrode: 800 Å; and Al wiring: 6000 Å. The relevant film areas are as follows: Ta absorber: 100 μm $\times$ 200 μm; Nb wiring: 6 μm $\times$ 60 μm; Al trap: $\approx$ 4500 μm^2; Al oxide junction: $\approx$ 1800 μm^2. The trap and tunnel barrier are quartic-shaped [17] to reduce the magnetic field required for critical current suppression. Fabrication procedures are presented elsewhere [13], [14]. The two devices reported on below are similar, but were produced in different fabrication runs. Parameters given are for device A.

The detector was cooled to 0.3 K in a pumped ^{3}He dewar, and biased with a 1 MΩ load line dc current source. The normal state tunnel junction resistance is 0.7 Ω, giving an estimated 5 μs for quasiparticles to tunnel out of the Al trap into the Al counterelectrode. The calculated trapping time is shorter [13]–[15]. A magnetic field of 7.6 G was applied in the plane of the junction, perpendicular to the long (200 μm) edge of the junction, to suppress the critical current for stable dc biasing and to reduce the dominant Fiske mode at $V \approx 90$ μV. The dc current bias was 200 nA (at 70 μV). The junction dynamic resistance is $\approx$ 1600 Ω, giving $R_{\text{dyn}}/R_{nn} \approx 2400$. This ratio increased with decreasing temperature to the lowest temperature studied, 0.25 K. X-rays from a radioactive ^{55}Fe source were used to illuminate the device. This source emits 88% in the Mn K_α line at 5.9 keV, and 12% in the Mn K_β line at 6.5 keV. The X-ray induced current pulse was integrated with a standard charge-sensitive configuration to give the charge pulse. We use an Amptek A250 amplifier with two 2SK147 FET's at room temperature as the input stage.

To first test the energy resolution at a given location along the Ta absorber, 90% of the absorber and all the trap of device A were shielded, so an area of only 100×20 μm^2 was exposed to X-rays, at the end near the Nb lead. A histogram of the collected charge for $\approx$ 1400 individual X-ray absorption events is shown in Fig. 2. The main peak corresponds to the 5.9 keV K_α X-rays, with energy resolution 102 eV FWHM. The noise of the electronics with the junction, measured with an injected charge pulse, is 95 eV. One would thus infer that the noise added by the detection process itself is about 40 eV, if the noise adds in quadrature. About 8.6×10^6 electrons were collected per K_α pulse. As inferred from the location of the K_α and K_β peaks, the device response is linear in X-ray energy to <1%. This linearity indicates that quasiparticle self-recombination due to X-ray generated quasiparticles is small. The risetime of the collected charge signal corresponds to a $1/e$ decay time of the current pulse of 10 μs, with a narrow distribution around this value. The risetime is $\approx$2 times longer than that expected in the absence of backtunneling [13]. We discuss this below.

To understand how the X-ray response depends on the location of the absorption event, we measured a similar device, B, where only half of the absorber and all the trap were masked. The exposed area was 100×100 μm^2. The data are shown in Fig. 3. We find the expected K_α and K_β peaks, and use these to index the energy scale. The collected charge for K_α X-rays is 5×10^6 electrons.[2] We find a higher energy (larger charge) tail above the main peaks. These pulses with larger charge have shorter rise times than those of the K_α peak centered at $\approx 7.4\ \mu$s, as seen in the inset to Fig 3. (With no mask, even more pulses at even larger charge are seen.) If these higher energy (faster) pulses are from absorptions *nearer* the trap, then the K_α peak is from absorptions at the *far* end of the Ta absorber, near the Nb lead.[3] The quasiparticles from these events at the far end lose $\approx 25\%$ more of their charge during diffusion to the Al trap, as compared to the events near the center of the absorber.[4] These losses are less severe than those seen in typical Nb films [18]. Modeling of our results assuming loss during quasiparticle diffusion in the Ta gives a histogram like that in Fig. 3. Such quasiparticle losses are commonly seen, due either to magnetic flux penetration in the absorber [9], [10] or recombination at inhomogeneities.

The energy resolution for a single location is 102 eV (Fig. 2). The losses seen in Fig. 3 seem to pose difficulties for larger detectors. However, Kraus has shown [9], [10] that with use of two traps, one at each end of an absorber 500 μm long, absorber losses can be normalized out with little degradation of the energy resolution achieved for a single location. The two-trap design also provides accurate position information, allowing an imaging single-photon spectrometer.

A final issue is the magnitude of the collected charge. We expect to create $\approx 5 \times 10^6$ quasiparticles in the absorber for a K_α event. We expect [13] to collect into the counterelectrode $\approx 4 \times 10^6$ electrons, given losses in the absorber and some multiplication during trapping into the Al trap. Yet, we collect charge of between 5×10^6 and 9×10^6 electrons. This implies that there must be some charge multiplication, either larger than expected during the trapping process, or during the tunneling process due to backtunneling [19].[5] Both the long measured collection time and the large charge indicate the presence of multiplication by backtunneling. The collection time and collected charge are both increased, by a factor as large as 2. This provides a self-consistent explanation of the data of Figs. 2 and 3.

