Effects of Dissipation on a Superconducting Single Electron Transistor

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We measure the effect of dissipation on the minimum zero-bias conductance, $G_0^{\min}$, of a superconducting single electron transistor (sSET) capacitively coupled to a two-dimensional electron gas (2DEG) in a GaAs/AlGaAs heterostructure. Depleting the 2DEG with a back gate voltage decreases the dissipation experienced by the sSET *in situ*. We find that $G_0^{\min}$ increases as the dissipation is increased or the temperature is reduced; the functional forms of these dependences are compared with the model of Wilhelm *et al.* in which the leads coupled to the sSET are represented by lossy transmission lines.

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There is currently much interest in the coherence of macroscopic quantum states of magnetic flux and electric charge in superconducting circuits. In the case of flux, the element is a superconducting loop containing one or more Josephson junctions, and the two quantum states involve clockwise and anticlockwise supercurrents [1]. Evidence for the coherent superposition of such states has recently been obtained through the observation of level splitting induced by coherent tunneling between the two quantum states [2,3]. In the case of charge, one system involves a Cooper pair "box" coupled to a superconducting reservoir via a Josephson junction [4]. Quantum oscillations between two charge states of the island differing by $2e$ have recently been observed [5]. In both kinds of experiments, to increase the decoherence time one needs to reduce the dissipation to which the quantum states are subjected; for either system to be of interest as a qubit [6,7] for quantum computation, the decoherence time will have to be lengthened drastically.

In the case of macroscopic quantum tunneling in Josephson junctions, the effects of dissipation have been extensively studied by adding a resistive shunt [8], and by varying the environment *in situ* [9]. In the case of charge devices, on the other hand, although the effect of the environment on charge tunneling rates in single, small junctions has been studied theoretically [10–13] and experimentally [14], there has been no previous experiment in which the environment could be varied *in situ* while all the other parameters of the system remained fixed. This Letter reports an experiment in which a superconducting single electron transistor (sSET) is capacitively coupled to a ground plane consisting of a two-dimensional electron gas (2DEG), the resistance of which can be varied *in situ* [15]. This technique enables us to make accurate measurements of the effect of varying the dissipation on the zero-bias conductance of the sSET.

The sSET consists of a small superconducting island connected to two superconducting leads via two small area tunnel junctions [16] each with self-capacitance C and normal-state resistance R_N. The island is coupled to a gate via a capacitance C_g. In the absence of dissipation, the behavior of the sSET is determined by two characteristic energies, the Josephson coupling energy of each junction, $E_J = \Delta R_K/8R_N$, and the charging energy to place an electron on the island, $E_c = e^2/2C_\Sigma$; here Δ is the superconducting energy gap, $R_K = h/e^2 \approx 25.8$ kΩ is the resistance quantum, and $C_\Sigma = 2C + C_g$. At (nonzero) temperatures $T < E_c/k_B \ll E_J/k_B$ the fluctuations in the phase differences across the junctions are small and the device behaves much like a classical Josephson junction, with a high conductance at zero bias. As E_c is increased, the charge becomes more localized and the fluctuations in the phases increase, resulting in a decrease in the zero-bias conductance. The zero-bias conductance is periodic in the gate voltage V_g with a period of e or $2e$ [17]. Progressively increasing the temperature increases fluctuations in both phase and charge. If we now introduce a dissipative element in parallel with the sSET, the phase becomes more localized, increasing the zero-bias conductance. In our experiment, we study the effects of varying this shunting resistance.

