Measurement of Single Electron Lifetimes in a Multijunction Trap

P.D. Dresselhaus, L. Ji, Siyuan Han, J.E. Lukens, and K.K. Likharev
Department of Physics, State University of New York at Stony Brook, Stony Brook, New York 11794-3800
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Single electron traps have been shown to hold a single charge for over 2 h at 50 mK (limited by observation time). The traps, each with an array of seven $Al/AlO_x/Al$ tunnel junctions of normal state resistance, $R \sim 300$ kΩ, and capacitance, $C \sim 0.15$ fF, have trapped electrons with the junctions in both the superconducting and normal states. The temperature dependence of the escape time has been measured for one trap in the superconducting state near 0.35 K and observed to follow an Arrhenius law with an energy barrier $\Delta U/k_B \sim 4$ K in agreement with theoretical estimates.

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Over the past several years, there has been a rapid development of devices and circuits in which the motion of single electrons can be controlled [1,2]. The key to these developments has been the ability to fabricate, in a controlled way, very small tunnel junctions with low capacitance C and high resistance R for which the charging energy for the motion of a single electron, $e^2/2C$, substantially exceeds the thermal and quantum fluctuations, resulting in a Coulomb blockade of electron motion for appropriate bias conditions. This effect has been used in single electron transistors (SET), which have a demonstrated charge sensitivity of 10 $\mathrm{yC}/\sqrt{\mathrm{Hz}}$ [3]. In a second class of devices, the motion of single electrons is synchronized with an rf modulation of the Coulomb barriers, effectively counting the number of electrons moving through the circuit and thus giving a direct measure of the current for possible metrological applications [4]. In addition, digital devices coding information bits by single electrons have been proposed [5].

A fundamental question about the operation of these latter two devices is the error rate. That is, how frequently and by what processes can electrons transit the device even when a Coulomb barrier to their motion exists? One of the clearest systems in which to study barrier confinement is a single electron trap where an electron should be held in a metastable (or bistable) state for long periods. Published results to date on the trapping of single electrons in these systems [6,7] have reported maximum trapping times of less than 1 s; published error rates on electron pumps are also about 1 s, each much shorter than might be expected on the basis of existing theory [4]. Recent results also report trapping of multiple electrons for longer periods [8]. In this Letter, we report observations of single electron trapping for over 10^4 s in traps consisting of one dimensional arrays of tunnel junctions. The temperature dependence of the escape time from the trap is compared with theories of thermally activated escape.

One of the simplest technologies for the fabrication of single electron devices has been $Al/AlO_x/Al$ tunnel junctions, where self-aligned masking techniques using electron beam lithography (EBL) [9] can give reasonably reproducible junctions with capacitances in the range of 100 aF. This technology has been used to fabricate a trap containing an array of seven junctions as shown in Fig. 1(a). The junctions separate aluminum "islands," with the bottom island serving as a "well" for the trapping of single electrons. An additional electrode with potential V_b is coupled to the well through the capacitance C_w. The charge state of the well may be detected by an SET electrometer capacitively coupled to the well from the bottom through a nanowire. Figure 1(b) shows the Gibbs' potential of the trap, relative to the potential of an uncharged configuration, ΔU as a function of electron position when the trap contains one electron located on one of the seven islands. An electron entering the trap from electrode "0" at potential V_0 must surmount a potential barrier $\Delta U_i(V_0, V_b)$ [cf. Fig. 1(b)] as it tunnels from the top through the successive junctions to reach the well where it is trapped by a barrier $\Delta U_o(V_0, V_b)$. A

