Shapiro Steps Observed in a Superconducting Single Electron Transistor


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The dc current-voltage (IV) characteristics of a superconducting single electron transistor irradiated with microwaves up to 18 GHz are experimentally studied. The switching current as a function of gate voltage demonstrates clear phase-charge duality in a Josephson junction. At higher microwave power levels, Shapiro steps in IV characteristics are observed. The step height in IV can be analyzed using the model an ac-voltage source applied to a single Josephson junction.

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I. INTRODUCTION

The quantum metrology triangle relating voltage (V), current (I) and frequency (ν) based on the Josephson, quantum Hall and single electron tunnelling effects is an important issue for state-of-the-art precision electrical measurements [1]. The relation between voltage and frequency is \( V = \frac{\hbar \nu}{2e} \), due to mode-locking of the internal frequency arising from ac Josephson effect in a Josephson junction to an external periodic signal [2]. The mode-locking phenomenon can be experimentally identified with voltage steps, called Shapiro steps, in current-voltage (IV) characteristics of a Josephson junction irradiated by microwaves [3]. Recently, lithography technology has triggered a great leap in integrated small Josephson-junction circuits, and yielded large application possibilities in quantum electronics. Unlike the large-area junctions have been well-studied, small junctions are of small capacitances and large resistances, and have significant intrinsic phase fluctuations, a drawback for phase coherent devices. On the other hand, the Coulomb blockade phenomenon in small junctions brings in novel single charge devices, such as single electron transistors, yielding applications in charge sensing and charge signal amplification [4]. In particular, the single electron tunneling provides a relation, \( I = e\nu \) between current and frequency in the quantum metrology triangle [5]. As such the properties of small Josephson junctions driven by a microwave signal are of great interest. Previous works have reported observations of Shapiro steps in superconducting single electron transistors (SETs) and claimed that the double-junction SET can be treated as a single junction whose critical current is controlled by a gate voltage [6]. Other works focused on the photon-assisted tunneling [7] and interband transition [8] in single charge devices. In particular, by using this interband transition technique, quantum superposition of the SET charge states has been demonstrated [9]. In this paper, we report an experimental study of dc IV character-
FIG. 1: (a) A scanning electron micrograph of a measured sample. The SET central island is marked by the dashed trapezoid. (b) The current-voltage ($I-V$) characteristic of the superconducting SET at the temperature of 50 mK. The Josephson-quasiparticle current peak and the threshold voltage of quasiparticle tunneling can be identified clearly.

II. EXPERIMENTS

An SET is a double-junction device having a small central electrode (island) capacitively coupled to a gate electrode. By changing the gate voltage one can tune the electrical potential of the island and in turn, modulate the conductance of the SET. The scanning electron micrograph of a measured device is illustrated in Fig. 1 (a). The devices were made of aluminum by standard e-beam lithography and shadow evaporation. The H-shaped central island marked by a dashed trapezoid has an extension part for sensing a nearby superconducting charge box, which is on the far right of the image. In this report, we will not mention about the box but will focus on the SET. The samples were sealed in a copper sample holder with a microwave antenna mounted inside and cooled down to 50 mK in a dilution refrigerator for transport measurement. The driving microwaves were delivered through a 0.085 SS coaxial cable from a microwave source at room temperature to the sample holder with the cable center metal connecting to the antenna and the outer metal
SHAPIRO STEPS OBSERVED IN...