We fabricated our sSET by double-angle evaporation [18] through a shadow mask, made with electron-beam lithography, onto a GaAs/$Al_{0.3}Ga_{0.7}As$ heterostructure with a 2DEG embedded 110 nm below the top surface. The heterostructure was grown on a GaAs substrate using molecular beam epitaxy and consists of the following layers: 500 nm of GaAs, 104 nm of $Al_{0.3}Ga_{0.7}As$, and 6 nm of GaAs. The $Al_{0.3}Ga_{0.7}As$ is selectively doped with Si donors situated 40 nm from the lower GaAs/$Al_{0.3}Ga_{0.7}As$ interface, at which the 2DEG forms. The reverse side of the substrate is attached to a metallic back gate. By applying a negative voltage V_{BG} to this back gate, we decrease the electron density in the 2DEG, increasing its resistance per square, R_{2D}, and decreasing the dissipation experienced by the sSET. The resistance of the 2DEG was measured using the van der Pauw method. We obtained the sheet density, n_s, from Shubnikov–de Haas oscillations in magnetic fields of 0.1 to 0.3 T. At $V_{BG} = 0$ V, $n_s = 1.5 \times 10^{11}$ cm^{-2} and $R_{2D} = 160$ Ω per square. At

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the maximum applied back gate voltage, $V_{BG} = -300$ V, n_s decreased to 1.0×10^{11} cm^{-2}, and R_{2D} increased to 600 Ω per square.

The configuration of the sSET is shown in Fig. 1(a); the data are shown in Figs. 2–4. The first layer of Al is 20 nm thick, and the second 35 nm thick. The 0.5 μm $\times$ 2 μm island is coupled to the 2DEG via a capacitance C_g. By applying a gate voltage V_g to the 2DEG, we can induce charge onto the island; from measurements of the periodicity of the zero-bias conductance with respect to this voltage with the device driven normal by a magnetic field we deduce $C_g = 1.8$ fF. The two Al-Al$_x$O$_y$-Al junctions formed by the overlap of the narrow Al lines are estimated (from scanning electron micrographs) to be 90 nm $\times$ 90 nm in area. Assuming a specific capacitance of 45 fF/μm^2 [19], we estimate $C \approx 0.37$ fF and thus $E_c/k_B \approx 360$ mK. The measured resistances R_N of the junctions (assumed equal) are 18 kΩ at 1.2 K, leading to $E_J/k_B \approx 380$ mK. The narrow leads from the island are each connected to a lead, of width $w = 10$ μm and length 760 μm, that connects the device to separate current and voltage pads. Each of these wide leads forms a lossy transmission line with the 2DEG.

As we see in Fig. 1(b), the total impedance shunting each junction consists of the self-capacitance C in parallel with the series combination of C_g, the resistance of the 2DEG between the island and the wide lead, approximately $R_{2D}/3$, and the impedance of the transmission line $Z_t(\omega)$. The factor of $\frac{1}{3}$ accounts for our estimate of the lateral spread in the current as it flows in the 2DEG from the island to the wide lead. The total impedance is thus

$$Z_{\text{tot}}(\omega) = \frac{R_{2D}/3 + Z_t(\omega) + 1/i\omega C_g}{1 + C/C_g + i\omega C[R_{2D}/3 + Z_t(\omega)]}. \quad (1)$$

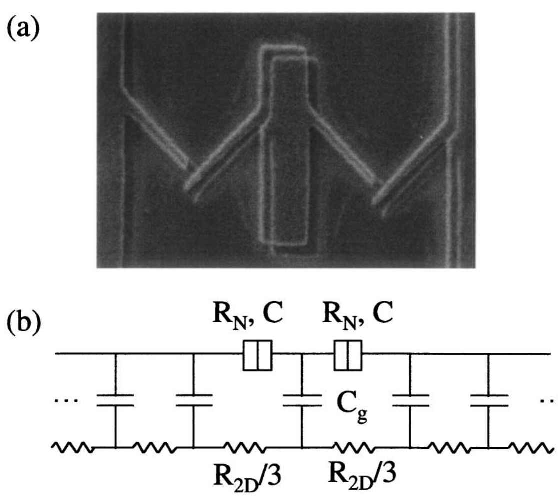

FIG. 1. (a) Electron micrograph of a superconducting single electron transistor. The central 0.5 μm $\times$ 2 μm island has an Al-Al$_x$O$_y$-Al tunnel junction on each side formed by the overlap of the two perpendicular, narrow lines. Each of the junctions is coupled to a 10-μm-wide Al strip that forms a lossy transmission line with the 2DEG below it. Only a very small portion of this line is visible. (b) Circuit model for the sSET, with junction resistance R_N and capacitance C, capacitively coupled to a 2DEG. The capacitance between the central island and the 2DEG is C_g. The other capacitors and resistors represent lossy transmission lines.

