SQUID READOUT
OF
CRYOGENIC PARTICLE DETECTORS

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0. Abstract

Cryogenic radiation and particle detectors are widely investigated nowadays. Their high intrinsic energy sensitivity makes them suitable for a wide range of applications. In order to take full advantage of the sensitivity of these newly developed cryogenic detectors, in general current sensors are needed with a white noise level of the order of 10^{-12} A/√Hz and a bandwidth larger than 1 MHz. We applied a Double Relaxation Oscillation SQUID (DROS) as a low-noise current preamplifier for measuring the current-voltage characteristics of a superconducting Nb/Al-AlO$_x$/Al/Nb Josephson tunnel junction. A white current noise level smaller than 2 pA/√Hz was obtained. Thanks to the large flux-to-voltage transfer of a DROS (typically 1 mV/ϕ_0), no modulation techniques are required, allowing simple room-temperature flux locked loop electronics. Since the Josephson junction was voltage biased, no magnetic field had to be applied to suppress the Josephson supercurrent, which eliminates distortion of the subgap I-V characteristics by Fiske resonances. The measurements show that a DROS is a serious alternative for the high resolution readout of an X-ray spectrometer based on a superconducting tunnel junction.

Keywords : superconductivity, SQUID, superconducting tunnel junction, particle detector

1. Introduction

Present state of the art particle and radiation detectors, like gas proportional counters, dispersive techniques using Bragg single crystals or grating spectrometers and semiconductor-based detectors all suffer from either a lack in sensitivity, a small quantum efficiency or a narrow energy band of operation. A detector performing well in all three aspects might be obtained using superconducting tunnel junctions (STJs). Theoretically, STJ-based cryogenic sensors [1] are well suited for a wide scope of applications requiring an energy sensitivity of $\Delta E/E \leq 1$ ‰ within an energy band ranging from 0.1 to 10 keV. Exemplary fields of application are in astrophysics for detection of optical, UV and X-ray radiation and in condensed matter research for Energy Dispersive X-ray analysis (EDX).

For operation as a particle or radiation detector, an STJ is voltage biased in the subgap, $V < V_g$, of its *I-V* curve (see fig. 1). Absorption of an incident photon in either the top or the bottom electrode of the STJ results in a rise of the subgap current, which lasts no longer than about 5 µs. The magnitude of the current pulse, typically of the order of 1 µA, is a measure for the energy deposited by the absorption of the photon. To exploit the full potential of the STJ-based spectrometer a current sensor with a bandwidth larger than 1 MHz and an input current noise of the order of 10^{-12} A/√Hz [2] should be applied as preamplifier. Moreover, the

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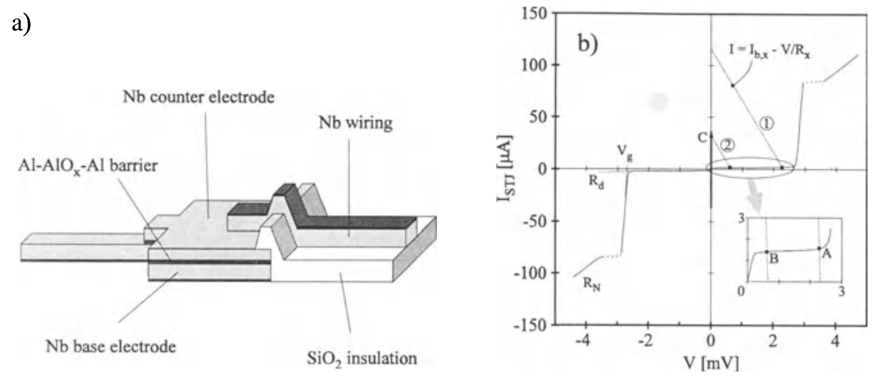

Figure 1. *a) Schematic view of a superconducting Nb/Al-AlOx/Al/Nb Josephson tunnel junction. b) The current voltage characteristic of the 10 x 10 μm^2 Josephson tunnel junction as measured by current biasing with standard electronics. A magnetic field was applied to suppress the critical current while recording the subgap.*

intrinsic resistance of the sensor should be as small as possible in order to obtain optimum voltage biasing of the STJ.

In principle, by applying a Superconducting QUantum Interference Device (SQUID) one can fulfill these demands. At present, SQUIDs are the most sensitive magnetic flux sensors available. The relative simplicity with which numerous physical quantities, amongst which current and voltage, can be transformed into a magnetic flux makes SQUIDs of interest for a broad range of applications far beyond the scope of direct magnetic field sensing. However, in most common dc SQUID systems, the bandwidth is limited to about 100 kHz. This restricted bandwidth is caused by the traditional dc SQUID readout scheme which is based on flux modulation, step-up transformers between SQUID and pre-amplifier and lock-in detection of the SQUID output voltage. Such a complex readout scheme is necessary because of the small flux-to-voltage transfer of standard dc SQUIDs. Direct voltage readout with a room-temperature amplifier would substantially decrease the sensitivity because of the noise of the pre-amplifier. Alternative SQUID types, such as SQUIDs with Additional Positive Feedback [3], series arrays of dc SQUIDs [2,4] or Double Relaxation Oscillation SQUIDs (DROSs) [5] have much larger flux-to-voltage transfer coefficients and therefore do not need modulated readout schemes, which allows straightforward room temperature voltage readout with a large signal bandwidth.