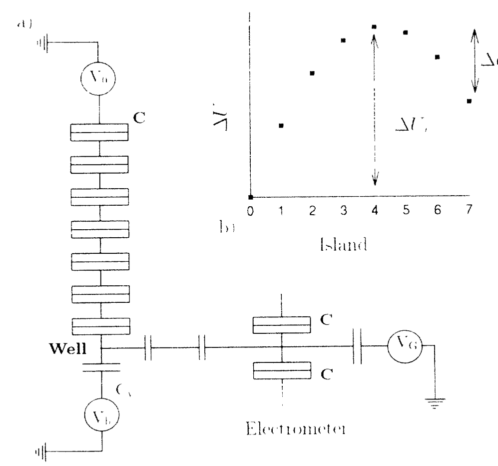

FIG. 1. (a) The schematic of a single electron trap and its monitoring SET electrometer. (b) The energy configuration diagram showing the change in free energy, ΔU, associated with placing an electron on a particular island.

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key feature of the trap is the existence of these barriers, which makes it possible for the trap to have metastable states, i.e., the charge state of the trap may be hysteretic with V_0. For example, V_0 can be adjusted to suppress the barrier ΔU_i, drawing an electron into the trap, then reset so that the system has equal energy barriers for trapping and escape ($\Delta U_o = \Delta U_i$). The escape barrier can prevent the electron from leaving the trap during the measurement. Clearly such a barrier requires at least two tunnel junctions ($N = 2$). The lifetime for thermally activated escape of an electron from the well, τ_o, is given by

$$\tau_o \approx RC \exp(\Delta U_o / k_B T), \tag{1}$$

where T is the temperature and k_B Boltzmann's constant. The time τ_i for thermally activated entry of an electron into the well is expressed similarly through ΔU_i.

Assuming the stray capacitances C_s of the islands are negligible, the height of the energy barrier for the equal barrier condition depends on the number of junctions in the array as [5]

$$\Delta U = \frac{e^2}{2C} \frac{N^2 C_w}{4(C + NC_w)}. \tag{2}$$

According to these relations an array of $N = 7$ junctions with $C = 150$ aF, $R = 300$ kΩ, and $C_w = 10$ aF implies an energy barrier $\Delta U \approx 3.5$ K; thus charge trapping should be observed for 1 s at $T \simeq 0.15$ K. For finite C_s, the barrier height should saturate as N increases beyond roughly $2\sqrt{C/C_s}$ [10]. For typical device parameters, $N = 7$ junction is the longest array in which stray capacitance will not play a major role.

Another consideration which makes it desirable to increase the number of junctions in the array is the suppression of higher order tunneling processes (cotunneling) in which an electron can tunnel directly into (or out of) the well without having to pass through the higher energy levels of the islands. These cotunneling times are given approximately by [5]

$$\tau_{\text{ct}} \simeq 2RC \left(\frac{4\pi^2 R}{R_K} \right)^{N-1} \frac{(2N-1)![(N-1)!]^2}{(\frac{N}{2})^{2N}}, \tag{3}$$

where $R_K = h/e^2 \simeq 25$ kΩ is the quantum unit of resistance. For a 7 junction, $R = 300$ kΩ normal state array, Eq. (3) yields $\tau_{\text{ct}} \approx 10^{13}$ s. For superconducting devices, R should be approximated by the much greater quasiparticle resistance, R_{qp}, yielding negligible cotunneling for $T \ll T_c$.