The transmission line has a resistance per unit length $r_t = R_{2D}/w$ that can be varied from 16–60 MΩ/m, a capacitance per unit length $c_t \approx 10^{-8}$ F/m (estimated using a dielectric constant of 12 for AlGaAs), and an inductance per unit length $\ell_t \approx 2.5 \times 10^{-8}$ H/m. The line impedance is dominated by resistive losses for frequencies less than $r_t/\ell_t \approx (0.6\text{–}2.5) \times 10^{14}$ rad/s, much higher than the highest relevant frequencies of the sSET [20], $1/R_K C \sim 1/R_N C \sim 10^{11}$ rad/s and the plasma frequency $(\pi\Delta/\hbar C R_N)^{1/2} \sim 3.5 \times 10^{11}$ rad/s. The attenuation length $(2/\omega c_t r_t)^{1/2}$ is shorter than the length of the line for frequencies above a few megahertz. Thus, for the relevant frequencies the line can be regarded as infinite with an impedance $Z_t(\omega) \approx (r_t/2\omega c_t)^{1/2}(1 - i)$ [21]. The real part of $Z_{\text{tot}}(\omega)$, $\text{Re}[Z_{\text{tot}}(\omega)]$, determines the dissipation experienced by the sSET, and is plotted vs R_{2D} as an inset of Fig. 3 for three frequencies. We note that $\text{Re}[Z_{\text{tot}}(\omega)]$ is an *increasing* function of R_{2D} for all values of interest; that is, the dissipation to which the sSET is subjected *decreases* for increasing R_{2D}.

The device was cooled to temperatures as low as 20 mK in a dilution refrigerator enclosed in a screened room. To eliminate effects due to noise sources at higher temperatures, we used several stages of filters designed according to the criteria of Vion *et al.* [22] to give an attenuation in excess of 200 dB at frequencies above about 400 MHz. For each lead, these consisted of four Cu-powder filters at the base temperature, a Cu-powder filter and RC filters at 4.2 K, and LC filters at room temperature.

The current-voltage (I-V) characteristic of the sSET (inset of Fig. 4) exhibited a supercurrentlike branch for bias currents below roughly 1.5 nA. As the current was progressively increased beyond this value, the voltage switched to a current step at $2\Delta/e$ and then another at $4\Delta/e$. The observed switching current, which is similar to that reported by others for comparable devices [17], is roughly 10% of the Ambegaokar-Baratoff prediction $\pi\Delta/2eR_N$ for a single junction, and roughly 30% of the critical current predicted when phase fluctuations of the sSET are taken into account [23]. We measured the zero-bias conductance in a four-terminal configuration using a lock-in detector at a few hertz. The amplitude of the excitation current was typically 0.5 nA, about 30% of the switching current. The corresponding excitation energy, eV, was always less than $k_B T/100$. As the voltage of the 2DEG was swept, the conductance oscillated with a period e/C_g, as shown in Fig. 2 for four temperatures and fixed R_{2D}. The conductance increased monotonically as the temperature was lowered. Generally, the amplitude

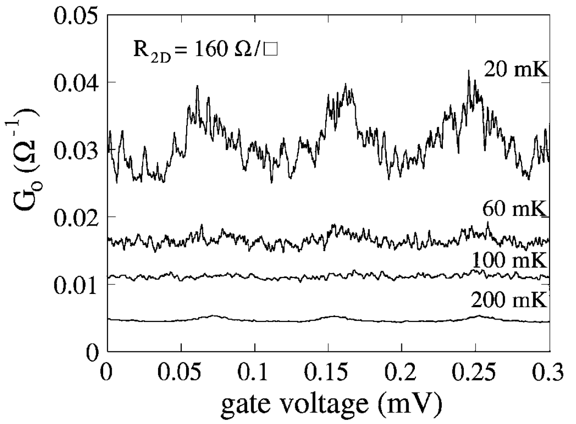

FIG. 2. Zero-bias conductance G_0 vs gate voltage at four temperatures for $R_{2D} = 160\ \Omega$ per square.