In the present work we present our preliminary measurements performed with an STJ coupled to the input coil of a gradiometric DROS. With this setup we recorded the subgap *I-V* characteristic of a voltage biased STJ in the temperature range between 4.2 K and approximately 1.6 K in order to demonstrate the feasibility of DROSs as current readout sensors for STJ-based X-ray spectrometers.

2. Experimental setup

The experimental setup is depicted in fig. 2. A 10 x 10 μm^2 superconducting tunnel junction was placed in series with the input coil of a gradiometric DROS. The main parameters of the DROS are listed in table I; detailed information about the DROS and its readout electronics has been published by van Duuren *et al.* [6] Since so far only low

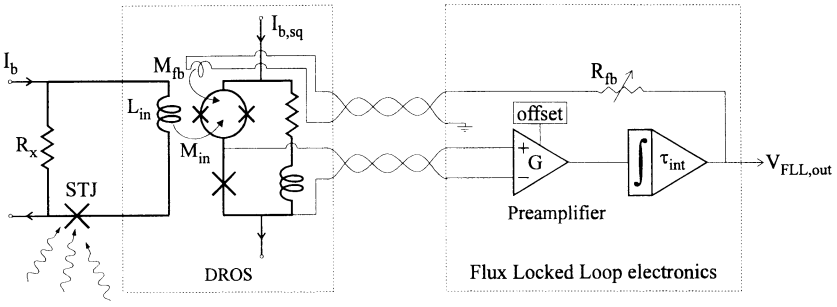

Figure 2. *Experimental setup for readout of superconducting tunnel junction with a Double Relaxation Oscillation SQUID.*

frequency I-V measurements have been performed, our current flux locked loop electronics with a bandwidth of only 100 kHz sufficed; for future X-ray spectroscopy experiments faster electronics is currently being developed.

The high quality STJ was fabricated on a thermally oxidized 2" silicon wafer, using standard Nb/Al technology. First, a Nb/Al-AlO$_x$/Al/Nb trilayer was deposited by dc magnetron sputtering and *in situ* oxidation of the first Al layer for one hour at an O_2 pressure of 10 mbar. The junction area of 10 x 10 μm^2 was defined by reactive ion etching in an SF_6 plasma. Insulation of the bottom electrode and the barrier was obtained with an RF magnetron sputtered SiO_2 layer. Finally, the top electrode of the junction was connected with a dc magnetron sputtered Nb wiring layer. The junction's current-voltage characteristics, recorded at 4.2 K with standard electronics, is shown in fig. 1b. At 4.2 K, the critical current of the junction I_0 was 37 μA. The gap voltage V_g was 2.8 mV and the normal resistance R_N was 42 Ω. Hence the critical current density of the junction J_c was 37 A/cm^2. The quality parameter of interest for application of STJs as radiation and particle detectors is the ratio between the dynamic resistance in the subgap, $R_d = \partial V/\partial I$ at $V = 2$ mV, and the normal resistance R_N. The R_d/R_N ratio for this junction was about 10^4.

Voltage biasing was obtained using a shunt resistor $R_x = 1.5\ \Omega$, satisfying the condition $R_x \ll R_d$. The principle of the voltage biasing circuit is illustrated in the I-V graph of fig. 1b.

Signal SQUID			
L_{sq}	(signal SQUID inductance)	~ 550	pH
2 x 25 turns integrated input coil			
L_{in}	(input coil inductance)	150	nH
M_{in}	(coupling input coil ↔ SQUID)	6.7	nH (k ≈ 0.75)
f_{RO}	(relaxation frequency)	~1	GHz
$\sqrt{S_\Phi}$	(white flux noise)	5 .. 6	$\mu\Phi_0/\sqrt{Hz}$
$\sqrt{S_I}$	(=$\sqrt{S_\Phi}/M_{in}$, current noise)	< 2	pA/$\sqrt{Hz}$
ε	(=$S_\Phi/2L_{sq}$,energy resolution)	~ 200	h
$\partial V/\partial\Phi$	(flux-to-voltage transfer)	1	mV/Φ_0 typically

Table I. *Main parameters of the DROS.*

The intersections of the loadline of R_x and the I-V characteristic of the junction represent stable operation points. For bias currents $I_{b,x} > I_o$ (loadline 1 in fig. 2), only one stable point ("A" in the inset) exists, and the junction is effectively voltage biased at a voltage equal to $V_{bias} = I_{b,x} \times R_x$. For bias currents $I_{b,x} < I_0$ (loadline 2), two stable points exist: one in the subgap of the junction, and one in the superconducting state (points "B" resp. "C"). In this case the junction can switch from the voltage state to the superconducting state. As a consequence, stable voltage biasing in the subgap is obtained only for voltages $V_{bias} > V_{min} = I_o \cdot R_x$ in which case $I_{b,x} > I_0$.

