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High-Resolution Superconducting X-Ray Spectrometers With an Active Area of $282\text{ }\mu\text{m} \times 282\text{ }\mu\text{m}$

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Abstract—Superconducting tunnel junctions coupled to superconducting absorbers may be used as high-resolution, high-efficiency X-ray spectrometers. We have tested devices with niobium X-ray absorbing layers coupled to aluminum layers that serve as quasiparticle traps. In this work we measure the current pulses from a large-area tunnel junction using an amplifier based on an array of 100 SQUIDs. Using this amplifier and a $282\text{ }\mu\text{m} \times 282\text{ }\mu\text{m}$ junction, we have measured an energy resolution of 19 eV FWHM for 1.5 keV X rays and 21 eV for 2.6 keV X rays. The area of this junction is eight times the area of any junction previously measured to have such high energy resolution.

I. INTRODUCTION

When a single 6 keV X-ray photon is absorbed in a superconductor, it produces more than a million electrons in excited states, called quasiparticles. The number of quasiparticles is proportional to the energy of the incident photon, and can be determined by measuring the increase in quasiparticle tunneling current through a superconducting-insulating-superconducting (SIS) tunnel junction. The energy resolution of an X-ray spectrometer based on this measurement could be limited only by the statistical fluctuations in the number of quasiparticles produced. For niobium, this fundamental limit is about 5 eV for a 6 keV photon[1],[2]. In practice, it may be difficult to achieve such high energy resolution because of additional statistical fluctuations associated with the tunneling and recombination processes[3],[4], but a resolution of 10 to 15 eV at 6 keV should be obtainable.

In addition to high energy resolution, a useful X-ray detector should also have a reasonably large effective area. Current high-performance SIS-based X-ray spectrometers have areas of $100\text{ }\mu\text{m} \times 100\text{ }\mu\text{m}$ or less[5]–[7] making them too small for most practical purposes. There are several possible approaches to increasing the active area, including the use of a separate absorber and quasiparticle trapping[8]–[10], and the fabrication of large arrays of smaller devices. In this paper, we simply increase the area of the SIS junction. Until re-

cently, this was considered impossible[11] because the increased area led to increased capacitance. This increased capacitance degrades the noise performance of the negative-feedback FET-based amplifiers typically used to measure the X-ray-induced current pulses. The recent development of broad-band current amplifiers based on arrays of SQUIDs[12] makes it possible to accurately measure current pulses from much larger tunnel junctions. The current noise of these amplifiers is, to a first approximation, independent of the source impedance of the device to be measured.

Using this type of amplifier, we have been able to obtain very high energy resolution for a junction with 8 times larger area than those previously found to exhibit high energy resolution. The measured resolution of 19 eV FWHM at 1.5 keV and 21 eV FWHM at 2.6 keV is comparable with the best results measured using a much smaller junction and an FET-based amplifier.

II. DEVICE DESCRIPTION AND FABRICATION

We are developing X-ray spectrometers that use niobium absorbing layers coupled to aluminum trapping layers on both sides of the tunnel barrier. We show in Fig. 1 a cross-section

Fig. 1. Cross-section of the measured detectors. X-rays are absorbed in the two niobium layers, and the resulting quasiparticles are trapped in the two aluminum layers. The thickness of the two aluminum trapping layers is 200 nm. Due to the proximity effect, the energy gap in these layers is elevated to 0.35 meV.

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of our test device. 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 test device is a square, 282 μm on each side, and has a normal resistance of 4.5 m Ω . We fabricated the detector at Conductus, Inc. using a modification of our standard photolithographic niobium-aluminum trilayer process [3],[13],[14].

The device functions as follows. An X-ray photon 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. Quasiparticles that have relaxed are trapped near the tunneling barrier, thus increasing the rate at which they impinge upon the tunnel barrier. This increases the tunneling rate and the measured current. 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. Under typical bias conditions, quasiparticle tunneling in either direction leads to charge transfer to the electrode at lower potential. If the tunneling rate is larger than the recombination rate, then each quasiparticle tunnels more than once, on average, increasing the duration of the pulses and therefore the total amount of charge that tunnels [3],[15].