Small $Al/AlO_x/Al$ tunnel junctions were fabricated on Si and SiO_2 substrates by double angle shadow evaporation of Al (30 nm and 50 nm thick, respectively) with a thermal oxidation step in between to form the tunnel barrier. A suspended PMMA/copolymer double layer resist mask patterned by electron-beam lithography (EBL) was used as a liftoff mask. The typical linewidth is about 70 nm and the resulting overlap between the base and the counter electrode was ~ 50 nm. Stand-alone single junctions, arrays, and electrometers were fabricated on the same 68-lead chip with the trap for the purpose of diagnostics. An estimate of the normal resistance of the junctions in the trap was obtained from the electrometer's resistance measured from its I-V curve at $eV \gg E_c = e^2/C_\Sigma$ (E_c is the charging energy and C_Σ is the total capacitance of the electrometer island), where the I-V curve is nearly linear. The typical tunnel resistance of the junction, which can be controlled during the fabrication by either adjusting the oxidation parameters or varying the junction's size, is ~ 300 kΩ. The sum capacitance, C_Σ, whose components are the junctions' capacitance and the sum of all gate capacitances, is measured from the maximum magnitude of the electrometer voltage modulation at low temperature (i.e., $V_m = E_c/e = e/C_\Sigma$). The typical junction capacitance is 0.15 ± 0.05 fF which dominates C_Σ, giving $E_c/k_B \sim 6$ K. This relatively small charging energy makes it necessary to cool the electrometer to below 1 K for sensitive measurements. Measurement of the electrometer response to variation of V_0 and V_b for a constant trap charge gives the effective capacitance between electrodes "0" and "b" and the electrometer as 14 aF and 4 aF, respectively.

Low temperature measurements were carried out in a dilution refrigerator. The sample was located inside a helium filled copper can, which provided both electrical shielding and thermal contact. All 68 leads entering the can had low pass filters, which were thermally anchored to the mixing chamber. The sample can was located on a temperature regulated platform which could be maintained at temperatures between 1 K and 15 mK. Extensive acoustic, as well as electromagnetic, isolation was required due to the high impedances involved. The electrometer was current biased ($I_b \simeq 50$ pA) through a room temperature 200 MΩ resistor at the point of maximum charge sensitivity. As the trap bias potential V_0, is varied, a cancellation signal, proportional to V_0, is applied to the electrometer gate such that the electrometer voltage V_{el} remains constant as long as the charge configuration of the array does not change. The resulting electrometer output is proportional to the change in the trap charge over a large range of trap bias voltage.

Figure 2 contains a series of curves showing the electrometer charge ΔQ_{el} as a function of trap bias V_0 for several temperatures. Vertical jumps corresponding to charge entering or exiting the trap are clearly seen. At lower temperatures, these jumps develop into hysteresis loops for which the trap has metastable states with barriers high enough to give lifetimes of at least the several seconds required to sweep the bias across the loop. For the highest temperature shown, 360 mK, the thermal fluctuations have become strong enough for the transition between the two states of the trap to occur on the time scale of the sweep. At this temperature two clearly defined levels are still observed (Fig. 3, inset), but no stable loop exists.

We argue that these levels, for which the charge in-

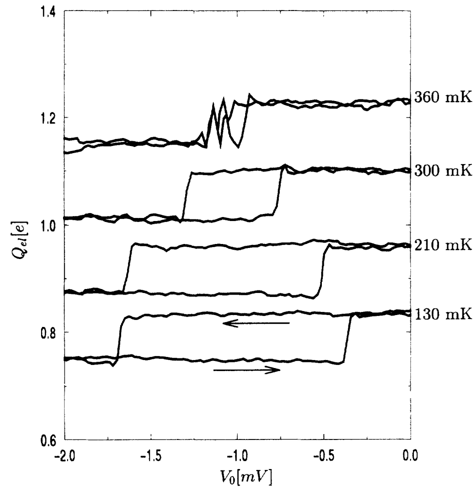

FIG. 2. Electrometer's charge vs applied trap voltage at (a) $T = 0.130$ K, (b) $T = 0.21$ K, (c) $T = 0.30$ K, (d) $T = 0.36$ K. V_0 is ramped at a speed of 0.3 mV/s. The arrows indicate the direction of the voltage sweep. The curves are vertically offset for clarity.