In summary, we have demonstrated X-ray detection with SIS junctions utilizing a Ta thin film absorber with a separate SIS junction. The device structure allows the absorber length to be increased, with the trap and tunnel detector remaining of the same sensitivity. In contrast to simpler structures where the tunnel device is incorporated vertically in the absorber(s) [16], we find only a *single* peak for each X-ray energy. This is essential for straightforward analysis of complex X-ray spectra. Extension to larger absorbers and to two-junction imaging spectrometers is possible.

[2] The charge collected by the two junctions differed, as the two junctions differed slightly in fabrication and biasing. The risetime for junction B, $\approx 7\ \mu$s, was shorter than for junction A.

[3] Absorption events nearer the trap will have shorter diffusion time. Note also that the velocity in the Ta will be less than the Fermi velocity because of the energy dispersion relation for quasiparticles near the gap edge. The resulting diffusion is slowed.

[4] An alternative explanation of the points above the main peak in Fig. 3 is that absorptions nearer the gap generate excess quasiparticle energy or phonons, which produce more quasiparticles when they move into the Al trap.

[5] Backtunneling includes pair mediated tunneling from counterelectrode to trap, and results in increased collected charge (see [15]). Experiments on junctions with two different contact areas between counterelectrode and wiring layer indicate that there is no significant confinement in this area (see [11]). Also, for the given geometry quasiparticle diffusion out the leads should be fast, so backtunneling might not be expected.

ACKNOWLEDGMENT

The authors would like to thank H. Kraus, C. A. Mears, M. Nahum, and A. H. Worsham for instructive discussions, S. B. Weiss for assistance with computer interfacing, and M. Rooks and the National Nanofabrication Facility at Cornell University, Ithaca, NY, for the manufacture of the photomasks. The devices were fabricated in the Yale Center for Microelectronic Materials and Structures, New Haven, CT.

REFERENCES

[1] S. Labov and B.A. Young, Eds., *Proc. 5th Int. Workshop Low Temp. Detectors,* in *J. Low Temp. Phys.* vol. 93, pp. 185–836, 1993.

[2] M. Kurakado, "Possibility of high resolution detectors using superconducting tunnel junctions," *Nucl. Inst. Meth.*, vol. 196, pp. 275–277, 1982.

[3] U. Fano, "Ionization yields of radiation. II. the fluctuations in the number of ions," *Phys. Rev.*, vol. 72, pp. 26–29 1947.

[4] S. H. Moseley, R. L. Kelley, R. J. Schoelkopf, A. E. Szymkowiak, D. McCammon, and Z. Zhang, "Advances toward high spectral resolution quantum x-ray calorimetry," *IEEE Trans. Nucl. Sci.*, vol. 35, pp. 59–64, 1988.

[5] M. Nahum, J. M. Martinis, and S. Castles, "Hot electron microcalorimeters for x-ray and phonon detection," *J. Low Temp. Phys.*, vol. 93, pp. 733-738, 1993.

[6] M. Nahum, and J. M. Martinis, "Hot electron microcalorimeters as high resolution X-ray detectors," *Appl. Phys. Lett.*, vol. 65, pp. 3203–3205, 1995.

[7] S. Brennan and P. L. Cowan, "A suite of programs for calculating X-ray absorption, reflection, and diffraction performance for a variety of materials at arbitrary wavelengths," *Rev. Sci. Inst.*, vol. 63, pp. 850–853, 1992.

[8] N. E. Booth, R. J. Gaitskell, D. J. Goldie, C. Patel, and G. L. Salmon, "Single crystal superconductors as X-ray detectors," in *X-Ray Detection by Superconducting Tunnel Junctions,* A. Barone, R. Christiano, and S. Pagano, Eds. New York: Elsevier, 1991, pp. 125–150.

[9] H. Kraus, F. von Freilitzsch, J. Jochum, R. L. Mssbauer, T. Peterreins, and F. Prbst, "Qusiparticle trapping in a superconductive detector system exhibiting high energy and position resolution," *Phys. Lett.*, vol. B231, pp. 195–202, 1989.

[10] H. Kraus, "Quasiteilchen-Einfang in supraleitenden Tunneldioden," Ph.D. dissertation, Tech. Univ. Munich, Germany, 1989.

[11] N. E. Booth, "Quasiparticle trapping and the quasiparticle multiplier," *Appl. Phys. Lett.*, vol. 50, pp. 293–295, 1987.

[12] S. B. Kaplan, C. C. Chi, and D. N. Langenberg, "Quasiparticle and phonon lifetimes in superconductors," *Phys. Rev.*, vol. B14, pp. 4854–4873, 1976.

[13] M. C. Gaidis, "Superconducting tunnel junctions as single photon X-ray detectors," Ph.D. dissertation, Yale Univ., New Haven, CT, 1994. (Available from University Microfilms Int., Ann Arbor, MI.)

[14] M.C. Gaidis, S. Friedrich, D. E. Prober, A. E. Szymkowiak, S. H. Moseley "Superconducting Al-trilayer junctions for use as X-ray detectors," *IEEE Trans. Appl. Superconduct.*, vol. 3, pp. 2088–2091, 1993.

[15] ——, "Superconducting Nb-Ta-Al-AlOx-Al tunnel junctions for X-ray detection," *J. Low Temp. Phys.*, vol. 93, pp. 605–610, 1993.

[16] C. A. Mears, S. E. Labov, and A. Barfknecht, "Energy resolving superconducting X-ray detectors with charge amplification due to multiple quasiparticle tunneling," *Appl. Phys. Lett.*, vol. 63, pp. 2961–2963, 1993.