III. READOUT ELECTRONICS

A schematic diagram of our SQUID-based current amplifier is shown in Fig. 2. The detector, modeled by the parallel combination of the dynamic resistance R_d and the junction capacitance C_j , is mounted in series with the input coil of the SQUID, with inductance L_{sq} . This series combination is mounted in parallel with a low-resistance bias resistor R_b . When a current i_b is injected as shown, a nearly ideal voltage bias is provided across the detector, provided that $R_b \ll R_d$,

Fig. 2. Schematic diagram of SQUID-based current measurement circuit.

and that the frequency is low enough so that $\omega L \ll R_d$. The shunt resistor R_b in parallel with the SQUID input coil provides RF filtering for the SQUID input.

The SQUID, manufactured by HYPRES Inc. [16], is a series array of 100 SQUIDS coupled to a single input coil. When coupled using the 0.3 μH input coil, it has a current responsivity of ~ 1200 V/A, and an input noise of ~ 5 pA/Hz^{1/2}. Because the output impedance of the SQUID array is well matched to room temperature bipolar transistors, no matching transformer is needed. We operate the SQUID with a constant bias current without feedback.

For X-ray detection experiments the bias voltage across the detectors is fixed at the desired value by adjusting i_b . An X-ray induced current pulse through the tunnel junction is accompanied by a corresponding pulse through the SQUID input coil. This results in a voltage signal at the output of the SQUID array, which is then amplified by a room temperature voltage amplifier. As long as $R_d > R_b$, the majority of the signal current passes through the SQUID input coil and is thus measured. If $R_d < R_b$, the majority of the current is shunted through the dynamic resistance.

At first glance, it appears that we should choose the value of the bias resistor to be as low as possible so as to provide the best voltage bias possible, and also maximize the current through the SQUID input coil. Upon closer inspection, we find that the series combination of the junction capacitance and the inductance of the SQUID input coil form an L-C tank

Fig. 3. Simulated pulses in the input coil of the SQUID amplifier for different values of the bias resistor R_b . In both cases the thinner line is the current pulse emitted by the detector, and the thicker line is the current through the coil. In (a), R_b is set to 0.044 Ω . In this case, the L-C circuit formed by the inductance of the input coil and the capacitance of the junction is underdamped, and oscillation results. In (b), R_b has been increased to 10 Ω , and the oscillation has been damped without significant distortion or loss of signal. In both cases the dynamic resistance is assumed to be 100 Ω , corresponding to a quality factor $Q = R_d/R_b = 3 \times 10^4$.

Fig. 4. Measured pulse caused by the absorption of a Cl K α X-ray ($E = 2622$ eV) in the top niobium film.

circuit that can be driven into oscillation by the sharp impulse of the X-ray induced current pulse. For typical values of $L_{sq} = 0.3$ μ H and $C_j = 4$ nF (for a 300 μ m $\times$ 300 μ m Nb/Al/Al $_2$ O $_3$ /Al/Nb junction), this oscillation frequency is given by $2\pi^{-1}(LC)^{-1/2} \approx 3$ Mhz. These oscillations can be damped by either the bias resistor R_b or the shunt resistor R_s . Critical damping can be achieved by either raising the value of R_b or lowering the value of R_s to their critical value. For the typical values of L_{sq} and C_j listed above, the critical value of $R_b = 7.8$ Ω , and the critical value of $R_s = 1.7$ Ω . Analysis of the contributions to the noise due to thermal fluctuations in these resistors shows that it is best to raise the value of the bias resistor to achieve damping. If the value of the shunt resistor is lowered to the critical value, its Johnson noise, even if it is cooled to 2.0 K, dominates the current noise of the SQUID.

To illustrate the effects of this damping, we have simulated the operation of the circuit for two representative cases. The results of these simulations are shown in Fig. 3. In Fig. 3a, we show a simulated pulse for an underdamped configuration, where R_s is set to 20 Ω , and the bias resistor is set to 0.044 Ω . This is the configuration we used earlier[5],[17] to measure the current in a 100 μ m $\times$ 100 μ m junction. When this same configuration is used for a larger, 282 μ m $\times$ 282 μ m junction, oscillations result as shown. To damp these oscillations it is necessary to increase the bias resistor R_b to a supercritical value of 10 Ω . The results of a simulation with this change made are shown in Fig. 3b. The oscillations are damped, and the current through the SQUID faithfully follows the current pulse generated in the detector, except for a slight increase in rise time.

The use of such a large value for the bias resistor puts constraints on the dynamic resistance of the detector junction. If the dynamic resistance is less than the resistance of the bias resistor, most of the current signal is shunted through the dynamic resistance and never reaches the SQUID input coil and is therefore lost. On the other hand, it is necessary for the junction to have a low normal resistance in order to have the short tunneling times needed to generate pulses large enough to be measured with high precision in the presence of the current noise of the SQUID. The normal resistance of our test device is 4.2 m Ω . A quality factor $Q = R_d/R_n$ of at least several times 10^3 is required for R_d to be greater than $R_b = 10$ Ω .