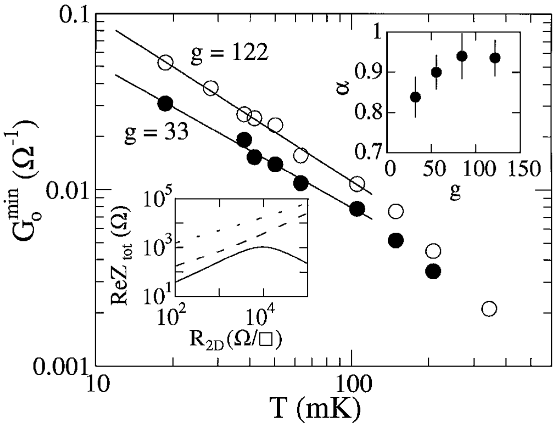

FIG. 3. Minimum zero-bias conductance $G_0^{\min}$ vs temperature for two values of the dissipation parameter $g \equiv 3R_K/4R_{2D}$. Lines are least squares fits to the data below 100 mK. Upper inset shows α vs g, where $G_0^{\min} \propto 1/T^{\alpha}$. Lower inset shows $\mathrm{Re}[Z_{\mathrm{tot}}(\omega)]$ vs R_{2D} for, from top to bottom, 10^8, 10^{10}, and 10^{12} rad/s.

of the conductance oscillations also increased as the temperature was reduced; however, for unknown reasons, no oscillations were discernible at 100 mK.

Even at the lowest temperatures, we always observed a periodicity of $1e$ rather than $2e$, and we briefly discuss this issue. Changing the gate voltage V_g changes the difference in the Coulomb energy of charge states differing by one Cooper pair on the island. If there are no quasiparticles in the system, the difference in the Coulomb energy varies from $4E_c$ at $V_g = 0$ to zero at $V_g = e/C_g$, the degeneracy point. In this case, the periodicity of the zero-bias conductance with respect to the gate voltage is $2e$. On the other hand, in the presence of quasiparticles, as is commonly the case in devices at higher temperatures or without normal state buffer electrodes, the sSET never reaches the degeneracy point [17]. The difference in the Coulomb energy then varies from $4E_c$ to $2E_c$, and the zero-bias conductance has a period of $1e$. To avoid issues concerning the $1e$ vs $2e$ periodicity, for subsequent analysis we measured the minimum zero-bias conductance, $G_0^{\min}$, corresponding to the gate voltage at which the energy difference between states differing by one Cooper pair is maximal, $4E_c$.

Figure 3 shows $G_0^{\min}$ versus temperature for two values of $g \equiv 3R_K/4R_{2D}$; the higher value of g represents greater dissipation. At a given temperature, the zero-bias conductance is higher for the larger value of g. At temperatures below about 100 mK, that is well below E_J/k_B and E_c/k_B, $G_0^{\min}$ appears to follow a power law dependence on T for fixed g. Figure 4 shows $G_0^{\min}$ versus g for five temperatures. As in Fig. 3, $G_0^{\min}$ increases as the temperature is lowered. At each temperature, $G_0^{\min}$ increases as the dissipation is increased, with a power law dependence.

To verify that C_g was not materially affected by the depletion of the 2DEG, with the Al film in the normal state we measured C_g by slowly sweeping the potential of the 2DEG so as to produce 10^3 Coulomb blockade oscillations. By taking a Fourier transform of these oscillations, we found that C_g increased by no more than 0.4% as V_{BG} was changed from 0 to -300 V, producing a negligible effect on the characteristics of the sSET compared with the effect of changing R_{2D}.