FIG. 2: (a) A zoom of the $IV$ curve in the zero-bias voltage region reveals a clear supercurrent structure. The switching current is defined as the maximal current that the zero-voltage state can sustain. The horizontal arrows indicate the switching for the SET from finite voltage state to zero voltage state and vice versa. (b) The average switching current as a function of gate voltage. The gate modulation is $1e$-period, probably due to quasiparticle contamination. The gate voltages corresponding to maximal and minimal switching current are referred to as $V_{g_{\text{max}}}$ and $V_{g_{\text{min}}}$, respectively.

soldered on the sample holder. Important parameters of the SET can be obtained by measuring the current-voltage characteristics, which is shown in Fig. 1 (b) when the microwave source is turned off. From the electron micrograph, the Al/AlO$_x$/Al junction area can be estimated of about 0.01 $\mu m^2$, giving a capacitance of about 0.45 fF. The charging energy is determined as $E_C = e^2/2C_{\Sigma} \approx 80\mu eV$, in which $C_{\Sigma}$ is the total central island capacitance. The superconducting gap, $\Delta$, is estimated as about 210 $\mu eV$ by using the threshold voltage of quasiparticle tunneling, $4\Delta + 2E_C$ of about 1mV[1]. The total tunneling resistance of the SET is 26.2 k$\Omega$, determined by using the slope of linear $IV$ characteristic in the bias-voltage region high above the threshold voltage of quasiparticle tunneling, namely, $V_b \gg 4\Delta + 2E_C$. Applying Ambekaoka-Baratoff equation and assuming that the two junctions are of the same resistance, one can estimate the Josephson coupling energy of a consisting junction of about 50 $\mu eV$ [10]. As shown in Fig. 2 (a), the SET switches from a zero-(bias) voltage state to a finite-(bias) voltage state at a switching current of about 70 pA. The zero-voltage state
FIG. 3: $IV$ curves of the SET at $V_{gmax}$ with 15GHz microwave irradiation at various power levels. Shapiro steps are clearly seen up to $n=4$. Inset shows the Shapiro step position, $V_S$ as a function of microwave frequency for $n=1$ and $2$ of two samples. The data (solid squares) follow well with the theoretical prediction indicated by the solid lines.

is a signature of coherent Cooper-pair tunneling, while the finite-voltage state features the dissipative charge tunneling. The resistance of the SET in the zero-voltage state is about 100 kΩ, reflecting that the superconducting phase coherence between the $IV$ measurement electrodes is weak. We note that the $IV$ curve is asymmetric in bias voltage when the bias voltage is swept in one direction due to a hysteretic behavior: The SET switches from the zero-voltage state to the finite-voltage state at a current of about 70 pA, but is re-trapped back at a smaller current of about 30 pA. Because of the large tunneling resistance of the Josephson junction, the superconducting phase is weakly damped and the $IV$ curves become hysteresis [2].

When the junction capacitance is small and the shunt resistance is large, the switching
from the zero-voltage state to the finite-voltage state can be viewed as a quantum tunneling process. As such one does not get exactly the same switching current $I_{sw}$ when repeating the switching process. Nevertheless, as illustrated in Fig 2(b), the average switching current can be periodically modulated by the gate voltage, which tunes the energies of the SET charge states. The gate voltage dependence of the switching current can be explained by the charge-phase duality in the superconducting SET [6]: At the gate voltage tuning two successive charge states degenerate, $V_g = V_{g_{\text{max}}}$, the charge fluctuation on the central island is pronounced and the phase fluctuation on the island is minimal, resulting in a robust superconducting phase coherency and a maximal switching current. Subsequently, we studied the dc $IV$ characteristics of the SET when irradiated with microwaves. By sweeping the microwave frequency at a constant power level, we found discrete narrow bands picked up by the sample holder cavity. Thus we focused our measurement on these resonant frequencies, at which the microwaves have a greater influence on the SET. Moreover, since the superconducting phase plays an important role in the mode-locking phenomenon, we chose the gate voltage $V_g = V_{g_{\text{max}}}$, at which the phase fluctuation is minimal. Fig 3 shows the $IV$ curves when the SET is irradiated with 15 GHz microwaves at various power levels. Step structures with constant bias-voltage interval of about 25 $\mu$V can be clearly seen. The step structure in $IV$ can be clearly observed when the microwave frequency is higher than 7 GHz. In the microwave frequency range (from 7 GHz to 18 GHz) and power range we have studied, the step interval increases as the frequency increases but keeps constant as power level increases. As shown in the inset of Fig 3, the step positions (in bias voltage), $V_S$, correspond well with the theoretical prediction, $V_S = n\hbar\nu/2e$, in which $n$ is the order of the mode-locking. Therefore we are confident that the observed steps can be identified as Shapiro steps arising from mode-locking of a dc-biased Josephson junction to the external microwaves. Ideally, each step in $IV$ curves represents a constant-voltage state, labeled by $n$, featuring a “coherent” charge tunneling generated by the mode-locking. In particular, the zero-voltage state can be assigned as the $n=0$ state. When the bias voltage is ramped, the SET would switch from one constant-voltage state to another, and eventually jumps to the finite-voltage state. Interestingly, in some situations, especially at a higher microwave power level, the SET would switch back and forth rapidly between two constant-voltage states. This suggests that these constant-voltage states are highly unstable. Moreover, the resistance of the constant-voltage states is larger than that of the zero-voltage state without microwave irradiation, an indication of considerable incoherency generated by microwave irradiation.