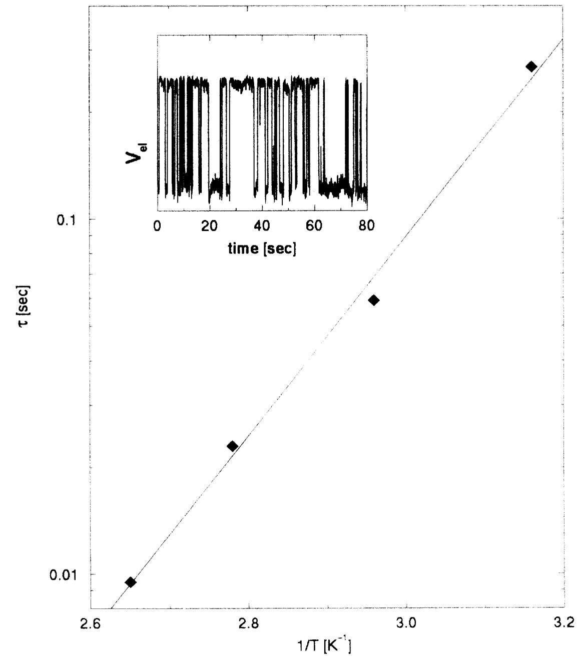

FIG. 3. Arrhenius plot of measured lifetime vs temperature. The slope of this plot gives the thermal activation energy $E_a = 6.4 \pm 0.3$ K and ln(prefactor) $= -21.7 \pm 1.0$. The inset is a time record of V_{el} at $T = 0.32$ K.

duced on the electrometer ΔQ_{el} differs by $0.09e$, correspond to charge states of the well differing by one electron. First, the jump amplitudes for the lowest level loops ($V_0 \simeq 0$) are always the same height for a given sample whether induced by repeated variations of the bias, V_0, or, at higher temperatures, by thermal fluctuations at fixed bias. Hence, the same amount of charge enters or leaves the well for each transition. For one sample, a magnetic field of 1 T was applied to drive the Al into the normal state. The jump amplitude did not change, thus excluding the possibility that the jumps are due to superconducting pairs entering and exiting the trap. Models of the free energy barrier give a much higher barrier for the transfer of multiple electrons; e.g., the simple model of Eq. (2) gives a barrier 4 times as high for a $2e$ transfer assuming the biases are adjusted for equal lifetimes. The observation that all transitions involve the same unit of charge, coupled with the lack of any plausible reason for charge to move in fixed multiple electron units, leads us to conclude that we observe single electron trapping and escape. This conclusion is also consistent with the signal amplitude calculated from the EBL defined circuit geometry [11].

The simplest configuration to observe the lifetime τ is at the bias point where $\Delta U_i = \Delta U_0$; thus the electron spends equal time trapped and untrapped. The temperature dependence of this lifetime has been measured near 0.35 K for the sample in the superconducting state. We have measured τ using two methods: the first is to directly record V_{el} as a function of time; in the second τ is extracted from the measured spectral density $S_V(\omega)$ of the switching between states. For the equal barrier configuration, the output voltage signal of the electrometer due to this switching resembles random telegraph noise. The spectral density of this signal S_V is given by [12]

$$S_V(\omega) = \frac{A^2\tau}{8\pi[1 + (\omega\tau/2)^2]}, \tag{4}$$

where A is the size of the voltage jump in electrometer's output caused by adding an electron to the trap and ω is the angular frequency. The direct measurement is most suitable for long lifetimes (0.05 s$< \tau < 10^3$ s) and the spectral measurement for shorter lifetimes (0.001 s$< \tau <$ 0.1 s). In the region where both methods are applicable, the results are in good agreement. As seen in Fig. 3, the lifetime is well described by an Arrhenius law as in Eq. (1).

