Single Photon Imaging X-Ray Spectrometers Using Low Noise Current Preamplifiers with dc Voltage Bias

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Abstract - **We have developed superconducting single-photon imaging x-ray detectors with an energy resolution of 54 eV at 6 keV and a spatial resolution of 1 μm over an effective length of 40 μm. They utilize a current-sensitive low-noise preamplifier with a dc voltage bias. It has a signal bandwidth of 300 kHz, current noise of i_n = 0.26 pA/√Hz and voltage noise of e_n = 0.5 nV/√Hz with an input capacitance of 200 pF under operating conditions. Injected pulses with a charge Q = $3.7 \cdot 10^6$ electrons have been measured with a standard deviation σ_Q = 3400 electrons, corresponding to an electronic noise of 13 eV at 6 keV.**

I. Introduction

Superconductor - Insulator - Superconductor (SIS) tunnel junctions can be used as high resolution single photon x-ray spectrometers [1]. When used in a double junction geometry, the two signals produced by a single x-ray photon allow one to infer both its energy and its absorption location [2]. These detectors require an electronic readout whose noise contribution does not exceed the intrinsic fluctuations of the device response.

In addition, a readout scheme with dc voltage bias is desirable to prevent junctions from temporarily switching to zero voltage if their dc Josephson current cannot be completely suppressed with a magnetic field. This is a special concern with double junction detectors, since small differences between the two junctions can preclude equally good suppression of both zero voltage currents below the thermal quasiparticle current, particularly at low temperature. Furthermore, a dc voltage bias helps to keep the bias point constant, as compared to using a dc current bias with the same fractional stability (Figure 1).

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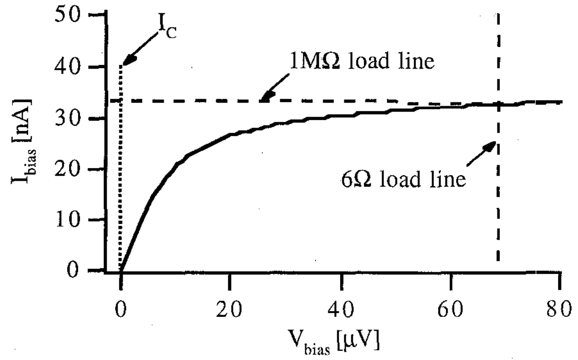

Fig. 1. Typical junction I(V) characteristics at 0.24 K. The dc Josephson current (I_C) is usually suppressed.

We have fabricated double junction x-ray detectors with a Ta absorber and an Al-AlOx-Al trap/ tunnel junction on either side. The readout circuitry utilizes two current-sensitive preamplifiers which combine low noise and large signal bandwidth with dc voltage bias. The detector is voltage biased relative to an amplifier's inverting terminal, which is held at virtual ground (Figure 2). The load line is set by the bias resistor, and with proper choice of components the circuit's noise contribution can be reduced below the shot noise of the device.

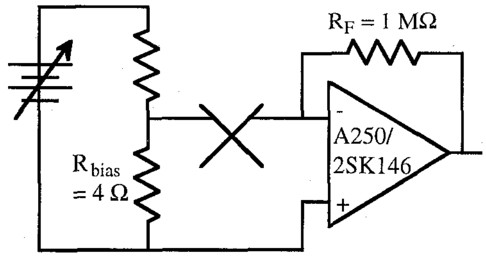

Fig. 2. Functional circuit diagram. The x represents the tunnel junction

II. CIRCUIT DESIGN

Noise considerations do not dictate whether to use a voltage, current, or charge sensitive preamplifier. The charge output of a detector usually gives a more direct measure of the energy of the incident radiation. However, current measurements are more closely related to the time-dependent processes inside a detector and therefore provide additional information for the analysis of their performance.

