

Quantitative study of quasiparticle traps using the single-Cooper-pair transistor

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We use radio-frequency reflectometry to measure quasiparticle tunneling rates in the single-Cooper-pair transistor. Devices with and without quasiparticle traps in proximity to the island are studied. A 10^2 - to 10^3 -fold reduction in the quasiparticle tunneling rate onto the island is observed in the case of quasiparticle traps. In the quasiparticle trap samples we also measure a commensurate decrease in quasiparticle tunneling rate off the island.

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In a superconductor charge may be transported coherently by Cooper pairs and incoherently by quasiparticles. For nanoscale Coulomb blockade devices such as the single-Cooper-pair transistor (SCPT) and Cooper-pair box (CPB), these two modes of transport are mutually exclusive.¹⁻⁴ The supercurrent is temporarily blocked while a quasiparticle is present on the device island. This effect, caused by the electrostatic energy cost of the quasiparticle, is known as quasiparticle poisoning and leads to Cooper-pair tunneling being stochastically switched on and off. Quasiparticle poisoning is usually unwanted, especially in charge-based superconducting qubits (e.g., the CPB), where it changes the qubit bias point in a random telegraphic way and places limits on quantum coherence.⁵⁻⁷

In order to suppress quasiparticle poisoning the density of quasiparticles in the device leads should be reduced. In principle this can be simply achieved by lowering the temperature, however this is not always sufficient and an additional approach is to use so-called “quasiparticle traps.” These are normal metal regions contacting the superconducting leads in proximity to the device island.¹ In this paper we measure quasiparticle tunneling rates for SCPTs with and without quasiparticle traps. We report quantitatively on the effect of the traps, and discuss the implications of our results for designing superconducting Coulomb blockade devices with reduced quasiparticle poisoning.

Quasiparticle traps provide a sink to reduce quasiparticle density. When a superconductor is brought in contact with a normal metal, an induced superconducting gap develops in the normal metal, this is known as the proximity effect. Quasiparticles in the superconductor diffuse into the normal metal side where they relax towards the gap edge on a time scale which depends on the electron-phonon coupling.^{8,9} The trapped quasiparticles eventually recombine, emitting a phonon with insufficient energy to break a Cooper pair in the superconductor. Quasiparticle traps have been studied in the context of x-ray photon detection^{8,10} and cooling through superconductor-normal junctions.^{11,12} Joyez *et al.* first applied quasiparticle traps to reduce quasiparticle poisoning in SCPTs;¹ copper leads were contacted at a distance of $< 1 \mu\text{m}$ from the junctions and a $2e$ -periodic supercurrent was observed at low temperatures. Quasiparticle traps have often been used where quantum coherence is of interest.^{5,13-16} A variety of results have been achieved with immunity from

quasiparticle poisoning not always evident,^{16,17} therefore providing a motivation for this work.

We make use of the enhanced superconducting gap of aluminum with decreasing film thickness.¹⁸ The SCPT island gap is made greater than the lead gap ($\Delta_i > \Delta_l$) to reduce the depth of the quasiparticle potential well on the island.² Also, the leads of the SCPTs are isolated from the normal metal contacts by a region of higher superconducting gap $10 \mu\text{m}$ away from the junctions, forming a quasiparticle barrier. This was designed to reduce the effect of quasiparticles in the leads being trapped by the normal metal bond pads, allowing the full effect of the intentional traps to be observed [Fig. 1(c)]. Neither the quasiparticle barrier region or the normal metal bond pads can be seen in Fig. 1(a). The island and quasiparticle barrier layers are 7 nm thick ($\Delta_i = 298 \pm 9.4 \mu\text{eV}$), while the leads are 30 nm thick ($\Delta_l = 209 \pm 11 \mu\text{eV}$).¹⁸ Devices were fabricated with and without direct contact to quasiparticle traps. We refer to these device types as QTs (quasiparticle traps) and NTs (no traps),

