Measuring the switching current of a superconducting single electron transistor in a tunable dissipative environment

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Abstract. We experimentally investigated the switching current $I_{SW}$ of a superconducting single electron transistor (sSET), with competitive Josephson coupling energy $E_J$ and charging energy $E_C$, in an \textit{in situ} tunable dissipative environment. At low temperature, averaged $I_{SW}$ shows a clear 1e periodic function of gate induced charge on the island. The relative contrast of this oscillation increases when $E_J/E_C$ is lowered. Increasing dissipation reduce the quantum fluctuations of the phase across the sSET, leading to an increased $I_{SW}$.

1. Introduction

A current biased hysteretic Josephson junction could escape out from its metastable zero-voltage state into the stable finite-voltage state when the bias current exceeded a threshold: switching current $I_{SW}$. This technique has been used to read out the states of superconducting quantum bits devices [1, 2] and to study the dynamics of a Josephson junction [3]. According to the resistively and capacitively shunted junction (RCSJ) model, the dynamics of phase difference $\varphi$ across the junction is governed by the Josephson coupling energy $E_J = \hbar L_c/2e$, charging energy $E_C = e^2/2C_0$ and the effective shunt resistance $R$ responsible for dissipation, where $L_c$ and $C_0$ are the junction critical current and capacitance respectively. Especially for small Josephson junction circuit with $E_J \leq E_C$, the charging effect plays a major role on its dynamics, one has to take into account the electromagnetic environment in which the junction is embedded [4].

In this paper, we will present the $I_{SW}$ measurement of a superconducting single electron transistor (sSET) which consists of two superconducting quantum interference devices (SQUIDs) in series by the central island (Fig. 1(a)). A two dimensional electron gas (2DEG) capacitively coupled to the sSET provides a dissipative environment. The SQUID configuration allows us to tune the effective Josephson coupling energy by applying a magnetic field perpendicular to the SQUID loop. Experimental and theoretical studies on a similar circuit as ours showed that increasing dissipation could compress the quantum fluctuations of the phase, causing a increased zero-biased conductance [5, 6]. These works were focus on the small region of the supercurrent branch of the IV curve. However, a systematic study on the switching current of such a device
is still lacking in the regime where \( k_B T < E_J \sim E_C \). In this experiment, we measured the \( I_{SW} \) of a sSET as a function of dissipation, gate voltage and temperature.

2. Sample description and experimental setup

The sSET fabrication involves the standard double angle shadow evaporation, with two layers of 22nm and 35nm Al. The Al/Al\(_{2}\)O\(_3\)/Al junctions were formed by oxidizing the first layer of Al in the mixture of 10% O\(_2\) and 90% He at 200mTorr for 3 minutes. The device is deposited on a GaAs/Al\(_{0.3}\)Ga\(_{0.7}\)As hetero-structure with a two-dimensional electron gas (2DEG) 100nm beneath its surface and capacitively coupled to the sSET. The backside of the 2DEG substrate is placed onto a gold plated Si which acts as a back gate. A negative voltage \( V_{BG} \) is applied to deplete the 2DEG charger carriers, causing 2DEG resistance \( R_{2DEG} \) increase with \( V_{BG} \). When \( V_{BG} \) is ramped up from 0 to -550V, \( R_{2DEG} \) increases from 36.5\( \Omega \) per square to 333\( \Omega \) per square. The circuit model of the sSET in such a in situ tunable environment is illustrated in Fig. 1 (b).

The Hamiltonian could be written as

\[
H_0 = E_C(n - Q_g/e)^2 - 2E_J(\Phi)\cos(\varphi/2)\cos(\theta) + H_{envi} \tag{1}
\]