In our SIS tunnel junction detectors, 6 keV x-rays induce current pulses with peak amplitudes around 100 nA and a total charge of several million electrons. Measuring these signals with a signal-to-noise ratio of 1000 in a ≈100 kHz bandwidth thus requires an input current noise around 0.3 pA/√Hz. (Vertically stacked SIS junction detectors or transition edge bolometers can provide larger signal currents, which eases the requirements on electronic noise [3], [4]. However, detectors which are used in double junction configurations will have slower charge collection leading to smaller signal currents.)

For low impedance devices, preamplifiers with SQUID input stages offer the best noise performance [3], while FET input stages are superior for device impedances in the kΩ range. A modern low-noise, large-bandwidth preamplifier is the Amptek A250 transresistance amplifier [5]. An external FET input stage can be selected to match the device capacitance for optimum performance. We use a Toshiba 2SK146 JFET, the dual version of the 2SK147, at room temperature with e_n = 0.5 nV/√Hz and negligible current noise. We obtain a gain-bandwidth product of 1.6 GHz with a dominant pole at 65 kHz.

To counteract the additional phase shift that the input capacitance adds to the loop gain, we have added 0.5 pF in the feedback loop. This limits the signal bandwidth to 300 kHz, which is still acceptable, but ensures amplifier stability for arbitrary input resistances. The signal bandwidth can be inferred from the roll-off of the noise spectrum of a 10 kΩ resistor at room temperature in place of the tunnel junction (Figure 4).

A complication in our biasing scheme arises from the fact that the internal circuitry of the A250 holds its input at constant +3 V. This constrains the source-drain voltage and the bias current of the FET, which may not be compatible with a gate voltage close to ground. We have solved this problem by adding a nulling loop to the drain of the FET (Figure 3). Its purpose is to sense the gate voltage and increase the bias current of the FET until the feedback required from the A250 to keep the gate voltage at ground is effectively zero.

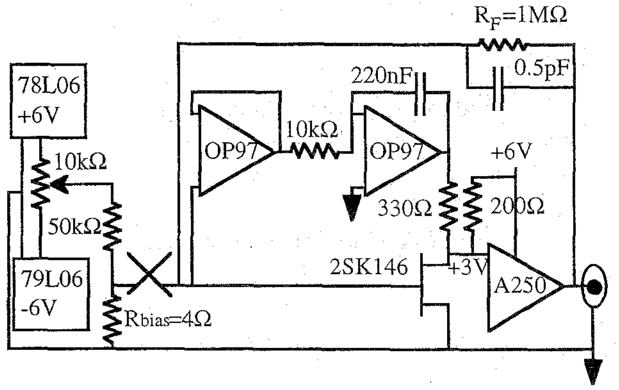

Fig. 3. Circuit diagram for a single junction readout. The RC filters at the ±6 V regulator outputs and the INA110 instrumentation amplifier for the dc voltage readout have been omitted for clarity.

The requirements of the input stage of this nulling loop are low input offset voltage and low current noise. The OP97E with V_{offset} < 25 µV and i_n = 20 fA/√Hz is our present choice. Its voltage noise is filtered out with the follower and the integrator as shown.

The bias resistor R_{bias} is at room temperature and chosen small so that its Johnson voltage noise is negligible, while still allowing an acceptable range of bias voltages. The feedback resistor R_F is chosen large for high signal gain and low current noise, keeping in mind the constraints imposed by its parasitic capacitance and the op-amp's finite open loop gain. The circuit's total current noise is i_n = 0.16 pA/√Hz, dominated by the Johnson noise of the 1 MΩ feedback resistor, which is at present at room temperature. The voltage noise is e_n = 0.5 nV/√Hz with C_{in} = 200 pF, set by the 2SK146 JFET (Figure 4).