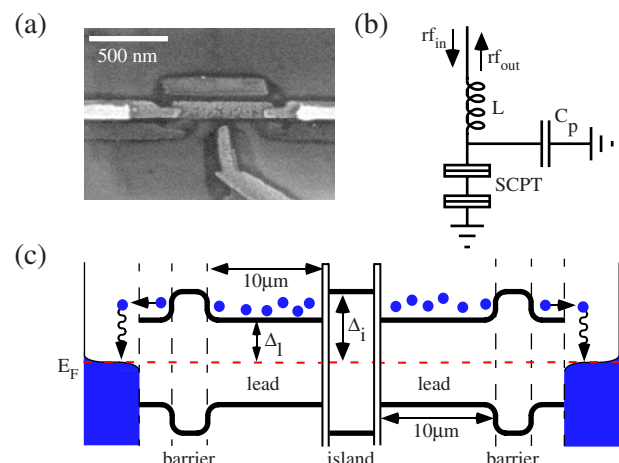


FIG. 1. (Color online) (a) Micrograph of a quasiparticle trap device with an island volume $\text{vol}_i = 750 \text{ nm} \times 125 \text{ nm} \times 7 \text{ nm}$. Bright features are the normal metal traps 200–300 nm from SCPT junctions. (b) The rf circuit has a resonance frequency of $\sim 320 \text{ MHz}$ and includes a chip inductor ($L = 470 \text{ nH}$), a parasitic capacitance ($C_p = 0.53 \text{ pF}$), and the SCPT. (c) Energy gap profile showing isolation of the leads from the normal metal bond pads.

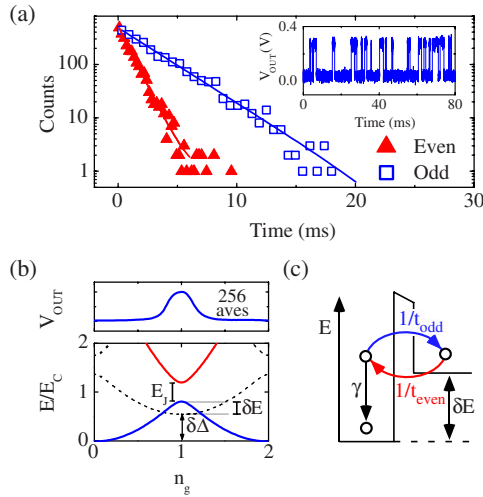


FIG. 2. (Color online) (a) Histogram of times spent in the even and odd states for a QT device, solid lines are fitted exponentials. Here $t_{odd}=3.1$ ms and $t_{even}=964$ μ s. Inset: switching between even and odd states at $n_g=1$. (b) Upper: Averaged supercurrent oscillations. Lower: Energy band diagram of the SCPT at zero current bias. The quasiparticle bands (dashed line) are lifted by an energy $\delta\Delta$ creating a potential well of energy δE relative to the lower Cooper pair band (solid line). (c) Allowed transitions of a quasiparticle including the relaxation rate to the bottom of the potential well on the island.

respectively [Fig. 1(a)]. AuPd alloy was chosen as the trap metal as we find this reliably gives a low contact resistance to aluminum. Our quasiparticle traps were typically 200–300 nm from the SCPT tunnel junctions and have approximately the same volume as the leads (vol= 2×10 μ m \times 100 nm \times 30 nm).

The SCPT bandstructure determines the energetics of quasiparticle tunneling [Fig. 2(b)]. The difference in superconducting gaps between the leads and the island lifts the energy minima of the quasiparticle state by an energy $\delta\Delta=\Delta_i-\Delta_j$.² In our devices, the quasiparticle state remains lower in energy than the ground band of the SCPT at $n_g=1$. Therefore a quasiparticle potential well is formed on the SCPT island with a depth given by $\delta E=E_c-\frac{E_J}{2}-\delta\Delta$.² The presence of a well means that a quasiparticle in the leads can tunnel into the island, relax, and after some time can be thermally activated out. We refer to the time constants for the poisoning process as t_{even} (the even state lifetime) and the unpoisoning process as t_{odd} (the odd state lifetime). From normal state Coulomb diamonds ($B=3$ T) we find the charging energy of the principal QT (NT) device is $E_c=e^2/2C_\Sigma=170$ μ eV (185 μ eV), the total device resistance at 4.2 K is 42 k Ω (54 k Ω), and the Josephson energy per junction from the Ambegoakar-Baratoff relation is $E_J=37$ μ eV (28 μ eV). The $\delta\Delta$ we expect from superconductor-insulator-superconductor (SIS) junction measurements is 89 ± 12 μ eV. Hence, the expected depths of the island potential well are $\delta E=62.5$ μ eV (82 μ eV) and in both cases $\delta E \gg kT$. For our set of devices, E_c and E_J are consistent to within 25%.

