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Highly precise comparison of Nb/Al/AlO$_x$/Al/AlO$_x$/Al/Nb Josephson junction arrays using a SQUID as a null detector

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Abstract

A direct comparison of two voltages at 0.6 V reproduced by programmable arrays with Nb/Al/AlO$_x$/Al/AlO$_x$/Al/Nb Josephson junctions was carried out using a SQUID as a null detector. The voltage difference was measured and found to be smaller than 1.2×10^{-17} V. Jumps of the current in the flux transformer loop can be attributed to phase-slipping events when the phase lock in the arrays is broken.

1. Introduction

Conventional Josephson junctions arrays based on superconductor–insulator–superconductor (SIS) Josephson junctions are used worldwide as basic Josephson effect voltage standards [1]. The precision of these voltage standards was checked by a comparison of two arrays at the 1 V level using an rf superconducting quantum interference device (SQUID) as a null detector [2]. The relative difference between the voltages was smaller than 2×10^{-17}. This method for comparison of single Josephson junctions was suggested by Clarke [3] and already used by others [4, 5] to establish the Josephson relation between voltage and frequency with an uncertainty of 2×10^{-16} for different types of Josephson junctions, and with an uncertainty of 3×10^{-19} for similar single superconductor–normal–superconductor (SNS) Josephson junctions. Meanwhile, new arrays of overdamped Josephson junctions with non-hysteretic current voltage (I–V) curves have been developed for programmable voltage standards [6–8]. The main difference from the previous experiment [2] is that we report the results of a comparison of two programmable superconductor–insulator–normal–insulator–superconductor (SINIS) series arrays with Nb/Al/AlO$_x$/Al/AlO$_x$/Al/Nb Josephson junctions, where the step voltage is defined just by the frequency f of the microwave generator and the number of Josephson junctions N in every array $V = Nf\Phi_0$, with $\Phi_0 = h/2e$ being the flux quantum defined as the ratio of the Planck constant h and the electron charge e. Furthermore, the steps are inherently stable and easy to adjust by the application of the appropriate current, but the stability of phase synchronization in the large series arrays of non-hysteretic Josephson junctions has never been measured with high precision.

2. Measurement set-up

Both arrays are in fact two halves of a 1–V array with nominally 8192 junctions. Due to some lithographic defects only 4086 junctions of each array contribute to the output voltage while ten junctions are shorted superconductively. The design of this novel circuit and the fabrication process have been described elsewhere [9]. The junctions are distributed symmetrical to the finline antenna along 64 striplines connected in parallel, each strip containing 128 junctions. The SINIS junctions have an area of 8 μm × 50 μm, a critical current of $I_c = 0.525$ mA, and a normal state resistance of $R_N = 0.19\ \Omega$, giving a critical frequency of $f_c = 2eI_cR_N/h \approx 50$ GHz. Upon irradiation with a microwave frequency $f = 72.845$ GHz, the first constant voltage step is developed at 0.615 V. The frequency of the Gunn oscillator has been phase-locked to a stable 10 MHz frequency reference using an EIP 578B frequency counter. The steps of both arrays are of a different width: for array 1 it is 100 μA, and for array 2 it is 500 μA at optimal microwave power. The measuring arrangement is shown in figure 1. The two SINIS arrays are biased to the middle of the steps by two current sources 1 and 2. The currents I_1 and I_2 are directed in such a way that the voltages are connected

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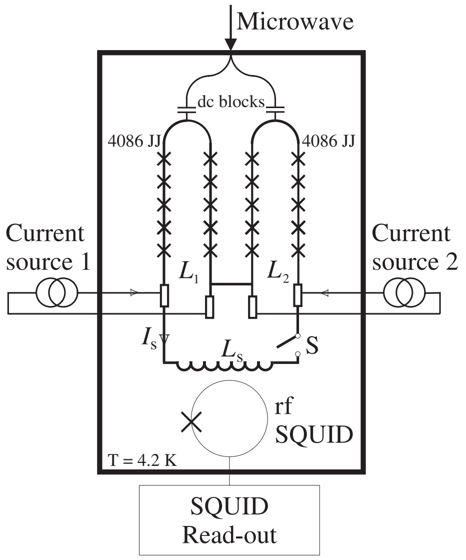

Figure 1. Arrangement for the comparison of voltages reproduced by two arrays of SINIS Josephson junctions using an rf SQUID as a null detector.

in a series opposition. For the measurements that have been carried out, the superconducting loop, including the signal coil of the commercial rf SQUID (*Cryogenics SCU 500*) was connected to the superconducting contact pads of the arrays by ultrasonic bonding of thin Nb wires to large Nb pads on a sapphire substrate, on to which the twisted Nb loop wires had been pressed. The current in the loop was sensed by the read-out electronics of the rf SQUID working in the usual flux-locked mode at a bandwidth of 1 Hz, which was maintained during all measurements. The output voltage was measured by a digital voltmeter and recorded by a computer.