It is not possible to bias the junction at a voltage below its minimum return voltage V_{return}, typically some hundreds of microvolts, even for very small bias resistors R_x. At voltages below V_{return} the junction will switch to the superconducting state. If $I_0 < I_{b,x} < V_{return} / R_x$, the bias circuit will act like a relaxation oscillator [7]. Because of these relaxation oscillations, the current through the junction oscillates between I_0 and (almost) zero, while the junction voltage oscillates between V_g and zero. The frequency of these oscillations is mainly determined by the time constant L_{in}/R_x. In the present setup, this time constant amounts to about 100 ns, implying a relaxation frequency of around 10 MHz.

3. Measurements

Experimentally, the relaxation oscillation effect at low voltages as described in section 3 could be observed in two ways: first, at a voltage between 100 and 200 mV, the $I_{b,x}$-V characteristic showed a discontinuity, marking the transition from the oscillating mode

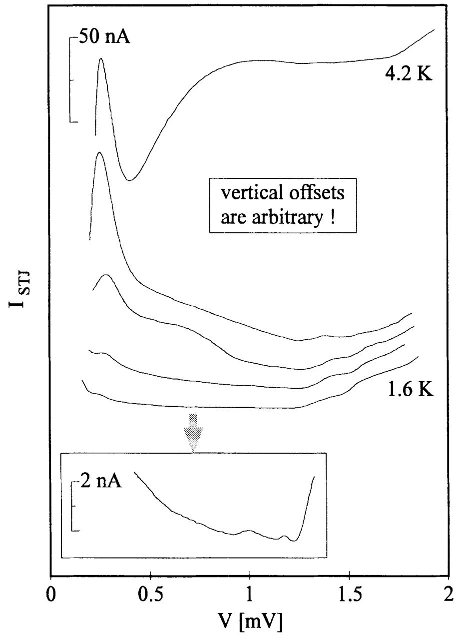

Figure 3. *Current-voltage characteristics of the Josephson junction at several temperatures with the presented setup. The temperature was varied by controlling the pressure above the helium bath. No magnetic field was applied. The inset shows an enlargement of the 1.6 K trace.*

to the stable mode. Second, at bias voltages between zero and ~ 150 mV, the DROS's V-Φ modulation disappeared completely, since the relaxation oscillations in the bias circuit sweep the input flux of the DROS over a range of more than 100 Φ_0 at a frequency of about 10 MHz, which wipes out the V-Φ modulation. At bias voltages $V_{bias} > V_{return}$, typically a few hundreds of microvolts, no relaxation oscillations can occur, and stable voltage biasing of the STJ is possible.

The subgap I-V characteristics of the STJ, measured in a helium-4 bath cryostat at different temperatures, is shown in fig. 3. Since a SQUID system in flux locked loop mode only measures flux changes, and not absolute values, the vertical offsets in the graph are arbitrary and different for each trace. An absolute zero could not be obtained since as soon as V_{bias} drops below either V_{return} or V_{min} the SQUID loses its flux locking.

Thanks to the bias circuit, no magnetic field was needed to suppress the Josephson current of the STJ, and hence the subgap structures are not obscured by Fiske resonances. As the junction is voltage biased, also the parts of the I-V trace with negative conductance $\partial I/\partial V$ could be measured. The peak at 260 μV in the 4.2 K trace is caused by the difference of 0.26 meV between the gap energy in the top and the bottom electrode of the STJ. The sensitivity of the DROS is demonstrated in the inset of fig. 3, which shows an enlargement of a part of the 1.6 K trace. Small structures of less than 1 nA are revealed, and the sharp rise of the subgap current at a voltage corresponding to half the gap voltage is evident [8].

4. Conclusions

We realized a measurement system for characterization of the subgap I-V characteristic of tunnel junctions based on a DROS. After upgrading of the present flux locked loop electronics to a larger bandwidth, the system is suitable for application in the field of particle detection. The sensitivity of the DROS, 2 pA/√Hz, will make readout of particle detectors with a spectral resolution of $\Delta E/E < 1$ ‰ attainable [2]. Further optimization of the input circuitry of the DROS for the readout of particle detectors or the introduction of an intermediate transformer could significantly improve the sensitivity.

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