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Underdamped Josephson junction as a switching current detector

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We demonstrate the narrow switching distribution of an underdamped Josephson junction from the zero to the finite voltage state at millikelvin temperatures. We argue that such junctions can be used as ultrasensitive detectors of the single photons in the GHz range, operating close to the quantum limit: a given initial (zero voltage) state can be driven by an incoming signal to the finite voltage state. The width of the switching distribution at a nominal temperature of about $T = 10$ mK was 4.5 nA, which corresponds to an effective noise temperature of the device below 60 mK. © *2013 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4824308]

Nowadays ultrasensitive sensors, based on superconducting materials, are widely used in the various fields of science and applications, including the detection of electromagnetic signals close to the quantum limit.[1] In particular, circuit quantum electrodynamic components,[2] which apply for microwave quantum engineering, require such type of detectors for information processing devices.[3] It is quite natural to optimize switching properties of a current-biased Josephson junction[4] (CBJJ) and utilize it as a microwave detector. In this letter we demonstrate similar detector with a noise temperature below 60 mK.

The CBJJ is a device in which the Josephson phase variable is trapped in a washboard potential. Modulation of the potential tilt or a radiation field can lead to an escape of the "particle" from the well, which corresponds to a voltage drop over the CBJJ.[5,6] This switching can also occur due to thermal activation (TA)[7–9] and due to macroscopic quantum tunneling (MQT).[10]

Quantitatively, the dynamics of a CBJJ can be described by a fictitious phase particle of mass $M = C(\Phi_0/2\pi)^2$ and damping coefficient $1/RC$ moving along the generalized coordinate φ in a washboard potential

$$U(i,\phi) = -E_J(i\phi + \cos\phi), \tag{1}$$

where R and C are the effective shunt resistance and capacitance of the junction, respectively, Φ_0 is the magnetic flux quantum, $E_J = I_c\Phi_0/2\pi$ is the characteristic scale of the Josephson energy, and $i = I/I_c$ is the normalized bias current. If thermal and quantum fluctuations are absent and the bias current is smaller than the critical one $i < 1$, the junction is in the zero-voltage state, so the corresponding phase particle is located in the potential well with the barrier height given by

$$\Delta U(i) = 2E_J[\sqrt{1-i^2} - i\arccos(i)] \tag{2}$$

and the oscillation frequency of the particle at the bottom of the well

$$\omega_0 = \sqrt{\frac{\partial^2 U/\partial^2\phi}{M}} = \omega_p(1-i^2)^{1/4}, \tag{3}$$

where $\omega_p = \sqrt{2\pi I_c/\Phi_0 C}$ is the plasma frequency. For $i < 1$ and finite temperatures $T > 0$, the particle may escape from the potential well either by thermal activation or by macroscopic quantum tunneling, resulting in the junction's switching from the zero to the finite voltage state. At high temperatures the escape of the particle from the well is mainly due to thermal activation processes, and its rate can be found from Kramers formula[11,12]

$$\Gamma_t = \frac{\omega_0}{2\pi} a_t \exp\left(-\frac{\Delta U}{k_B T}\right), \tag{4}$$

where $a_t = 4/(\sqrt{1 + Qk_BT/1.8\Delta U} + 1)^2$ is a temperature and damping dependent thermal prefactor, and $Q = \omega_0 RC$ is the quality factor. For even larger temperatures or for bias currents approaching the critical current, when the condition $\Delta U \gg k_B T$ is not fulfilled and the Kramers formula can not be applied, one can resort to a more general expression.[13] For smaller temperatures T, the quantum tunneling becomes dominating over thermal activation. In the MQT regime the escape rate is given by[14,15]

$$\Gamma_q = \frac{\omega_0}{2\pi}\sqrt{\frac{B}{2\pi}}\exp(-B), \tag{5}$$

with $B = \frac{\Delta U}{\hbar\omega_0}[7.2 + 8A/Q]$. The second term in B represents the dissipative corrections, where A is a numerical factor. These corrections are particularly important for low-current-density Josephson junctions.[15,16]

The temperature at which the system passes from the MQT to the TA regime is called the crossover temperature[17]

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$$T_{cr} = \frac{\hbar\omega_0}{2\pi k_B}\left[\sqrt{1+\left(\frac{1.2A}{2Q}\right)^2} - \frac{1.2A}{2Q}\right]. \tag{6}$$

For a Josephson junction this temperature is equivalent to the noise temperature[18] of a switching current detector. Note, additionally, that increase of dissipation lowers T_{cr} in Eq. (6) and diminishes quantum tunneling effects in Eq. (5) (T_{cr} is the decaying function of $1.2A/2Q$).

