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A. Sosso · M. Fretto · V. Lacquaniti · E. Monticone · R. Rocci · D. Serazio · B. Trinchera

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Abstract Cryogen-free operation of is essential to spread applications of superconductivity and is indeed unavoidable in some cases. In electrical metrology applications higher temperature operation to reduce the refrigerator size and complexity is not yet possible, since arrays of Josephson junctions for voltage standard applications made with high temperature superconductors are not yet available. The SNIS technology developed at INRIM uses low temperature superconductors, but allows operation well above liquid helium temperature. It is thus interesting for application to a compact cryocooled standard.
We studied SNIS devices cooled with a closed-cycle refrigerator, both in DC and under RF irradiation. Issues related to thermal design of the apparatus are analyzed. The dependence of RF steps on the number of junctions observed is discussed in detail and interpreted as a consequence of power dissipated inside the chip.

Keywords Josephson Junctions and SQUIDS · Superconductor Circuits and Systems · Techniques · Instrumentation for Electronics Applications

1 Introduction

Josephson effect application to voltage metrology dates back to a few years after the discovery of the physical phenomenon, and still represent one of the most complex and successful achievement in superconducting electronics. To achieve the output level required for quantum standards, a great effort was spent in research and development. Following an idea by Levinsen [11], hysteretic Superconductor-Insulator-Superconductor (SIS) technology was successful adopted to fabricate arrays with tens of thousands of highly uniform junctions, generating up to 10 V.

A. Sosso · M. Fretto · V. Lacquaniti · E. Monticone · R. Rocci · D. Serazio · B. Trinchera
INRiM – Istituto Nazionale di Ricerca Metrologica
Strada delle Cacce 91, 10135 Torino, Italy
Tel: +39 011 39191
Fax: +39 011 3919448
E-mail: a.sosso@inrim.it

Primary DC voltage calibrations at 10 V now attain relative uncertainties as low as 10^{-11}.

More recently [4], voltage standard research has focused on the application of Josephson arrays to AC (programmable) and arbitrary signals [5] (pulsed). Programmable Josephson arrays using bias currents to activate/deactivate array sections are so far the most successful solution. They are subdivided in sub-circuits with series connected junctions to generate voltages following a power of two sequence, thus controlling the output voltage as in digital to analog converters of semiconductor electronics. This is not the case for SIS junctions used in DC standards, were steps are overlapping.

High noise immunity, low power dissipation, reduced dimensions are essential for primary metrology. First, the critical current I_c, which sets an upper limit on the amplitude of the steps, should be large for noise immunity, yet a too high value increases dissipation. For proper signal to noise ratio, critical currents at least at the mA level are required. The area of the junction must be small to reduce array dimensions, but avoiding the difficulties of sub-micron patterning. Presently, I_c values ranging from few kA to tens of thousands kA/cm^2 appear to be the best choice. The characteristic voltage, V_c sets the microwave optimal frequency ($f_d = V_c\,2e/h$) and thus the step voltage and the number of junctions needed to achieve the highest voltage. Frequencies close to 70 GHz (V_c around 150 µV) are a good compromise to limit microwave sources cost with a feasible number of junctions in the chip [4].

1.1 Towards an helium-free standard

Cryogen-free operation of superconducting devices is becoming crucial to widespread the applications of superconductivity [3] and bears a special interest for Josephson standards, owing to the potential impact of a new generation of voltmeters with integrated quantum accuracy. Yet, nowadays cryocoolers suitable for low temperature superconductors operation are expensive, weighty and far from integration inside an instrument case. On the other side, large arrays fabricated with higher critical temperature superconductors, like YBCO or the more recent MgB_2 [2], are not available up to now. The most interesting results so far have been achieved using YBCO bi-crystal shunted junctions, with quantized steps above 100 mV measured near 77 K [14].

A relevant issue is thus the operation above 4.2 K of junctions based on low temperature superconductors. NbN/TiN/NbN have demonstrated operation at notably high temperatures, achieving a sound result such as a 11 bit DAC with 20 V output at 10 K [15]. However, they require temperature stabilization within 0.1 K and have a strong demand on both power and fabrication process. The temperature stability needs can be relaxed if temperature variations effects on junction behaviour are reduced. This is of interest in applications where a simplified refrigerator is useful such as RSFQ and voltage standards [1]. The other technologies that look promising above 4.2 K, Nb/Nb_xSi_{1-x}/Nb (SNS) and Nb/Al-AlO_x/Nb (SNIS: Superconductor-Normal metal-Insulator-Superconductor) junctions, both allow to engineer the electrical properties of the barrier over a wide range of values by a suitable control of the fabrication parameters. An outstanding 20 V output level was recently reported with Nb/Nb_xSi_{1-x}/Nb arrays [12]. The authors also

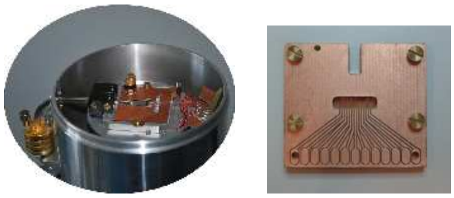

Fig. 1 Cold head, including waveguide, and thermometer. On the right the sample holder

discuss the interest for cryocooler operation of the low power dissipation exhibited by such arrays when $I_c < 3\,\mathrm{mA}$ without sacrificing step width. However, an experimental study of cryocooler operation hasn't yet been published.

The SNIS junction technology, based on low temperature superconductors but capable of operation above liquid helium temperature, is interesting for application to a cryocooled standard, allowing to set a compromise between device and refrigerator requirements.