Radio-frequency reflectometry is employed to perform high-bandwidth measurements of quasiparticle tunneling.¹⁹

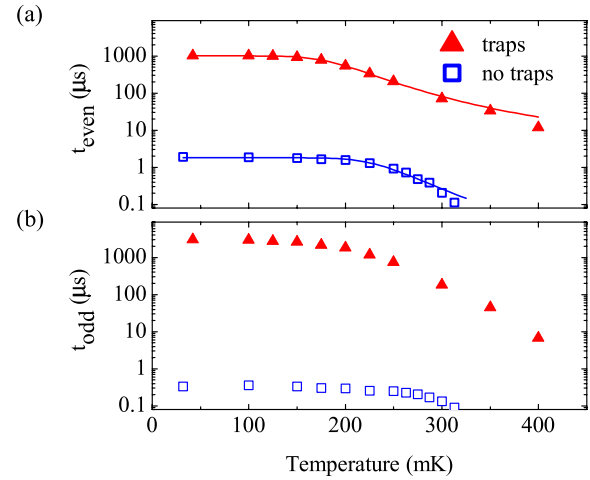


FIG. 3. (Color online) Temperature dependence of (a) t_{even} and (b) t_{odd} for a QT device (triangles) and a NT device (squares). Solid lines are fits to the quasiparticle density in the leads (see text).

This consists of embedding the SCPT in a resonant circuit and detecting the amplitude (and phase) of a small rf signal reflected from the circuit at resonance [Fig. 1(b)]. The reflected carrier signal passes through a low noise cryogenic amplifier before being further amplified and demodulated. Briefly, the presence of a quasiparticle on the device island shifts the supercurrent oscillation by a gate charge of e . This changes the impedance of the SCPT and changes the amplitude and phase of the reflection coefficient.^{3,4}

We monitor the demodulated signal rf signal (V_{OUT}) with the device biased on a supercurrent peak [upper graph Fig. 2(b)] and observe two-level switching due to quasiparticle tunneling [Fig. 2(a) inset]. Traces consist of 10^6 data points and $\sim 1 \times 10^4$ switching events, and are analyzed by comparing V_{OUT} to a median value. We plot a histogram of times spent in each state [Fig. 2(a)], an exponential is fitted to the histogram and the decay constant defines the state lifetimes. A good fit indicates Poissonian tunneling processes. Finite receiver bandwidth causes a systematic overestimate of time constants and we follow Ref. 20 to correct for this. Low pass filters of between 1.0 and 10.7 MHz are used and the receiver bandwidth is estimated for each filter. We operate at an rf bias where the time constants are not significantly perturbed, corresponding to a carrier power of -100.5 dBm (-104 dBm) for the QT (NT) devices.³

For the QT device, a dramatic increase in t_{even} (reduction in poisoning rate), compared to the NT device, is observed across the whole temperature range [Fig. 3(a)]. The saturated low temperature values are $t_{even}=1$ ms for the QT case and $t_{even}=1.9$ μ s for the NT case. The equilibrium expression for quasiparticle density is $n_{qp}=D(\epsilon_F)\sqrt{2\pi}\Delta_j/kT \exp(-\Delta_j/kT)$, where $D(\epsilon_F)=1.45 \times 10^{47}$ m⁻³ J⁻¹ is the normal-state density of states (including spin) of aluminum at the Fermi energy. Since t_{even}^{-1} is proportional to the quasiparticle density in the leads, we fit to the following expression $t_{even}^{-1}=B[n_{qp}(T_{qp}, \Delta_j)+n_{qp}(T, \Delta_j)]$, where B is a constant, T_{qp} is the saturation temperature, and n_{qp} refers to the quasiparticle density in the leads.³ For the NT and QT devices, we find the minimum quasiparticle temperatures are $T_{qp}=248 \pm 3$ mK

and $T_{qp}=204\pm 1$ mK; the superconducting gaps $\Delta_l=210\pm 20$ μeV and $\Delta_r=120\pm 3$ μeV ; and the constant $B=2.2\pm 1.9\times 10^{-15}$ m^3s^{-1} and $B=4.0\pm 0.6\times 10^{-19}$ m^3s^{-1} , respectively.