In the adiabatic approximation (see, e.g., Ref. 19), i.e., when the bias current variation is slow in comparison with characteristic time scales of the system, the probability for the particle to escape from the well and therefore to generate a voltage drop for current $i(t)$ is

$$P(i) = \exp\left[-\frac{1}{\partial i/\partial t}\int_0^i \Gamma(i')di'\right]. \tag{7}$$

The escape of the Josephson tunnel junction phase is investigated experimentally by measuring its switching statistics from the zero-voltage state to the finite voltage state. The so-called switching current probability distribution $W(I) = \frac{\partial P(i)}{\partial i}\frac{1}{I_c}$ is found by averaging over a large number of measurements of the switching current I_{SW} and generating a histogram.

The sample, a current-biased Josephson junction, was fabricated using the 30 A/cm^2 process at VTT, Finnland.[20] A small current density was chosen to reduce the heating power connected to switching of the junction into the voltage state and therewith heating of the sample. The junction consists of a NbAlO$_x$ Nb trilayer and has a nominal capacitance of $C \approx 0.33$ pF and a total damping resistance of $R \approx 0.44\,\mathrm{k}\Omega$. The sample was thermally anchored to the base of a dilution refrigerator, providing a minimal temperature below 10 mK and enclosed by both, a mu-metal and superconducting shielding. Further penetration of noise to the sample was avoided by the use of filtered twisted-pair lines in a four point measurement design for the connection of the junction to the measurement devices. An *RC*-filter with cut-off frequency of 10 kHz at the 4 K stage together with a *LC*-filter with similar cut-off and a copper-powder filter both at base temperature stage were used. The switching current distributions of the sample were measured at bath temperatures T between 10 mK and 1000 mK. The current was ramped up by the following law: it is set in steps of $\Delta I = 0.1\,\mathrm{nA/ms}$ during 10 ms with a waiting time of 10 ms between steps.

In Fig. 1 the temperature dependence of the mean $\langle I_{SW}\rangle$ and the standard deviation σ of the switching current I_{SW} (symbols), together with the results calculated from the TA and MQT theories (curves) are shown. In the temperature range between 1 K and approximately 56 mK σ decreases with T indicating that TA is the dominant escape mechanism. In this temperature range, $W(I)$ depends weakly on C and R, so the critical current I_c can be determined by fitting $W(I)$ using the TA theory. In our case the I_c has a value of 2.2 μA. One can see that below the crossover temperature, σ demonstrates saturation at the level ~4.5 nA, meaning that the quantum tunneling through the barrier is the main mechanism of escape in this case.[21–24] The numerical factor

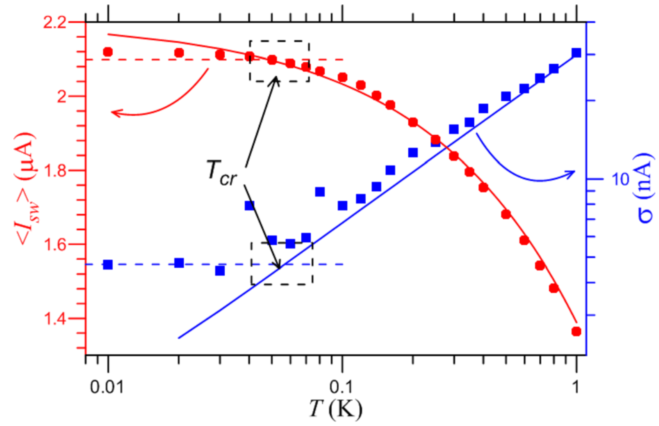

FIG. 1. The standard deviation σ (rectangular symbols) and the mean value $\langle I_{SW}\rangle$ (circular symbols) of the $W(I)$ distribution vs. the nominal temperature T of the mixing chamber of the dilution fridge. The solid curves mark the predictions from TA theory. Dashed lines—from MQT theory. The experimental MQT-to-TA crossover temperature T_{cr} around 56 mK is indicated.

A can be determined using $W(I)$ at this regime, and an agreement to the data was found for $A \approx 10$. Taking the $W(I)$ peak position in the MQT regime, we find that the crossover temperature calculated from these parameters is roughly $T_{cr} \approx 56\,\mathrm{mK}$.