2 SNIS technology

A specific feature of SNIS junctions is the possibility of achieving high values of current densities (up to $0.5\,\mu\mathrm{A}/\mu\mathrm{m}^2$) and characteristic voltages (up to 0.7 mV at 4.2 K). It is then possible to fabricate junctions with dimensions below $1\,\mu\mathrm{m}^2$, with critical currents in the mA range, which ensures that the Shapiro steps with suitable amplitude can be obtained along with a reduced chip area [8].

The specific normal conductance of these devices, ranging from $0.3 \times 10^{-8}\,\Omega\,\mathrm{cm}^{-2}$ to $0.7 \times 10^{-8}\,\Omega\,\mathrm{cm}^{-2}$, is of the same order of magnitude as in high-current-density single-barrier Josephson junctions.

In SNIS junctions, the subgap resistance R_{sg} observed at very low voltages is around $0.3\,\Omega$ at 4.2 K, i.e. comparable with the junctions resistance of normal state R_N [9]. Moreover, the highly transparent oxide guarantees reproducible barriers free from pinholes or other leakage mechanism [7].

The general explanation of the self-shunting phenomenon in high specific-conductance devices, can be found in the enhanced subgap conductivity. The same result has been verified in SNIS junctions.

The high value of V_c at 4.2 K is also beneficial for operation above liquid helium temperature, since the parameter scales down when the temperature is increased. An additional requirement is temperature stability of the electrical parameters above 4.2 K. For SNIS junctions, changing the Normal/Superconductor relative thickness in the Nb/Al first electrode, the temperature dependence can be properly tailored [6]. Experiments in helium vapor have proved that sufficiently wide quantized steps can be achieved up to 8.3 K with a single junction [8], and 0.25 mA wide on the 8192 junctions of the whole array (1.25 V) up to 6.5 K [10].

3 Experimental setup

Our system is based on a GM refrigerator with 1 W cooling power at 4.2 K. An additional disk was connected at the top of the cold finger, with a thermometer

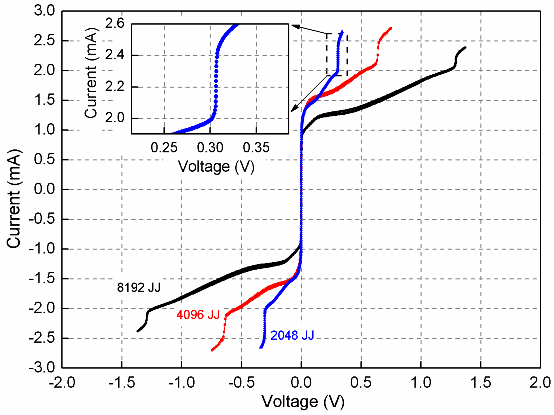

Fig. 2 Voltage steps measured on a binary-divided array with 8192 Josephson junctions irradiated nearly 74 GHz. The inset shows the detail of the quantized step.

inside and an heater wire wound around it, allowing to monitor and control the temperature. The chip under test is fastened to the copper sheet of a printed circuit board (PCB) with pads for soldering the wires and then bonded. Reliable cryocooler operation of a voltage standard necessitates a very specific thermal design to cope with problems like minimization of thermal gradients.

Thermal links to the outer environment can compromise the refrigerating effectiveness. Arrays are irradiated to generate quantized steps trough a microwave guide, whose heat load from the microwave guide must be limited. To that aim, a stainless steel guide was adopted. Gold plating allowed to reduce the dramatic signal attenuation due to the low electrical conductivity of stainless steel. Furthermore, the low power dissipation along the guide avoids unnecessary Joule heating. However, owing to the higher thermal conductivity of gold with respect to stainless steel, the thermal conduction of the thin plating layer is non negligible. A thermometer close to the chip was used to study the guide loading and thermal optimization.

At present, the devices can be cooled with the guide in place down to temperatures near 3 K in few hours. The temperature stability during the experiments is guaranteed by an active feedback loop, that maintains fluctuations within a few tens of millikelvin. No thermal oscillations related to cryocooler operation was detected from temperature measurement nor from the electrical behavior of junctions. A more detailed description of the measurement and cooling setup can be found in [13].

4 Results

The behavior of SNIS devices cooled with a closed-cycle refrigerator has been investigated, both in DC and under RF irradiation. We measured segments from 1 to 8192 junctions of SNIS arrays fabricated in cooperation with the Physikalisch Technische Bundesanstalt (PTB) [10] to evaluate the effect of the RF and DC dissipated power. The critical current densities ranged from 5 to 20 kA/cm^2 V_c from 250 to 500 µV. The operating temperatures were from 3.5 to 6 K.

Quantized steps were observed in segments with a low number of junctions up to temperatures well above 6 K, while, increasing the number of junctions an increase in the temperature of the sample holder was detected. This, and the reduced strength of electromagnetic shielding limited the step width, decreasing from 1 mA with 2 junctions to 0.1 mA with 8192 (Fig. 2).

5 Conclusions

The SNIS junction technology developed at INRIM with low temperature superconductors is capable of operation above liquid helium temperature. It is thus interesting for application to a cryocooled standard.

Experiments on SNIS arrays have been carried out in a cryocooler to study optimal operating conditions. Further tests are needed for increasing operation to a high number of series connected junctions. This requires to use devices with minimal temperature dependence of the electrical parameters and an improved measurement environment, with a better thermal exchange between the junctions and the cold finger.

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