A reduction in quasiparticle temperature is seen for the QT device, however, this only partially explains the change in t_{even} . If the effect of the quasiparticle traps was purely to thermalize the leads we would expect the temperature dependencies to overlie one another at high temperature with the QT case saturating at a lower temperature. To illustrate this further we take the expression for $n_{qp}(T)$ and estimate the difference in t_{even} for the observed change in minimum quasiparticle temperature, $n_{qp}(248\text{ mK})/n_{qp}(204\text{ mK})=t_{even}(204\text{ mK})/t_{even}(248\text{ mK})\sim 9$, a relatively small fraction of the total change.

The NT gap parameter extracted for the leads ($\Delta_l=210\pm 20$ μeV) agrees with our expected value, but a significant suppression is seen for the QT device ($\Delta_l=120\pm 3$ μeV). We check if this corresponds to a real reduction in Δ_l by performing a voltage-biased measurement of quasiparticle tunneling threshold. This threshold occurs at $V_{ds}=2e\Delta_l+2e\Delta_r=998$ μeV for the QT device so, assuming an unchanged $e\Delta_r=298$ μeV , then $e\Delta_l=201$ μeV , which is close to the NT case. We conclude that Δ_l is not significantly changed by the presence of the normal metal.

Furthermore we can look at the values of the proportionality constant, B , for the tunneling rate. Theoretical analysis of the tunneling rates show that $t_{even}^{-1}=\frac{Gn_{qp}^l}{2e^2D(\epsilon_F)}\nu_i(\delta E+\Delta_i)\frac{\delta E}{\delta E+\Delta_i}$,^{21,22} where $\nu_{i,l}(E_k)=\frac{E_k}{\sqrt{E_k^2-\Delta_{i,l}^2}}$ is the quasiparticle density of states and $G=G_1+G_2$, in S , is the total tunnel barrier conductance. Thus our proportionality constant is predicted to be $B=1.6\times 10^{-15}$ m^3s^{-1} , showing close agreement with the measured value in the NT case but not in the QT case. From these fitting parameters it appears that the density of quasiparticle excitations, and their rate of tunneling onto the SCPT island in the NT case, is well described. However, in the QT device, we observe that the quasiparticle density in the superconducting side of a superconductor-normal bilayer is significantly reduced and is not given by the equilibrium expression for quasiparticle density $n_{qp}(T_{eff})$ at an effective temperature T_{eff} . We note that the increased t_{even} for the QT devices is reproduced among our sample set, which consists of three of each device type [Fig. 4(a)].

We now discuss qualitatively how the quasiparticle density is affected by the presence of a quasiparticle trap. In a superconductor the number of quasiparticles (N_{qp}) and phonons (N_ω) with $E>2\Delta$ are closely coupled and described by the Taylor-Rothwarf equations.²³ In the presence of a quasiparticle trap, it is necessary to add additional terms to describe loss to ($-\Gamma_T N_{qp}$), and gain from ($\Gamma_U N_{qp}^T$), the trap.²⁴ Quasiparticle population of the trap is given by N_{qp}^T . The constants G and R represent the quasiparticle generation and recombination rates in the superconductor. The quasiparticle master equation for the superconducting film follows. Other equations treat the quasiparticle density in the trap (N_{qp}^T) and the phonon density in both films,

$$\frac{dN_{qp}}{dt}=2GN_\omega-\frac{RN_{qp}^2}{\nu_{ol}}-\Gamma_T N_{qp}+\Gamma_U N_{qp}^T. \quad (1)$$

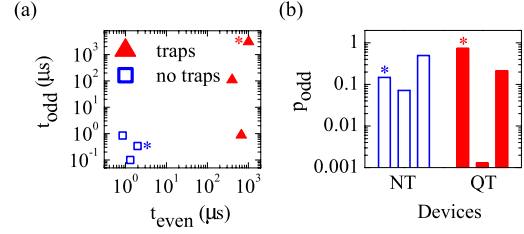


FIG. 4. (Color online) (a) Values of t_{odd} and t_{even} plotted for QT (triangles) and NT devices (squares) at fridge base temperature. (b) The probability of having a quasiparticle on the island (p_{odd}), determined from the time constants at this temperature. QT (NT) devices are indicated as filled (unfilled). The principal QT (NT) device is noted with an asterisk (*).

