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Due to Multiple Quasiparticle Tunneling**

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Energy-Resolving X-Ray Detectors With Charge Amplification Due To Multiple Quasiparticle Tunneling

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A single 6 keV x-ray absorbed in a superconductor produces more than a million electrons in excited states, called quasiparticles. The number of quasiparticles is proportional to the energy of the incident x-ray, and can be determined by measuring the increase in tunneling current through a thin oxide barrier between two superconducting layers. The energy resolution of an x-ray detector based on such a measurement in principle could be limited only by the statistical variation in the number of quasiparticles produced. If this is the case, the resolution for 6 keV x-rays absorbed in niobium ($\Delta = 1.5$ meV) should be better than 5 eV.^{1,2} While high resolution has been achieved with superconducting tunnel junction detectors, the best resolution obtained is about 10 times worse than this limit.^{3,4} The energy resolution of previous work was often limited by electronic noise produced in the charge-amplification system.

In order to minimize the effects of electronic noise, we developed a detector using a new geometry where each quasiparticle produced is trapped near the tunnel barrier and tunnels several times before it recombines into a Cooper pair, thus increasing the charge measured for a given x-ray. Because of this larger charge, the contribution of electronic noise to the energy resolution of the detector is minimized.

We studied a square detector junction 100 μm on a side shown in Figure 1. A base electrode of niobium (240 nm thick) is covered with aluminum (200 nm), an aluminum oxide tunnel barrier, aluminum (200 nm) and niobium (150 nm) again on top. The device functions as follows. An x-ray is absorbed in either of the niobium films. The resulting quasiparticles diffuse into the aluminum, where they lose energy by emitting one or more phonons and relax to a state near the aluminum energy gap. A phonon emitted in this process may have enough energy to break a Cooper pair in the aluminum, resulting in quasiparticle multiplication. Quasiparticles that have relaxed are trapped near the tunneling barrier, thus reducing the inverse tunneling rate τ_t . τ_t is the time that each quasiparticle spends in a given electrode before tunneling through the barrier.^{4,6} After a quasiparticle tunnels, it is still trapped in the aluminum layer on the other side of the barrier, and is free to tunnel again. When $eV_{\text{bias}} \gg kT_{\text{eff}}$, charge is transferred to the electrode at the lower potential, independent of the direction in which the quasiparticle tunneled.^{7,8} Here $-e$ is the charge of an electron, V_{bias} is the voltage applied across the tunneling barrier, k is Boltzmann's constant, and T_{eff} is the effective temperature of the quasiparticle distribution. If τ_t is shorter than the recombination lifetime of the quasiparticle, τ_r , then each quasiparticle tunnels more than once, on average, increasing the measured charge.

Figure 1 Cross section of measured x-ray detector.

The detector was fabricated at Conductus, Inc. using a modification of their standard photolithographic niobium-aluminum trilayer process.⁹ We cooled the detector to about 100 mK and exposed it to Mn K α and Mn K β x-rays at 5.89 and 6.49 keV from an ⁵⁵Fe source. A spectrum of charge collected in each pulse is shown in Figure 2. The line near channel 680 is the response to an electronic pulser used to characterize the contribution

Figure 2 Collected-charge spectrum measured when test device is irradiated by Mn K-shell x-rays.

average of $\tau_r/\tau_t = 6$ times, increasing the measured charge by this amount. Although we have shown multiple tunneling slightly broadens the resolution due to statistics and thus degrades the resolution obtainable without electronic noise,^{10,11} we note that without multiple tunneling, the signal would have been about 6 times smaller, and x-ray linewidth would have been dominated by electronic noise, yielding a resolution of about 140 eV.

We have operated for the first time an x-ray detector which uses multiple tunneling of trapped quasiparticles to amplify the signal before it leaves the detector. This detector has an energy resolution of 41 eV at 6 keV, which is the best resolution measured to date in a superconducting tunnel junction x-ray detector. The amplified signal eases the noise performance required of the amplifier for high resolution operation.

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of electronic noise to the measured x-ray linewidth. All the other features are induced by x-rays. We observed two sets of two peaks due to absorption of x-rays in either the top or the bottom niobium film. The width of the top-film $K\alpha$ line is 41 eV FWHM. The width of the line produced by the electronic pulser is 23 eV, indicating that for this detector, electronic noise was not the dominant source of the measured x-ray linewidth.

From our measured value of the normal state resistance of the junction, $R_N = 80$ m Ω , we calculate the inverse tunneling rate $\tau_t = 1.2$ μ s at 0.12 mV. The quasiparticle lifetime, τ_r , is determined by measuring the decay time of the current pulse through the tunneling barrier; for this device $\tau_r = 7.2$ μ s. Therefore in a given pulse each quasiparticle tunneled an

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