The thermal activation energy can be determined by measuring the lifetime τ as a function of temperature. The slope of the Arrhenius plot ($\ln\tau$ vs $1/k_BT$) gives the apparent thermal activation energy E_a (cf. Fig. 3). For superconducting junctions, however, the resistance R in Eq. (1) is approximately the subgap quasiparticle resistance, which ideally also has an exponential temperature dependence on $1/T$ for $T \ll T_c$ [13],

$$R_{qp} \propto R_N \exp(\Delta_{Al}/k_BT). \tag{5}$$

Here Δ_{Al} is the superconducting gap energy of aluminum, measured from the I-V curve of a single junction fabricated on the same chip to be 0.22 meV (2.55 K) for

$T \ll T_c$. In order to get a qualitative check for the subgap quasiparticle resistance of the junctions in the array, we have measured the retrapping current, I_r [14], of a single junction fabricated on the same chip. The quasiparticle resistance implied from I_r varied exponentially between 0.25 K and 0.5 K in agreement with Eq. (5) and other works [15]. The measured thermal activation energy would then be the sum of $\Delta_{\rm Al}$ and the free energy barrier ΔU, i.e., $\Delta U = E_a - \Delta_{\rm Al}$. The apparent activation energy determined from the data of Fig. 3 is $E_a = 6.4 \pm 0.3$ K with a prefactor of 3×10^{-10} s (with a factor of 3 uncertainty). These data imply that $\Delta U = 3.8 \pm 0.5$ K and the prefactor is of order $R_N C$. The close agreement of the measured ΔU with the value of 3.5 K calculated using Eq. (2) is somewhat fortuitous, since the uncertainties in C and C_w give at least a factor of 2 uncertainty in the calculated ΔU even neglecting the approximate nature of the model used. Unknown residual charges Q_r of a fraction of e induced on the array islands may change the barrier calculated in Eq. (2). Occasionally changes of the residual charge were observed, e.g., when the sample was warmed to 1 K. Since the application of appropriate values of V_0 and V_b recovered a barrier height within 20% of the original, we conclude that the uncertainties due to residual charge are small compared to the uncertainty in capacitances when determining barrier size. These results are consistent with calculations of ΔU with random values of $Q_r < e/2$ on the islands.

More refined calculations of the energy barrier have been carried out based on the complete matrix of capacitances among all elements of the device, modeled from the programed pattern input to the EBL system. These results, which will be presented in detail elsewhere [11], are consistent with those of the approximate model of Eq. (2). However, the calculations based on the complete capacitance matrix are potentially more accurate once the sample parameters can be more accurately determined.

The quantitative rate measurements above have been possible on only one sample to date due to excess charge noise. However, hysteresis loops in V_0 vs $V_{\rm el}$, which manifest the trapping of a single charge, have been observed in both the superconducting and the normal states on several samples fabricated with the same nominal parameters and design. The temperature at which all the hysteresis loops were destroyed by thermal fluctuations (approximately corresponding to $\tau \sim 0.1$ s) varied from ~ 0.2 K to ~ 0.7 K. The thermal activation energy estimated from the onset of the hysteresis loop is hence between 4 and 14 K assuming a roughly constant prefactor $R_N C \sim 10^{-10}$ s.

The establishment of an experimental limit for the low temperature trapping time is limited both by the patience of the observer and by the charge noise associated with the electrometer. The electrometer output shows long term drift as well as discrete jumps which are unrelated to the state of the trap. These jumps, which have characteristic times of a few seconds to several hours, seem to have no systematic dependence on controllable parameters and present a serious problem for potential device application of single electronics. As a result of this noise, the state of the trap for long times cannot be reliably determined simply by observing $V_{\rm el}$; rather a "destructive readout" of the trap state is required. At various intervals, ranging up to 2 h, the trap potential V_0 was varied to retrace the trap hysteresis loop and determine the state of the trap. For periods of reasonably low electrometer noise the trap was found in its initial state when the readout was made.

In summary, single electron traps have been made using a relatively simple array design. The thermal activation energy has been measured to be 3.8 ± 0.5 K which is in reasonable agreement with the estimated barrier height. This implies that the trapping time of a single electron could exceed 10^{18} s at low T (~ 0.05 K). The observed trapping time of ~ 2 h was limited by the measurement time.

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