We turn now to a discussion of our results. Grabert *et al.* [11,12] and Ingold and Grabert [13] have calculated the effects of dissipation on a small, *single* junction shunted by a resistor R. For $g \gg 1$, $eV/k_BT \ll 1$ and in the limit of Coulomb blockade $gE_c/k_BT \gg 2\pi^2$ ($\hbar/RC \gg 2\pi k_BT$) [11] they show that G_0 scales as g/T^2. In our experiment, this regime corresponds to temperatures below about 0.1 K. These authors [12] also consider the case of a junction coupled to a *lossless* transmission line. None of these results, however, is directly applicable to our experiment in which an sSET is coupled to a *lossy* transmission line. This system has been studied by Wilhelm *et al.* [24], using a perturbative expansion in E_J/E_c. For a lumped circuit model in which

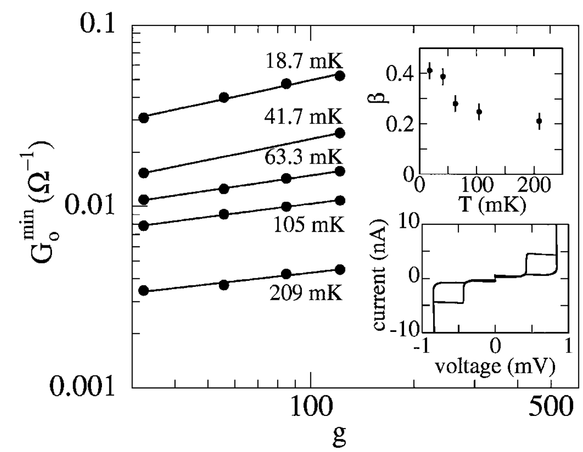

FIG. 4. $G_0^{\min}$ vs $g \equiv 3R_K/4R_{2D}$ at five temperatures. Lines are least squares fits to the data. Upper inset shows β vs T, where $G_0^{\min} \propto g^{\beta}$. Lower inset shows current-voltage characteristic of sSET at 40 mK.

the transmission line is replaced with a large capacitor they find that G_0 scales as g/T^2, thus recovering the result of Refs. [11] and [12]. For the lossy transmission line, Wilhelm *et al.* predict $G_0 \propto g^{1/3}/T^{5/3}$.

To test these results, we assume that $G_0^{\min}$ is of the form g^{β}/T^{α}. The lines in Fig. 3 are least squares fits to the data for $T \lesssim 0.1$ K, and the resulting values of α are plotted in the upper inset vs g. We see that α increases slightly, from 0.84 ± 0.04 to 0.93 ± 0.04, as g is increased from 33 to 122, and is always substantially lower than the prediction of either the lumped circuit or lossy transmission line model. In Fig. 4, the least squares fits to the data yield the values of β plotted in the upper inset. As T is lowered, β increases from about 0.2 near 200 mK to about 0.4 at the lowest temperature. These values of β are well below the prediction of the lumped circuit model, but embrace the prediction of the lossy transmission line model, $1/3$. However, the observation that α depends on g and β on T implies that the dependences of $G_0^{\min}$ on temperature and dissipation are not separable by a function of the form g^{β}/T^{α}.

In conclusion, we have shown that the zero-bias conductance of an sSET increases as the resistance of a 2DEG to which it is capacitively coupled is decreased or as the temperature is lowered. The dissipation and temperature dependences are compared with the calculations of Wilhelm *et al.* [24] which involve both a lumped-circuit approximation to the sSET and its environment and a more realistic model involving lossy transmission lines. In neither case do we find quantitative agreement. A likely source of the discrepancy for the latter case lies in the fact that $E_J \approx E_c$ in the experiment while the theory involves an expansion in E_J/E_c. It may be that the inclusion of higher order terms would reconcile the differences between experiment and theory. From an experimental standpoint, one might be able to replace the capacitive coupling between the superconducting leads and the 2DEG by Ohmic contacts using openings in the upper layer of the heterostructure. Such an arrangement would be a good approximation to a lumped-circuit model.

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