Spectroscopy of charge states of a superconducting single-electron transistor in an engineered electromagnetic environment

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Abstract. We study charge states of a superconducting single-electron transistor (SSET) fabricated on a heterostructure substrate that can be switched from insulating to conductive. We probe the charge states by microwave irradiation and subsequent observation of photon-assisted Josephson quasiparticle current, which allow us to obtain the energy dispersion relation in the quasicharge space. When the substrate is insulating, the charge states show an energy-dispersion curve with a gap, manifesting that coherent superposition of the two charge states is realized. When the substrate becomes conductive, its two-dimensional electrons capacitively couple to the SSET and modify the degree of dissipation to its electromagnetic environment. The dispersion relation then becomes linear, and its slope agrees with the value estimated from the charging energy including the capacitance of the two-dimensional electrons. This indicates that quantum coherence between the two charge states is lost due to the coupling with the environment.

1. Introduction
There has been great interest in how a quantum mechanical system interacts with its environment. A classic example is a superconductor-insulator transition, in which increasing the dissipation drives the system into a superconducting state by making the charge fluctuation larger and the superconducting phase more localized. This phenomena is closely linked to a more recent topic of ‘decoherence’ in charge or flux states of superconducting circuits [1, 2], which are building blocks of future quantum mechanical devices, i.e., quantum computers. In these examples, it is desired that the system-environment coupling can be controlled in order to gain insight into the role of dissipative environment. One way of introducing the dissipation is to prepare a Josephson device on a two-dimensional electron gas (2DEG) and control their capacitive coupling by gate voltages [3, 4, 5]. It is observed that a 2D Josephson-junction array changes its current-voltage characteristic from superconducting to insulating as the resistance of the 2DEG is increased [3]. Similarly, the decrease of the zero-bias conductance of a superconducting single-electron transistor (SSET) as increasing the 2DEG resistance is reported [4].

While these experiments are advantageous in that the control of dissipation is performed in situ and that it does not affect other system parameters such as the Josephson energy $E_J$, the drawback is that 2DEG is present at zero voltage and depleting it completely requires
hand, the first of the two sequential quasiparticle tunneling process across the probe junction \( \Delta \) is the superconducting gap and \( |\psi_0\rangle \) and \( |\psi_1\rangle \) are for the maximum and minimum \( E_J \), respectively. The inset shows examples of microwave response at 15 GHz for maximum (solid) and minimum (dotted) \( E_J \). The vertical scale of the inset is arbitrary and offset for clarity.

hundreds of volts. In this contribution, we study an SSET fabricated on a heterostructure wafer that is designed to be insulating at low-temperatures unless infrared light is illuminated. Upon illumination, the 2DEG layer becomes conductive, which persists sufficiently long after the illumination was terminated. This conveniently realizes switching from the complete absence of dissipation to the presence. In addition, in order to address the problem of coherence directly, we performed microwave spectroscopy developed by Nakamura et al. [6]. When the system Hamiltonian is written as a sum of two terms describing the charging and Josephson effects, an energy gap is created at points \( Q_g = \) odd in the quasicharge space. Here, \( Q_g \) is the gate-induced excess charge in an SSET normalized by the elementary charge \( e \). If we concentrate on the region around \( Q_g = 1 \), the energy gap between the two charge states \( |0\rangle \) and \( |2\rangle \) is given as \( \delta E = \{4E_C(Q_g - 1)^2 + E_{J_1}^2\}^{1/2} \) with \( E_C \) the total charging energy of the SSET. This energy dispersion relation is obtained experimentally by microwave irradiation and subsequent observation of photon-assisted Josephson quasiparticle (PAJQP) current, when coherently superposed charge states \((|0\rangle \pm |2\rangle)/\sqrt{2}\) are indeed realized at \( Q_g = 1 \).

2. Experiments
An MBE-grown GaAs/AlGaAs heterostructure wafer has an inverted structure, namely, there is a 50 nm-thick GaAs layer between the surface and the 2DEG, below which an undoped Al\(_{0.35}\)Ga\(_{0.65}\)As layer exists. The doping was achieved by three delta-doped Si layers, which are inserted in the AlGaAs layer and separated from the 2DEG by 20 nm, 120 nm and 130 nm. The carriers are induced by light illumination and the 2DEG layer becomes conductive. After sufficient illumination, the 2DEG had a sheet resistance of about 4 k\( \Omega \), which did not change significantly during the measurements.

An Al-based SSET was fabricated on this wafer [Fig. 1-(a)]. Coherence between the states \( |0\rangle \) and \( |2\rangle \) is created across the junction \( J_1 \), and its time scale is given as \( h/E_J = 8e^2R_1/\Delta \), where \( \Delta \) is the superconducting gap and \( R_1(2) \) is the resistance of the junction 1 (2). On the other hand, the first of the two sequential quasiparticle tunneling process across the probe junction \( J_2 \) already destroys the state \( |2\rangle \). This occurs with the rate \( \Gamma \sim 2(\Delta + E_C)/e^2R_2 \) [7]. Thus, the
condition $E_J > \hbar \Gamma$, and correspondingly, $R_1 \ll R_2$, must be satisfied for observing the energy gap. To meet this requirement, we used a three-angle shadow evaporation technique, which allows the two junctions to be prepared in different oxidation processes.