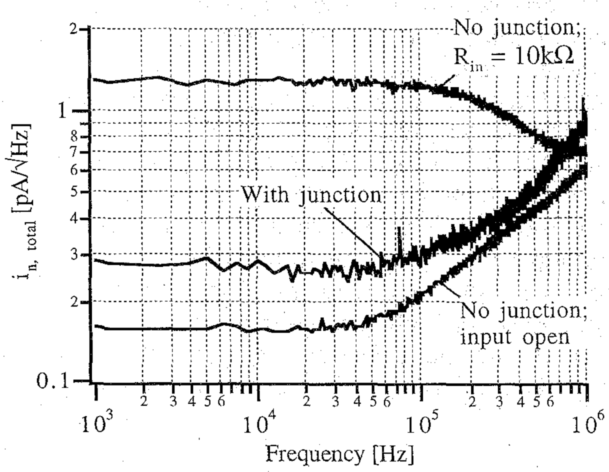

Fig. 4. Amplifier noise characteristics

The slope of the dc load line is set by the sum of the bias resistance, lead resistance and R_F/A_{OL}, where A_{OL} is the open loop gain of the composite amplifier. We have measured a load line resistance of 6 Ω, dominated by the 4 Ω bias resistor. This is low enough for our applications given that typical device resistances are around 10 kΩ.

III. Results

At an operating temperature of 0.24 K and a bias voltage of 70 μV, our detector junctions have a subgap current of ≈30 nA and a dynamic resistance of ≈10 kΩ (Figure 1). We irradiate the entire device with an ^{55}Fe source that emits two Mn x-ray lines at 5.89 and 6.49 keV. We digitize and record the unfiltered current waveforms on disk and later apply various digital filters and integrate them numerically for best resolution. Details of the device fabrication, geometry and the experimental setup have been published elsewhere [6] - [8].

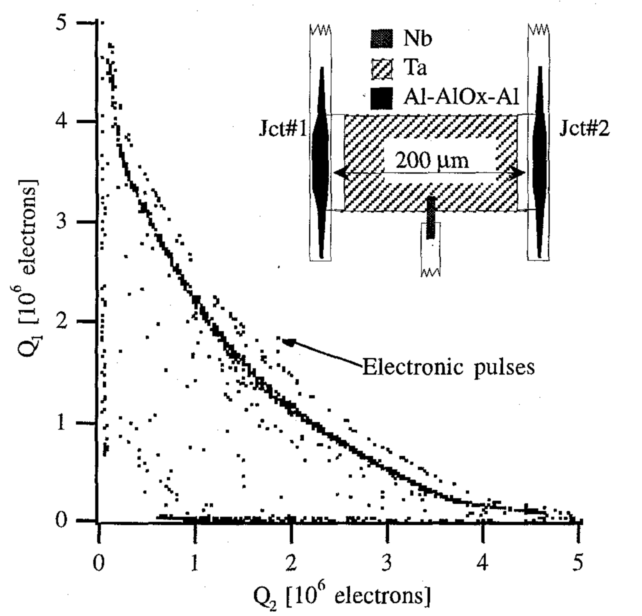

Fig. 5: Detector output charge in response to an ^{55}Fe x-ray source. 90 % of the photons correspond to K_α with an energy of 5.89 keV and 10 % correspond to K_β at 6.49 keV. The inset shows the device geometry.

Figure 5 shows a plot of the two detector charge outputs Q_1 vs. Q_2, filtered with a fifth order 4 to 65 kHz Butterworth bandpass filter. The total charge $Q_1 + Q_2$ collected from the central region of the absorber is less than the charge collected when an x-ray is absorbed near either end indicating quasiparticle loss during diffusion.

Since the variation of the total charge is also larger for events in the center (Figure 6), the quasiparticle losses may be related to the niobium contact located on one side in the center of the absorber. Niobium with its large energy gap is supposed to prevent quasiparticles from diffusing into the leads, but metallic suboxides which provide local quasiparticle traps might have formed on its surface. The fraction of quasiparticles that is lost at this low gap contact would then depend on the distance of the absorption location from the contact. This problem might be solved by passivating the niobium surface with a layer of niobium nitride or by using a very narrow tantalum contact instead.