Interestingly, the same number can be obtained by making use of the simplified consideration. Suppose that the current (and, therefore, the Josephson junction energy) fluctuations are caused by the thermal noise kT.[25] This way, the switching event occurs at the junction phase φ in the vicinity of $\pi/2$ so that $\Delta\phi = \pi/2 - \phi \ll 1$. Therefore, the Josephson energy close to the switching point $(\Phi_0 I_c/2\pi)\cos\phi$ can be written as $(\Phi_0 I_c \sin\Delta\phi)/2\pi$. Taking into account $\Delta\phi > 0$ we obtain that $\Delta I = I_c \sin\Delta\phi$ is half of the width of the experimentally obtained switching current distribution. Thus, the noise temperature or T_{cr} can be reconstructed from $kT_{cr} = (\Phi_0\Delta I)/2\pi$ and $T_{cr} \simeq 54\,\mathrm{mK}$.

Let us now consider possible ways to reduce the crossover temperature. In Fig. 2 its theoretically obtained value is presented versus the current rate for different values of the capacitance C. For the underdamped Josephson junction the increase of the bias current rate $\dot{I}$ leads to an approach of the mean switching current $\langle I_{SW}\rangle$ to the critical current I_c.

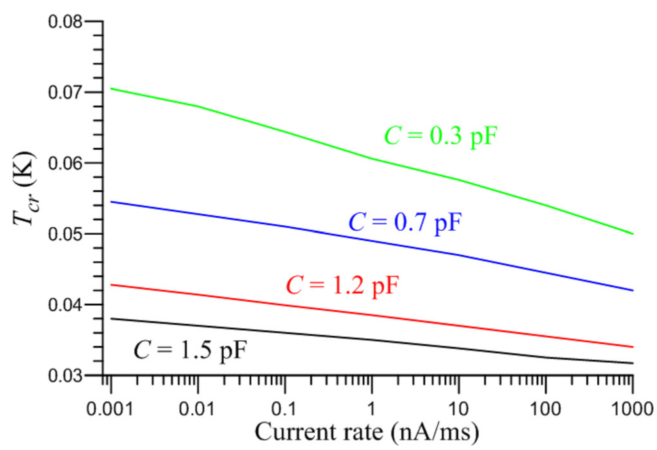

FIG. 2. The crossover temperature T_{cr} vs current rate $\dot{I}$ for different values of junction capacitance C.

The rapid current growth does not allow thermal fluctuations to shake the system and to switch it to the finite voltage state.[26,27] Similar picture arises in the MQT regime as well. The dependence $T_{cr}(\dot{I})$ is logarithmic with different slope for different C values. Thus, the increase in the rate $\dot{I}$ and accordingly the increase of $\langle I_{SW} \rangle$ leads to a decrease of the frequency ω_0 (Eq. (3)) and the crossover temperature T_{cr} (Eq. (6)), see Fig. 2. On one hand the crossover temperature decreases with increasing in capacitance by an exponential law. On the other hand the changing of C leads to changing of ω_0 by a square root dependence. In such a way for creation of a high sensitive detector the parameters reducing T_{cr} should be selected according to the operating frequency range.

In summary, the switching current distribution measurements presented here demonstrate a relatively low temperature crossover $T_{cr} \approx 56\,\text{mK}$. It is important to note that this result was obtained for a low critical current and a slow current rate. The given device has important applications in the context of supersensitive detection. For example, the ambitious task of implementation of a single-photon detector in the GHz range has certain perspectives. Indeed, the amplitude of the current which corresponds to a single-photon at the frequency of 2.5 GHz can be estimated as $I = \sqrt{h\nu/L_R}$, where L_R is the inductance of the corresponding part of the transmission line. Since usually such parts are $\lambda/2$ (Ref. 28) or $\lambda/4$ (Ref. 29) waveguide resonators, corresponding estimations yield 12 nA and 18 nA, respectively. These numbers are quite optimistic since half of the switching current distribution of 2.2 nA was realized. However, apart from adiabatic regime, here dynamical properties of this quantum mechanical system should be analysed, and first step has already been done.[4] Additionally, such detectors can be used in more complex superconducting schemes, where the information is transferred by magnetic flux quanta moving along in a similar transmission line.[30,31] Any external influence is changing the flux dynamics, whether it is an external magnetic field or a superconducting qubit state, is registered by the readout device. It is important to notice that in this case the quantum non-destructive measurements, which play an important role in applications, can be realized.

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