In the first term, \( n \) is the island charger number and \( E_C \equiv e^2/2C_\Sigma \) is the charging energy of the sSET where \( C_\Sigma = 4C_0 + C_g \) is the total capacitance of the island. Here, we assume four junctions are identical with self-capacitance \( C_0 \), \( C_g \) denotes the gate capacitance and \( Q_g = C_gV_g \) is the gate induced charge. The second term refers to the Josephson energy where \( E_J(\Phi) \) is the Josephson energy of the SQUIDs: \( E_J(\Phi) = E_J^0|\cos(\pi\Phi/\Phi_0)| \), here \( E_J^0 \) is the zero-field Josephson coupling energy of SQUID and \( \Phi \) is the flux through its loop. Defining \( \varphi_1 \) and \( \varphi_2 \) as the phase of two SQUIDs respectively, \( \varphi \equiv \varphi_1 + \varphi_2 \) is the phase across sSET and regarded as a classical variable, while \( \theta \equiv (\varphi_1 - \varphi_2)/2 \) is the conjugate variable to \( n \). Indeed, one sSET behaves effectively as a single Josephson junction with gate dependent critical current \([7, 8]\). \( H_{envi} \) is determined by the electromagnetic environment seen by the sSET. The effective impedance shunting the sSET consists of \( C_0 \) in parallel with \( C_g \), the distributed 2DEG resistance between the island and the lead, \( \sim R_{2DEG}/3 \), and the impedance of the transmission line \( Z_\ell(\omega) \).

When the sSET is in the zero-voltage state, the characteristic frequency is the plasma frequency of the SQUID \( \omega_p = \sqrt{2I_0^0/\Phi_0C_0} \sim 10^{11}\text{rad/s} \) where \( I_0^0 \) refers to the SQUID critical current. Thus the transmission line can be regarded as infinite with an impedance \( Z_\ell(\omega) \approx (r_\ell/2\omega c_\ell)^{1/2}(1 - i) \) where \( r_\ell = R_{2DEG}/W \) and \( c_\ell \approx 10^{-8}F/m \) are the unit length resistance and capacitance. The total effective impedance shunting the sSET is

\[
Z_{total}(\omega) = \frac{R_{2DEG}/3 + Z_\ell(\omega) + 1/\omega C_g}{1 + 2C_0/C_g + 2i\omega C_0(R_{2DEG}/3 + Z_\ell(\omega))}
\]

and its real part \( Re(Z_{total}(\omega)) \) determines the dissipation level.

Figure 1. (color online) (a) Scanning electron microscope image of the sSET. The source and drain are 10\( \mu \)m wide and 600\( \mu \)m long Al thin film. Four Josephson junctions are formed by the overlap of two perpendicular arms, located on both side of the 300nm\( \times \)3\( \mu \)m island. (b) Circuit diagram of the sSET capacitively coupled to the 2DEG underneath. The leads are modeled as lossy transmission lines with unit inductance, capacitance and resistance: \( l_\ell \), \( c_\ell \) and \( r_\ell \).
Figure 2. (color online) (a) IV characteristic of the sSET for three different $E_J$. (b) $<I_{SW}>$ as a function of gate charge under different dissipation, $E_J/E_C = 1.4$. (c) $<I_{SW}>$ as a function of gate charge at different T. (d) $<I_{SW}>$ versus $C_g V_g/e$ for different $g$, $E_J/E_C = 0.54$

It is a monotonic function with respect to $R_{2DG}$ in the relevant frequency range. When $Re(Z_{total}(\omega))$ is lowered, the sSET is experiencing more dissipation. We define the dissipation factor $g \equiv 3R_K/4R_{2DG}$ where $R_K = h/e^2 = 25.8k\Omega$ is resistance quantum.

The measurement was performed in a dilution refrigerator with a base temperature $\sim 30$mK. The devices were mounted inside an rf-tight Cu box with a superconducting solenoid outside for producing a small magnetic field. All electrical leads are filtered with $LC$ low pass filters at room temperature, miniature $RC$ filter and Cu-powder filters at the base temperature.

When we measure the switching current, the bias current is ramped up at a constant rate ($\sim 50$nA/s). When $I_{SW}$ is reached, the sSET escapes into the finite voltage state. The output voltage is amplified by a PAR 113 preamplifier and then sent to a 200MHz Agilent 5335A universal counter. $I_{SW}$ is calculated by the product of ramping rate and the period in which current increases form zero to the switching current. Considering the switching events are stochastic, it is suitable to characterize the switching current by the averaged value $<I_{SW}>$. For a fixed $V_g$, $g$ and T, at least 1200 switching events were collected.