The step height (in current), which defined by the switching current for each constant-voltage state can be modulated by the microwave power level. As shown in Fig. 3, the zero-voltage ($n=0$) step height first decreases when the microwave power is increased and diminishes at a power of -30dBm. As the microwave power increases further, the $n=0$ step starts to build up, and the $n=1$ step falls behind it. The Shapiro step height has been calculated in previous theoretical works by using an ac-voltage source model, in which the microwaves act as a pure voltage source parameterized by an ac voltage, $V_{ac}$. A voltage drop $V$ across the Josephson junction would result in a time-varying superconducting phase with a phase velocity, $d\phi/dt = 2eV/\bar{h}$. Using the Josephson relation, $I = I_C \sin \phi$, we have
FIG. 4: The Shapiro step height ($I_n$) as a function of 15GHz microwave amplitude for $n=0$, 1, 2, and 3 marked as solid squares shows an oscillatory behavior. The solid curves are the fitting results for $n=0$ and 1 using the theoretical prediction, $I_n = I_C J_n^2 \left( \frac{2eV_{ac}}{h\nu} \right)$. Although deviations are large for higher $n$-values, the peak positions of experimental data are consistent with those of theoretical prediction, which are marked by the vertical arrows.

the $n$-th step height for a single Josephson junction[2],

$$I_n = I_C \left| J_n \left( \frac{2eV_{ac}}{h\nu} \right) \right|,$$

(1)

in which $J_n(x)$ is the $n$-th order Bessel function, and $I_C$ is the critical current of the junction. In general, since the Cooper-pairs tunnel sequentially through the consisting junctions of an SET, we can treat the tunneling in the two junctions as independent events. With a hand-waiving argument, the step height can be deduced to have a square dependence [6],

$$I_n = I_C J_n^2 \left( \frac{2eV_{ac}}{h\nu} \right).$$

(2)

Fig. 4 shows the step height, $I_n$, as a function of 15 GHz microwave amplitude and the
fitting curves using Eq. (2). The microwave amplitude, $V_{ac}$, can be determined relatively by taking the square root of the microwave power. When the microwave amplitude is large, the instability of constant-voltage states results in scattered and spread data. Although discrepancies in fitting are significant for large $n$ and large signal amplitude, the peak positions of the oscillatory dependence, which marked by the vertical arrows are consistent with the theoretical prediction. The discrepancies may result from possible ac current coupling and incoherent Cooper-pair tunneling due to large environment impedance.

III. CONCLUSIONS

In summary, we observed Shapiro steps in dc $IV$ measurements for superconducting SETs irradiated with microwaves. The experimental data, including step positions (in voltage) and step height (in current) can be explained using mode-locking of ac Josephson effect and the microwaves. The result demonstrates quantitatively the phase coherency of the superconducting SET with a significant charging effect. It also gives an estimation how well the superconducting SET is as a phase coherent device.

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References

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