To fully explain the t_{even} behavior of the QT samples, the solution of this equation should be fitted to the data in Fig. 3(a). We do not perform this analysis but note that the significant reduction in quasiparticle density of the superconducting film implies that trapping, rather than recombination, becomes the dominant loss term. In this case, where tunneling to the trap is the fastest time scale, the quasiparticle density in the lead is given by detailed balance between the lead and the trap, $\Gamma_T N_{qp}=\Gamma_U N_{qp}^T$. The trapping (Γ_T) and untrapping rates (Γ_U) will depend on the lead-trap interface. Since N_{qp} is smaller for QT devices, it follows that the number of recombination phonons (N_ω) is also reduced.

Now we turn to the behavior of t_{odd} . Two of three QT samples show a significant increase in t_{odd} over the NT devices.²⁵ The increase is comparable to that for t_{even} : there is a factor of 9000 for the principal QT and NT devices [Fig. 3(b)]. We can estimate the reduction in temperature needed from $t_{odd}^{-1}\propto\exp(-dE/kT)$. Taking the mean value of quasiparticle potential depth ($dE=72$ μeV) for the two principal devices, a reduction in phonon temperature from 248 mK to 67 mK can explain the difference observed in t_{odd} . Phonons (with $E\geq 2\Delta$), resulting from quasiparticle recombination, should be considered in addition to the thermal phonons. If the effect of the thermal phonons was to dominate the unpoisoning process, then t_{odd} should saturate at the phonon temperature of the sample. We expect the phonon temperature to be lower than the quasiparticle temperature and close to the base temperature of the dilution refrigerator ($T\sim 50$ mK). In these devices t_{odd} saturates at a temperature close to t_{even} implying that recombination phonons may play a significant role in the unpoisoning process. The relative effect of thermal and recombination phonons may depend on sample parameters. In a previous device with lower charging energy,³ t_{odd} was observed to saturate at a lower temperature than t_{even} .

In the QT device with $t_{odd}=880$ ns [Fig. 4(a)], we see no temperature dependence of t_{odd} , suggesting the quasiparticle exits without thermalization. This behavior may be explained by the existence of two unpoisoning mechanisms.²¹ Either the quasiparticle tunnels off the island immediately, in an elastic unpoisoning process [Fig. 2(c)], or it relaxes to the bottom of the potential well with a rate γ which strongly depends on the island potential depth ($\gamma\propto dE^{3.5}$). Subse-

quently, thermal activation is required for the unpoisoning event to occur. The escape rate $t_{odd}^{-1} = \frac{G\delta_i}{2e^2} \nu(T) \frac{\delta E}{\delta E + \Delta}$ for the first scenario is governed by the conductance of the junctions, the quasiparticle level spacing on the island, δ_i , and the initial energy of the quasiparticle (of order T).^{21,22} We calculate $t_{odd} = 280$ ns, in reasonable agreement with the measured value. The reason for the dominance of the elastic process in this sample is not clear. One possibility is variation of the thin films leading to a reduced potential well depth on the island.

Our measurements are sensitive to unpoisoning and poisoning processes, however this is not always the case. For example, in electrometry of a CPB by a single-electron transistor, averaged measurements of the box charge are typically performed.⁶ This yields the average probability of having a quasiparticle on the island p_{odd} without directly providing details of the individual tunneling rates. Taking our measured times for the QT (NT) device, then $p_{odd} = \frac{t_{odd}}{t_{even} + t_{odd}} = 0.75$ (0.15) at base temperature. The time the SCPT remains poisoned is greater in the QT device, even though the tunneling rate onto the island is significantly reduced. Thus

one might conclude from p_{odd} that the quasiparticle traps actually had a negative effect. Figure 4(b) plots p_{odd} for all the samples measured and shows no obvious trend between the QT and NT devices. This is consistent with the electrometry measurements of a CPB observing no clear benefit of quasiparticle traps.¹⁶

In conclusion, quasiparticle traps definitely reduce quasiparticle poisoning in superconducting qubits: a reduction of 2–3 orders of magnitude in poisoning rate was observed here. However, quasiparticle traps are only part of the solution to the quasiparticle poisoning problem. They should be used in conjunction with small charging energy devices and graded superconducting gaps to ensure high unpoisoning rates.

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²²The expression given in Ref. 21, $\Delta_i = \Delta_j$. Here we include a modification for different gaps which is valid as long as $\Delta_i, \Delta_j > \delta E \gg kT$.

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²⁵The island volume for the QT devices was approximately three times that for the NT case. This accounts for a factor of 3 difference in t_{odd} times (Ref. 21).