The device was cooled with a dilution refrigerator down to 60 mK. An external magnetic field was applied to vary the magnetic flux threading through the SQUID loop involving the split junction 1 and tune its Josephson energy. The height and width of the JQP current peak correspond to the central JQP peak, compared with those for the minimum field. The inset of Fig. 1-(b) shows that the peak positions at 15 GHz for the maximum $E_J$ are closer to the central JQP peak, compared with those for the minimum $E_J$. That the width of the JQP peak is broadest (narrowest) for the maximum (minimum) $E_J$ indicates that our device indeed satisfies the condition $E_J/h \Gamma > 1$. The solid curve is a fit by microwave frequency $f = \delta E/h$ using $E_J$ as a parameter. From the fitting, $E_J$ is determined as 38 $\mu$eV. The finite $E_J$ clearly demonstrates that coherent superposition of the two charge states is realized. The points with large error bars (upper right) occur because at those frequencies the PAJQP peak overlaps with an unspecified peak around $|Q_g| = 0.5$. The peak is observed in the absence of the microwave irradiation, and does not depend on the frequencies. The origin of the peak is not completely identified. We tentatively assign it as the singularity-matching peak [8], although we do not discuss the detail here. On the contrary, at the minimum $E_J$, the peak positions are on the dashed line given by $f = 4E_C(Q_g - 1)/\hbar$, and the energy gap is not discernible within the accuracy of the present measurement.

3. Results and discussion
First, the system parameters were estimated from the current ($I$) measurements as a function of $V_g$ and $V_q$ (in the dark without microwaves). We obtained $C_1 = 1.4$ fF, $C_2 = 130$ aF and $C_g = 23$ aF. $\Delta$ was about 250 $\mu$eV, which is larger than the value of bulk Al, possibly due to disorders in the film. These values will not be affected by the illumination, since it has a negligible effect on the SSET itself even though the 2DEG couples capacitively with the SSET and the dissipation of the electromagnetic environment is modified significantly. The charging energy is estimated as $E_C = e^2/(2(C_1 + C_2 + C_g)) = 53$ $\mu$eV. $R_1 + R_2 = 820 \Omega$ was measured in the normal state (4 K), but $R_1$ and $R_2$ are not obtained separately. Assuming that the junction resistance is proportional to the inverse of the respective junction capacitance, we roughly estimate $E_J/h \Gamma$ to be about 3.3.

Figure 1-(b) shows the result of spectroscopic measurement before light illumination. The positions of the PAJQP peaks are determined from the average of the absolute values of the photon-absorption (left) and -emission (right) peaks when both the peaks were observed, and the absolute value is plotted when only either of them was observed. It is apparent that the PAJQP peaks exhibit quite different frequency dependence for the maximum and minimum $E_J$. The inset of Fig. 1-(b) shows that the peak positions at 15 GHz for the maximum $E_J$ is determined as 38 $\mu$eV. The finite $E_J$ clearly demonstrates that coherent superposition of the two charge states is realized. The points with large error bars (upper right) occur because at those frequencies the PAJQP peak overlaps with an unspecified peak around $|Q_g| = 0.5$. The peak is observed in the absence of the microwave irradiation, and does not depend on the frequencies. The origin of the peak is not completely identified. We tentatively assign it as the singularity-matching peak [8], although we do not discuss the detail here. On the contrary, at the minimum $E_J$, the peak positions are on the dashed line given by $f = 4E_C(Q_g - 1)/\hbar$, and the energy gap is not discernible within the accuracy of the present measurement.

When the carriers are introduced by light illumination, the $I$-$V_g$, characteristic of the SSET is mostly the same as that in the dark. The current near the zero bias slightly changed in consistent with the previous result [4], but the detail measurement in this region was difficult due to frequent charge jumps caused by fluctuating carriers. Moreover, we get no response as sweeping $V_g$ applied from the gate electrode. This is because the 2DEG exists beneath the gate electrode as well, and screens the electric field. Therefore, it is more effective to apply $V_g$ from the 2DEG side via Ohmic contacts on the surface (see the circuit diagram of Fig. 2-(a)). The oscillation of the JQP peaks is recovered, and from the period we estimate $C_{2d} = 340$ aF. We note that increasing positive voltages (larger than 100 mV) results in longer oscillation period (smaller $C_{2d}$) because the 2DEG starts to be depleted. Therefore, the range of the gate voltage was usually restricted to $-10$ mV $\leq V_g \leq 10$ mV. On the other hand, we still applied microwaves.
through the gate electrode. Although higher power was generally required to observe the PAJQP peaks and at some frequencies the peaks were not observed, the spectroscopy can still be carried out, as shown in Fig. 2-(b). It is seen that the two sets of plots now nearly overlap and follow the same linear relation $f = 4E'_{C}/h$ with $E'_{C} ≡ e^2/(2(C_1 + C_2 + C_{2d}) = 44 \, \mu\text{eV}$. These results suggest that quantum coherence between the two charge states is lost due to the coupling with the electromagnetic environment. The positions of the PAJQP peaks were difficult to determine at frequencies below 10 GHz, because they are broader than those before illumination and overlap with the central peaks. The broader PAJQP peak reflects the level broadening of the state $|2\rangle$, and is consistent with our picture that coherence of the system is highly disturbed. However, clarifying the role of the dissipative environment requires further investigation.

4. Summary
To summarize, we spectroscopically investigated coherence of the charge states of the SSET in the absence or presence of the 2DEG as a dissipative electromagnetic environment. By introducing the dissipation, we observed breakdown of coherently superposed charge states otherwise present. Further investigation will be conducted to clarify the role and nature of the dissipative environment.

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