NbN-Nb-Al Superconducting Tunnel Junctions as photon counting detectors

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Single photon detection at visible and X-ray wavelengths with Nb-Al Superconducting Tunnel Junctions

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Performance of a SQUID read-out system for Superconducting Tunnel Junctions

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Abstract: Superconducting Tunnel Junctions (STJs) have traditionally been read-out using low noise JFET based charge sensitive amplifiers. In some applications, low temperature SQUIDs could be used instead. The advantages are that the first amplification stage is also cooled to cryogenic temperatures and can be physically closer to the STJ, the detector can be voltage biased by means of a small fixed resistor and the detected current pulse shapes can be measured more directly. This work will outline the actual SQUID amplifier configuration and explain its virtues as well as its limitations.

1. INTRODUCTION

Superconducting Tunnel Junctions (STJs) have been extensively investigated as photon detectors covering the range from near-infrared to X-ray energies [1-3]. Conceptually, they consist of a three layer sandwich composed of two superconducting materials separated by a very thin insulator. Photon absorption in the superconducting material results in the excitation of bound Cooper pairs into quasiparticles. Detection is achieved by measuring the excess current induced by these quasiparticles. The average number of quasiparticles created in excess of any thermal population is directly proportional to the absorbed photon energy, $N_0 = E/\epsilon$. The average energy, ϵ , needed to generate one quasiparticle in Tantalum or Niobium, the commonest two superconductors used in our measurements, has been calculated to be $\sim 1.75\Delta$, where Δ is the superconductor's bandgap; 0.664meV for Ta and 1.5meV for Nb.

The advantage of STJs over conventional, e.g. semiconductor, detectors arises directly from the three orders of magnitude difference in bandgap. For an STJ based on Niobium or Tantalum the limiting intrinsic resolution for 6keV photons is predicted to be $\sim 4\text{eV}$ and $\sim 3\text{eV}$ respectively (full width at half maximum, FWHM) and depends upon the statistical fluctuations of the initial number of quasiparticles created in the absorption process. In practical applications, however, this resolution is limited by spatial non-uniformities, loss of quasiparticles, electronic noise and back-tunnelling [4]. The best resolution thus far achieved is 16eV (FWHM) for a highly collimated beam of 6keV photons incident on a $100 \times 100 \mu\text{m}^2$ Ta device if one quadratically subtracts the electronics read-out noise [5].

The obvious drawback of STJs is the need to cool them to very low temperatures, typically one tenth of the superconductor's critical temperature T_c . Another problem is the high capacitance of the junctions which is a direct result of the thickness of the oxide barrier, of order 1nm.

2. JFET AMPLIFIERS

To date, most laboratories have used charge sensitive pre-amplifiers (CSA) with extremely low noise JFETs as the input stage. These transistors exhibit noise voltages below $1\text{ nV/Hz}^{1/2}$. This noise voltage is magnified by the input capacitance. Additional noise is generated by the STJ biasing circuit and feedback components in the CSA as well as shot noise from the bias current. The STJs require an extremely precise and low (few $100\mu\text{V}$) bias voltage with noise levels below $1\mu\text{V}_{\text{rms}}$; fluctuations in the bias voltage translate to changes in responsivity and degrade the detector's resolution. The signals are further amplified and filtered by a fast ($\sim 1.5\text{ }\mu\text{s.}$) and a slow ($\sim 15\text{ }\mu\text{s.}$) pulse shaping stage. Pulse amplitude and decay time are extracted from the peaks of these signals. For the measurement reported in the previous section, the electronic noise contribution to the spectral resolution was $\sim 5\text{ eV}$ (FWHM). Knowing that the 5895 eV photons ($\text{Mn K}\alpha$) produce an average measured charge of 1.25×10^8 electrons, which includes the STJ's internal amplification due to back-tunnelling, the equivalent noise charge (ENC) at the amplifier's input is about 10^5 electrons (FWHM). For our best measurements with optical photons, electronic noise is less than 5000 electrons (FWHM) due to the better optimization achievable in the amplifier's input stage.

2.1 Noise analysis

Three major noise components can be identified in a JFET based CSA [6]. The detector bias current is responsible for shot noise ($2qI$). In our applications, the bias currents are of order 1 nA which corresponds to $1.8 \times 10^{-14}\text{ A/Hz}^{1/2}$ white noise. The amplifier's feedback consists of a resistor in parallel to the integrating capacitor (avoiding amplifier saturation) which will also contribute to a white parallel noise component at the input node given by $4kT/R$. For X-ray measurements the resistor is $1\text{ M}\Omega$ and contributes a noise current density of $1.3 \times 10^{-13}\text{ A/Hz}^{1/2}$. The third source of noise is the JFET's input referred (series) voltage noise which has a white and a $1/f$ component. The white noise levels are of order $1\text{ nV/Hz}^{1/2}$. The series noise component is directly influenced by the input node capacitance. For large STJs, this noise source can become predominant.