To reduce the external flux noise the cryoprobe was placed into a ferromagnetic screen. In addition, the sample holder with the array and the SQUID were arranged in separate superconducting lead shields, while the twisted Nb wires of the loop were threaded into superconducting lead tubes. In spite of the careful shielding, the set-up was sensitive to mechanical shocks, indicating an ambient magnetic field that generates currents inside the loop when the loop is moved.

In order to adjust the currents, switch S (figure 1) was opened and the usual process of setting the array to a quantized voltage was performed. The SQUID parameters were adjusted so that the best *triangle characteristic* of the SQUID read-out could be observed on an oscilloscope. When switch S was closed, the period of the *triangle characteristic* of the SQUID read-out increased by ≈30%, because the coupling of the resonance circuit to the SQUID hole decreased due to screening by the superconducting transformer.

3. Measurements

The measurements were started 1 to 2 h after the cryoprobe had been stabilized in liquid helium, when mechanical stress and flux disturbance had relaxed to steady state. At the beginning of the measurement, the transient process due to the mechanical shock after closing of switch S was visible. Then, the disturbance relaxed and the main part of the recording consisted of flat regions of constant loop current I_s and jumps of small amplitude, as shown in figure 2. The output voltage of the SQUID was converted to the loop current; 1 μA corresponds to an output voltage of 21.5 V. Taking the longest flat region of this record that lasted for about 15 min, we estimated the minimal drift of the supercurrent in the loop to be $\mathrm{d}I_s/\mathrm{d}t = 6 \times 10^{-12}$ A s^{-1}. Such a drift rate can be related with a possible voltage difference of the arrays

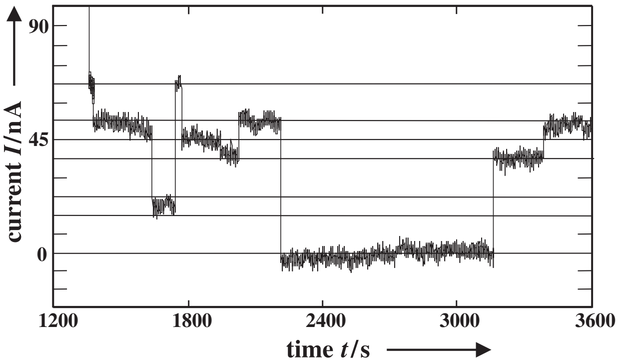

Figure 2. Recording chart of the SQUID output signal of two arrays at a step voltage of 0.615 V. The lines have been drawn to emphasize the possibly quantized behaviour of the jumps.

$$\Delta V = V_2 - V_1 = L_s\,\mathrm{d}I_s/\mathrm{d}t = 1.2 \times 10^{-17}\ \mathrm{V},$$

where $L_s = L + L_1 + L_2 \approx 2.1$ μH is the inductance of the superconducting loop, that is dominated by inductance $L \approx 2$ μH of the SQUID's signal coil. L_1 and L_2 are parasitic inductances associated with the interconnection wires.

The jumps of the current in the recording represented in figure 2 can be induced only by a flux movement in the measuring loop, as the change of one Φ_0 in the feedback circuit of the SQUID corresponds to a change of the loop current by 0.13 μA. Here it is important to note that such jumps were never observed in the recordings made at 0 V with small currents biasing the $n = 0$ ($I < I_c$) step. This means that these jumps might be attributable to phase-slippage events in the Josephson arrays. When the phase lock of the Josephson junctions to the microwave signal is broken for a short time, flux enters, or comes out of the loop. The statistics of such runs made with two different combinations of current sources shows that, during a 1-h run, approximately 10–15 jumps such as those visible in figure 2 occur. The amplitude of a jump most frequently observed is $\Delta I_s \approx 0.040$–0.050 μA. This value corresponds to a change of the flux $\Delta\Phi = L_s \Delta I_s \approx 40$–$50$ Φ_0 in the loop.

4. Discussion and conclusions

The stability of the phase lock in overdamped Josephson junctions was discussed theoretically [10]. As we operated our junctions at a relative frequency of $f/f_c \approx 1.45$, the phase lock should be stable. However, in SINIS arrays with more than 200 junctions, self-irradiation of Josephson junctions embedded in the strip line plays an essential role in the formation of the steps observed [11]. The stability of the phase lock in SINIS arrays could be reduced if the frequency of the external microwave generator was not equal to the frequency of an internal resonance inside the system of Josephson junctions coupled into the microwave stripline. This problem is very interesting from the viewpoint of physics, and the SQUID-based technique is adequate for further investigations into the stability of phase lock in SINIS arrays.