Fig. 5. X-ray spectrum measured using absorption events occurring in the top niobium film. The measured resolution is more than 5 times better than that obtainable with semiconductor based ionization detectors. The smaller, wider line just below the main peaks are due to absorption events in the overhanging niobium region near the edge of the junction.

Note that this constraint is at least an order of magnitude less severe than that required for good performance when an FET based amplifier is used.

IV. EXPERIMENTAL RESULTS

The device was cooled in zero magnetic field to below 1.0 K in an adiabatic demagnetization refrigerator. After reaching the operating temperature, a magnetic field of 10 to 20 mT was applied in the plane of the junction diagonally across the square to suppress the dc Josephson current. The results reported in this paper were all obtained using the refrigerator in an unregulated mode with the temperature drifting up from 80 mK to 200 mK. There was no dependence of device behavior on temperature for temperatures less than 220 mK.

The detector was irradiated using an X-ray fluorescence source with an aluminum target coated with a thin layer of sodium chloride. When irradiated with an X-ray tube, this configuration emits the characteristic X rays of these three elements. We observed current pulses that rose from 10% to 90% of the maximum in 350-500 ns and decayed approximately exponentially with a decay times ranging from 5.0 μ s to 10.5 μ s. In Fig. 4, we plot an example of a pulse produced when a Cl K α X ray is absorbed in the top niobium film. Note that there is no discernible oscillatory behavior.

The values of the rise time and decay time depend on the bias voltage applied across the device. Also, the rise times of pulses produced when X rays are absorbed in the different niobium layers differ significantly. This allows us to produce an X-ray spectrum due to absorption events in either one of the absorber films independently[5].

Each data set consists of 5000 pulses digitized every 100 ns using a 10-bit transient digitizer. The rise time, and decay time of each pulse is determined using the digitized data. Immediately after the measurement of the X-ray pulses the baseline noise is characterized and used to construct the optimal filter [18]. The height of each X-ray pulse is then deter-

mined by optimally filtering. In Fig. 5 we show an X-ray spectrum measured at a bias voltage of 140 μ V, and an applied magnetic field of 12.1 mT. We first constructed a histogram using only those pulses with rise times less than 0.50 μ s. Pulses with these short rise times are due to absorption events in the top niobium film. Using this procedure, we can remove peaks in the spectrum due to absorption in the bottom layer, and in the substrate under the junction. In this spectrum, we can clearly identify the Na K α , Al K α , Cl K α and Cl K β characteristic emission lines. The width of the Al K α line is 19 eV FWHM, and the Cl K α line is 21 eV FWHM. These resolutions are comparable to those we measured earlier using a junction with eight times less active area, and an FET-based current amplifier[6], and are roughly five times better than what is obtainable using a semiconductor based ionization detector. The pulser peak indicates the contribution of electronic noise to the width of the X-ray induced lines. Since the width of this line (17.5 eV FWHM) is nearly the same as the width of the X-ray induced lines, we conclude that the dominant source of linewidth in this detector is electronic noise.

At energies directly below each peak, there is a smaller, wider satellite line. These first devices were made with an etch process that had not been completely optimized. In these devices, an over etch of the aluminum resulted in an overhanging region of the top niobium without an aluminum trap directly beneath it. We believe that these satellite lines are due to absorption events in this cantilevered region, and should not be present in future devices. At even lower energies, there is a broad peak. We believe this is due to absorption events in the SiO₂ layer deposited on top of the junction area. This layer can also be removed in subsequent fabrication runs.

V. CONCLUSIONS

We have modeled and demonstrated the use of a broad-band SQUID array as a sensitive current amplifier to measure the current pulses produced by a superconducting X-ray spectrometer. We found it necessary to damp the oscillations caused by an L-C resonance between the capacitance of the detector junction, and the input inductance of the SQUID. By using this amplifier, we were able to accurately measure current pulses from a tunnel junction with an active area of 282 μ m $\times$ 282 μ m, which is eight times the active area of previous devices. We measured resolutions of 19 eV at 1487 eV FWHM, and 21 eV at 2622 eV FWHM. This resolution is more than five times better than that obtainable with current semiconductor-based ionization detectors.

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