The follow-on shaping stage generally consists of a differentiator and an n -stage integrator with time constant τ and is referred to as a Semi-Gaussian filter because of its impulse response shape. Its role is twofold: to optimize the signal-to-noise ratio by band-pass filtering and providing a short time-domain pulse to reduce the effects of pile-up.

The shaping stage leaves two degrees of freedom: its order ' n ' and the choice of time constant τ . The order is typically 3 or 4, increasing n further does not result in a significant increase in signal-to-noise ratio (SNR). The time constant's choice depends on the application. Increasing τ will increase the parallel noise contribution while decreasing it will increase the (white) series noise contribution to the ENC. There is usually an optimum value for which the noise levels off at a value determined by the $1/f$ contribution in the series noise. In our case, this optimum ranges from 3 to 20 microseconds.

3. SQUID PRE-AMPLIFIERS

For X-ray detection and large format STJ array read-out, SQUIDs are now being considered as a potential replacement for the JFET CSA preamplifier. SQUIDs combine the two physical phenomena of flux quantization in a closed superconducting loop and Josephson tunnelling.

Although several SQUID configurations could be used (RF, DC, DROS etc.) in combination with STJs, our focus has been on the commercially available high speed DC-SQUID from Hypres which was originally developed at NIST [7]. The DC-SQUID consists of two Josephson junctions connected in parallel in a superconducting loop. In order to suppress the junctions' hysteretic behaviour, they are shunted by very low valued resistors. If biased above the junctions' critical current, the SQUID presents a periodic voltage to flux relation as schematically shown in figure 1 (for details see for instance [8]). In the Hypres design, a series connection of 100 SQUIDs are coupled to a $0.3\mu\text{H}$ input coil and a smaller feedback coil. The series design has the advantage of being able to connect the SQUID array directly to a room temperature voltage amplifier eliminating the need for AC flux modulation with lock-in detection as well as an output flux transformer.

Lower noise current densities than those reported for the Hypres SQUIDs are achievable but those designs either lack the large bandwidth required for STJ current pulses or require much more sophisticated lock-in techniques, impractical for large format STJ array read-out. A typical current pulse is depicted in figure 2; risetime is of order 100ns, decay time ranges between 5 and 30 microseconds depending on the particular detector design and the peak value is of order $1\mu\text{A}$ for a 6keV photon. Although the feedback coil can be used in a closed loop configuration (flux locked loop technique) to increase linearity and dynamic range, we only use it to position the operating point in the middle of a $V-\Phi$ cycle for maximum amplification. The detector's peak current of about $1\mu\text{A}$ is well below the $5\mu\text{A}$ needed for reaching the maximum of the modulation curve ($V-\Phi$ curve, figure 1).

Figure 1: SQUID V vs. Φ characteristic

Figure 2: Typical current pulse from a 6keV photon absorbed in a Tantalum STJ.

3.1 SQUID Pre-amplifier configuration

The SQUIDs are coupled to the STJ as shown in figure 3 [9]. Resistor R_d and capacitor C_d model the detector. Typical values are 100kOhms and 900pF (100x100 μm^2 detector). Resistor R_2 effectively produces a voltage bias to the STJ. Its value should be low (compared to R_d) to provide good voltage biasing and low Johnson noise. Resistor R_1 forms in conjunction with the SQUID's input coil a low pass filter and should be tuned for an optimal damping of the L_{sq} - C_d circuit. Conflicting requirements arise here since R_1 should be small to provide sufficient low-pass filtering but at the same time high to reduce the effects of thermal noise. In our case it is designed to have a cut-off frequency of several MHz and a damping coefficient of 0.7. A typical design for a 100x100 μm^2 STJ detector with 900 pF capacitance would need R_1 to be 10 Ohms and R_2 5 Ohms. The resulting R-L-C filter has a cut-off frequency of 8 MHz and a damping coefficient of 0.85. The voltage noise induced by R_2 onto the STJ ($4.k.T.R_2.BW$) is $2.5 \times 10^{-8} \text{ V}_{\text{rms}}$ (at 0.3K) and is well below the specification. The noise current density generated by R_1 is $1.3 \text{ pA/Hz}^{1/2}$ (at 0.3K), which is less than the SQUID's noise. The detector's dynamic resistance has not been included in the calculations since its value is much larger than the other resistors involved.

The SQUID array is coupled to a room-temperature voltage amplifier followed by appropriate filtering and sampling. For a single STJ readout, a minimum of six wires are required; ground return, STJ bias resistor current, SQUID bias and read-out, feedback coil (flux bias) and the on-chip heater (flux detrapping). The number of connections per STJ to room temperature can be reduced for arrays, since the bias resistor R_1 and ground return can be shared amongst many STJs and all the SQUID heaters can be connected in parallel.