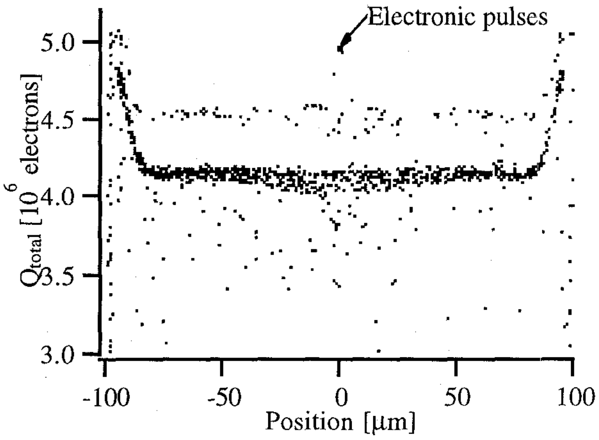

Fig. 6. Total charge vs. absorption location, corrected for loss.

One can model the charge output assuming a constant quasiparticle loss rate, extract the total charge after correction for losses and display it as a function of absorption location as shown in figure 6 [2]. Ignoring the ends where the trap overlaps the absorber and the collected charge is higher, the energy resolution over the full length of the absorber is 87 eV full width at half maximum (FWHM) for 6 keV x-rays. It improves to 54 eV FWHM, if only pulses from the region between +40 μm and +80 μm are considered. Based on the energy resolution, we can infer a spatial resolution of 1 μm over the entire absorber [2].

Immediately after the x-ray measurements we inject electronic pulses. Their shape is determined through numerical simulations of the detector response based on measured device parameters and matches both peak current and total charge of the x-ray induced pulses closely. We measure an amplifier noise of 13 eV FWHM. This agrees with a total standard deviation of

$$\sigma = \sqrt{\int (i_n^2 + (e_n^2 / Z_{in}^2))\, F(f)df} \qquad (1)$$

using the appropriate Butterworth filter function F(f) to determine the effective bandwidth and the measured baseline noise shown in Fig. 4. The electronic noise could be further reduced by cooling the relevant resistors and the JFET, or by using an input transistor with a higher transconductance per unit capacitance like the 2SK152. The shot noise contribution of the junction's dc bias current can be reduced either by lowering the junction temperature or reducing its area.

TABLE 1
PROJECTED CIRCUIT PERFORMANCE

Design modification	i_n [pA/√Hz]	e_n [nV/√Hz]	C_{in} [pF]	Resolution [eV]
Present setup	0.26	0.5	200	13
Cold resistors	0.1	0.5	200	5.3
10 x smaller jct.,				
Cold 2SK152	0.031	1.2	15	1.6
T = 0.1K	0.006	1.2	15	0.4

Table 1 summarizes the improvements in electronic resolution equation (1) predicts for future modifications of the circuitry, assuming that junction capacitances and dynamic resistances scale linearly with junction area and that leakage currents do not add more than 0.1 nA to the BCS value of the bias current. The current noise $i_n^2 = 2eI_{bias} + 4kT/R_F$ will be dominated by the shot noise of the bias current, the voltage noise e_n is set by the input FET and the input capacitance is given by $C_{in} = C_{jct} + C_{leads} + C_{FET}$. Table 1 shows how the electronic noise can be reduced below the detector's theoretical Poisson limited resolution of ≈3 eV. Furthermore, low electronic noise allows the use of these detectors for photon energies in the ultraviolet.

IV. SUMMARY

We have developed superconducting single photon imaging x-ray spectrometers, which have a resolution of 87 eV over an effective area of 160 µm by 100 µm, probably limited by quasiparticle losses in the absorber. The energy resolution improves to 54 eV if the area is reduced to 40 µm by 100 µm. The inferred spatial resolution is 1 µm over the entire absorber. These results were obtained using low noise current preamplifiers with a dc voltage bias. Their electronic noise is 13 eV FWHM for pulses corresponding to photon energies of 6 keV. Straightforward modifications can lower the noise by at least an order of magnitude such that the range of detectable photons can be extended into the ultraviolet.

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