Besides the voltage difference between two arrays there are some parasitic effects that might be the reason for a change of the loop current. It is unlikely that all these effects can compensate one another so that the flat regions visible in figure 2 can be observed for a long time. Possible sources for a change of the loop current can be derived from the equation of flux quantization in the superconducting loop [2]:

$$\begin{aligned} &L_s I_s + L_1(I_1 + I_s) - L_2(I_2 - I_s) + \Phi_{\text{ext}} \\ &\quad + (\Phi_0/2\pi)\sum_{j=1}^{N}(\phi_{1j} - \phi_{2j}) = m\Phi_0 \qquad (1) \end{aligned}$$

where Φ_{ext} is the external magnetic flux, ϕ_{1j}, ϕ_{2j} are the phases of the jth junction in arrays 1 and 2 and m is an integer number. The influence of the external magnetic flux is difficult to estimate, but it should be negligible as no changes of the loop current were observed for hours at 0 V.

The last term on the left side of the equation describes the sensitivity to a change of the microwave phase and amplitude in the stripline of the arrays. Due to the symmetrical design of the power dividers and the ground plane, which covers both arrays, the phase difference between the microwaves in the two arrays should be very small and stable during the measurements. The influence of a microwave power drift is expressed as the sensitivity of I_s to the microwave voltage V_{rf} [2],

$$|\mathrm{d}I_s/\mathrm{d}V_{\text{rf}}| < n(L_{1\text{J}} + L_{2\text{J}})I_c/NLV_{\text{rf}}$$

where n is the step number ($n = N$), and $L_{1\text{J}} = L_{2\text{J}} = N\Phi_0/\ 2\pi I_c \approx 2.6$ nH the respective Josephson inductance of each array. If we assume a typical drift of Gunn power of $\mathrm{d}V_{\text{rf}}/\mathrm{d}t \approx 0.3\%\ \text{h}^{-1}$, we can estimate a current drift of $\mathrm{d}I_s/\mathrm{d}t \approx 1.2\ \text{pA s}^{-1}$ that is about five times smaller than the observed drift.

The reason for the observed drift of $\mathrm{d}I_s$ could also be a drift of both current sources 1 and 2, because the noise and the drift of the SQUID read-out were by an order of magnitude smaller when the currents through the array were switched off. The sensitivity of the measuring set-up to a change of the loop current was checked by changing the current $I_1 = 1098\ \mu$A in steps of 1 μA. The corresponding change of loop current I_s is 0.026 μA. From equation (1), $\mathrm{d}I_s/\mathrm{d}I_1$ can easily be deduced to be

$$\mathrm{d}I_s/\mathrm{d}I_1 = (L_1 + L_{1\text{J}})/(L_s + L_1 + L_{1\text{J}} + L_2 + L_{2\text{J}}).$$

We estimate for our array that $L_1 + L_{1\text{J}} \approx 1.3 \times 10^{-8}$ H and hence $\mathrm{d}I_s/\mathrm{d}I_1 \approx 6.5 \times 10^{-3}$, a value four times smaller than that measured. However, as a result of the large open area of $\approx$1 cm^2 of untwisted leads connected to the contact pads, extensive inductive coupling from the current sources to the superconducting loop takes place, which might be responsible for this discrepancy. The drifts of the current sources were separately quantified and found to amount up to 400 pA s^{-1} depending on the condition of the batteries. As the drift of both sources compensates itself in the first order, an estimation is difficult. Nevertheless, a drift by 300 pA s^{-1} is quite possible. This would result in $\mathrm{d}I_s/\mathrm{d}t \approx 8\ \text{pA s}^{-1}$, a drift larger than that observed.

The measuring arrangement was checked by recording the SQUID output voltage when the current through array 1 was shifted by $\Delta I_1 = -100\ \mu$A down the step. In this case the superconductivity of the measuring loop is broken, flux conservation no longer exists, and $\mathrm{d}I\text{s}/\mathrm{d}I_1$ must be of the order of unity. A large rise of the SQUID signal appears because the flux-locked loop of the SQUID is suspended. After some minutes, the operation of the SQUID is restored and an exponential transition of the output to a new value voltage is observed. Such a behaviour can be explained as follows: when the current through array 1 is shifted from the step, a large voltage difference arises in the circuit. This voltage difference results in a loop current I_s that is taken from current source 2. The current through array 2 therefore decreases ($I_2 - I_s$), whereas the current through array 1 increases ($I_1 + I_s$). As the step width of array 2 is large enough, array 2 is still on the step while array 1 is returning to the step. As the resistance r close to the step of array 1 is small near the step, the relaxation has a large time constant L/r. The process stops when array 1 is back on the step and the superconducting loop is restored. Both arrays now are on the step; only the flux is frozen in the loop and current $I_s \approx 50\ \mu$A circulates in the loop.

In conclusion, the difference voltage between two programmable Josephson arrays of SINIS junctions which are phase-locked to a voltage step at about 0.615 V by a single microwave generator, is smaller than 1.2×10^{-17} V as measured by a SQUID-based null detector. Jumps of the current in the superconducting loop can be attributed to phase-slippage events, when the phase lock is broken by noise. The last phenomenon will be studied in more detail in the future.

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