The advantages of the SQUIDs can be summarized as follows:

- the SQUIDs are coupled to the STJs by means of inductive transformers and, hence, the STJ current rather than the charge is measured. Since SQUIDs only exhibit parallel noise, the detector's capacitance doesn't play a direct role in the ENC and therefore these devices could be used in conjunction with large area, large capacitance junctions.
- SQUIDs need to be cooled to cryogenic temperatures as well and can be placed directly next to the STJs, avoiding the necessity of coupling the STJs to the first amplification stage by means of very long, and again capacitive, wires. These wires remain a necessity, of course, but will carry larger signals from a lower impedance source and be less sensitive to microphonic noise pick-up.
- The lower output impedance of the SQUID array will reduce the crosstalk between pixel wire connections to room-temperature for STJ array read-outs.
- STJ biasing is simpler since this can be achieved by current biasing a small fixed resistor located next to the STJ. Several STJs can actually be biased in parallel by the same circuit, drastically simplifying the circuitry for STJ array read-out.

Figure 3: SQUID amplifier circuit

Figure 4: ENC for different pulse decay times

3.2 Noise evaluation

For the present equivalent noise charge (ENC) calculations, we have considered the above mentioned design example for the $100 \times 100 \mu\text{m}^2$ detector.

The reported noise current of the SQUID array is $2 \text{ pA}/\text{Hz}^{1/2}$ with a $1/f$ corner frequency of 1 kHz . Actual noise performance depends however very significantly on the environment. The chips are enclosed in a superconducting Niobium shield and much care needs to be taken in the wire layout, minimizing flux coupling. The transfer function is about $2000 \text{ V}/\text{A}$ which implies an output noise voltage density of $4 \text{ nV}/\text{Hz}^{1/2}$. In order not to degrade the signals further, the follow-on amplifier therefore still needs to have a very low noise voltage.

In order to evaluate the equivalent noise charge at the input of the SQUID and compare it to previous results with traditional CSAs, we considered a SQUID amplifier followed by a voltage amplifier (gain A_1) and an n -stage integrator (shaper) with time constant τ_1 and DC-gain A_2 . In principle, a differentiator is not needed since the current amplifying SQUID replaces the integrating CSA. In a real application however, a high-pass filter needs to be implemented to reduce the effects of low frequency noise.

For analysis purposes, we only considered the SQUID's white noise of current density i_w . Our goal was to determine the optimum shaping time and compare this with ENC values obtained for JFET CSAs. Clearly, if we consider a Dirac impulse at the SQUID's input, the optimum shaping time would be as small as possible. However, the pulses from the STJ have finite rise and decay times. Since the rise times are at least an order of magnitude smaller than the decay times, we only considered the latter, τ_0 . The output voltage's Laplace transform for a single electron charge at the input is given by equation (1).

The rms noise voltage ($V_{n,o}$) at the output is given by equation (2). Total ENC is obtained by calculating the ratio of the noise voltage to the peak of the inverse Laplace transform of (1).

$$V_o = A_1 \cdot A_2^n \cdot R_{sq} \cdot \left(\frac{1}{1 + s \cdot \tau_1} \right)^n \cdot \frac{e}{1 + s \cdot \tau_0} \quad (1)$$

$$|V_{n,o}|^2 = A_1^2 \cdot A_2^{2n} \cdot R_{sq}^2 \cdot \int_0^\infty |i_w|^2 \cdot \left| \frac{1}{1 + j \cdot 2 \cdot \pi \cdot \tau_1 \cdot f} \right|^{2n} \cdot df \quad (2)$$

The ENC (FWHM) has been calculated for a noise current density of 2pA/Hz^{1/2} and different pulse decay times. The results as a function of shaping time (τ_1) are plotted in figure 4 and summarized in table 1. The table gives the minimum ENC in electrons (FWHM) and the corresponding optimum shaping time for each of the pulse decay times considered (τ_0). No major improvement over the JFET CSA can be observed. A real advantage for SQUIDs could occur if the detector's capacitance is larger than 70nF (900x900 μ m² STJ), in that case, the white voltage noise of the JFET by itself would induce an ENC equal to 10⁵ electrons. On the other hand, the SQUID amplifier is very tolerant with regard to detector leakage currents since a 12 μ A current is required to reach the SQUIDs 2pA/Hz^{1/2} white noise floor.

Table 1: Minimum ENC for different τ_0

ENC min (e)	τ_1 at min (μ s.)	τ_0 (μ s.)
< 4.3x10 ⁴	< 1	0.5
< 4.9x10 ⁴	< 1	1.0
< 6.1x10 ⁴	< 1	2.0
8.5x10 ⁴	1.3	4.0
1.2x10 ⁵	2.9	8.0
1.7x10 ⁵	5.5	16.0

4. CONCLUSIONS

DC-SQUIDs have been considered as a replacement of the traditional JFET CSA as preamplifiers for STJ detectors. The complexity involved with their shielding and our noise calculations reveal that currently available DC-SQUIDs are not competitive compared to low noise JFETs for our applications. However, with the advent of SQUIDs with <1pA/Hz^{1/2} noise current densities and in conjunction with very large and/or leaky detectors, SQUIDs could become the elements of choice.

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