3. Results and discussion

A normal state resistance $R_N = 29.8k\Omega$ for single junction was obtained and led to the SQUID critical current $I_0 = 20.5nA$ and $E_0/k_B \approx 490$mK. Single junction was estimated to be $80\mu m \times 80\mu m$ with self capacitance $C_0 \approx 0.29fF$ assuming a specific capacitance of $45fF/\mu m^2$. The gate capacitance $C_g = 1.5fF$ was obtained from the periodicity of $<I_{SW}>$ with gate voltage. Thus, $E_C$ is estimated to be $350$mK.

We show in Fig. 2 (a) the IV characteristics of the sSET in different field at $30$mK ($g = 532$). If the bias current is below $I_{SW}$, the sSET stays in the supercurrent branch. When the bias current is increased further, the sSET escape into the $2\Delta/e$ state and then $4\Delta/e$ state. Applying magnetic field will decrease the $E_J(\phi)$ and $I_{SW}$. We present the results for two different flux,
zero and $0.38\Phi_0$. The corresponding $E_J/E_C$ ratio are 1.4 and 0.54 respectively.

$<I_{SW}>$ is shown as a oscillating function of gate charge in both cases of $E_J/E_C$ at low temperature. The period with respect to $C_V g_e^2/e$ is obvious below $\sim 220\text{mK}$ for $E_J/E_C=1.4$ (Fig. 2 (c)) and $\sim 125\text{mK}$ for $E_J/E_C=0.54$ respectively. As shown in Fig. 2 (b) and (d), $<I_{SW}>$ increases when $g$ is increased for a fixed gate charge. When more dissipation is coupled to the sSET, the quantum fluctuations of the phase is reduced, causing the phase more localized and higher $<I_{SW}>$. The gate charge dependence of $<I_{SW}>$ disappear at different $T$ for two $E_J/E_C$ cases. We interpret this result with different reasons. For $E_J/E_C=1.4$, when $T$ is above $\sim 0.6E_C$, thermal noise starts to wash out the charging effect completely. While for the other situation, $E_J(0.38\Phi_0) \approx 187\text{mK}$, thermal fluctuations firstly starts to diminish the Josephson energy. Although its charging nature still exists, gate dependence $<I_{SW}>$ is lost. Note that the relative amplitude increases when $g$ is increased or $E_J/E_C$ is decreased. Higher dissipation increases $<I_{SW}>$ and causes the contrast of oscillation greater. When $E_J/E_C$ is lowered, the charging energy is more dominating in determining the sSET transport, leading to the increased contrast.

The period of $<I_{SW}>$ with respect to gate charge is $1\text{e}$ in our measurement, corresponding to a gate voltage $V_g = 105\mu\text{V}$. This is confirmed by another experiment on a sSET with similar geometric parameters but a higher $R_N = 65\text{k}\Omega$ (data not shown). Because $R_N \gg R_K$, its $I - V_g$ relation showed $2\text{e}$ periodicity with $V_g (215\mu\text{V})$ at low excitation and $1\text{e}$ period ($106\mu\text{V}$) when the excitation is above $2\Delta/e$. Considering the comparable $E_J$ and $E_C$ and the slow current ramping frequency ($5\text{Hz}$), because of the absent of special quasi-particle filter or trap on chip, the much faster quasi-particle poisoning ($\sim 50\text{kHz}$) washed out the $2\text{e}$ nature of the parity on the sSET island although the transport is dominated by Cooper-pairs [9, 10, 11].

In summary, we have experimentally studied the effect of dissipation on the switching current of a sSET with $E_J \sim E_C$. $<I_{SW}>$ shows a clear $1\text{e}$ oscillation with respect to the gate charge, indicating that the charging effect is dominating. Introducing dissipation will compress the quantum fluctuations of the phase variable, causing $<I_{SW}>$ increased. Our results qualitatively agree with the quantum theory of a sSET in a capacitively coupled dissipative environment [6].

4. Acknowledgments

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