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Modulation of the charge of a single-electron transistor by distant defects

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We have systematically measured two-level fluctuator (TLF) noise in a single-electron tunneling transistor. From the amplitude, duty cycle, and presence of intermediate states, we conclude that there is a *cluster* of triggered TLF's in this case. The systematic dependence of switching rate on gate voltage, and the lack of rate dependence on a finer scale or on source-drain voltage, tell us unambiguously that the TLF's are not located in the tunnel barriers. We thus conclude, as has been previously inferred, that noisy defects outside the barrier can lead to significant modulation of the transistor island charge (up to about 0.2 e). [S0163-1829(97)08836-X]

In the decade since their discovery, single-electron tunneling (SET) devices have received a great deal of attention,[1] both in terms of the physics of the Coulomb blockade and for potential device applications. The most advanced application to date is for single devices used in a capacitance standard.[2,3] Other applications, including a current standard as well as digital memory or logic, will require integration of large numbers of SET devices. A basic difficulty with achieving this integration is the charge offset problem. In the context of a SET transistor (SETT), with one gate and one island onto which electrons tunnel, this problem manifests itself by an effective random offset to the induced charge on the island. Since the transistor action (source-drain current versus gate voltage) is periodic, this random offset makes it impossible to predict the (on or off) state, and thus very difficult to design an integrated device.

For SET devices (in particular, those based on metal-insulator-metal (MIM) tunnel junctions), it is widely believed that, in addition to obvious sources of charge polarization such as nearby electrodes, an important source of the charge offset is trapped, possibly mobile, atomic-sized charged defects in the disordered thin films or interfaces. These charged defects, if mobile, will also give rise to time-dependent two-level-fluctuator (TLF) (i.e., telegraph) noise for a single defect, or to $1/f$ noise for a larger number, consistent with a wide range of observations of TLF noise in other small lithographic devices operated at low temperatures.[4]

Thus, we wish to investigate the identity of these trapped charges, which have also been observed to give rise to TLF noise in SET devices.[5] One simple question is the *location* of these defects: for the MIM devices, are they in the oxide tunnel barriers, or elsewhere? A simple argument by Song *et al.*[6] based on the size of the electric fields (the voltage drop and therefore the field is predominantly inside the barriers) suggests a difference between these two locations: for a single defect (with effective charge 1 e) in the tunnel barrier, the amplitude of the static charge offset and/or the time-dependent fluctuation (noise) induced on the SET island can be a significant fraction of e (i.e., greater than 0.1 e). For a defect outside the barrier, the amplitude of the charge offset and noise should have a smaller magnitude (and thus the mobile defects will only contribute to the $1/f$ noise, but not produce large TLF's). More recently, Zorin and co-workers[7] showed a correlation in the $1/f$ noise (and in some TLF's) between two SETT's near each other, which they interpreted as meaning that a significant fraction of the noise-producing defects *were not in the barriers*. They also modeled the capacitive coupling, and showed that significant coupling to the island is possible for a narrow region around the islands.

However, the experimental observation of such a large capacitive coupling to the island charge from defects not in the tunnel barriers has not been confirmed to date (i.e., the observation of a single TLF from a nonbarrier defect). In this paper, we describe just such observations, from measurements of time-dependent noise in a particular SETT, which had a conventional design but which was unusually noisy. The noise can only be understood as arising from a cluster of TLF's. We show that the dependence of the switching rates on gate voltage unambiguously demonstrates that the TLF's are not in the tunnel barriers. By examining the time traces, we can conclude that individual TLF's, even though not in the tunnel barriers, can indeed modulate the SETT island charge by a significant fraction of e (electronic charge). This conclusion is independent of the detailed microscopic nature of the TLF's, and does not depend on the presence of the cluster (which simply made it easier to observe in this particular device).

We fabricated Al/AlO$_x$/Al SETT's on unoxidized Si using standard lithographic and processing techniques,[8] and measured their electrical behavior at temperatures of about 15 mK, where they are superconducting; for experimental details, see Clark *et al.*[3] We measured the source-drain current I_{SD} as a function of bias voltage V_{SD} and gate voltage V_A. For the measurements reported here, we kept V_{SD} near 4Δ (on the edge of the superconducting gap), where I_{SD} is most sensitive to changes in V_{SD} or V_A.

When we first measured the device on which the results are reported here, we observed fairly standard performance; I_{SD} (V_A) is shown in Fig. 1(a). We see here the periodic dependence of the SET oscillation, with a period e/C_g corresponding to the addition of one extra electron on the island.[1] The measurements reported herein were done with the configuration shown in Fig. 1(b), where C_{cryo} was 1 pF, C_{stray} was about 15 pF, and C_g was about 0.5 fF. The value of C_{stray}, and thus the values of V_A given V_{source}, were both

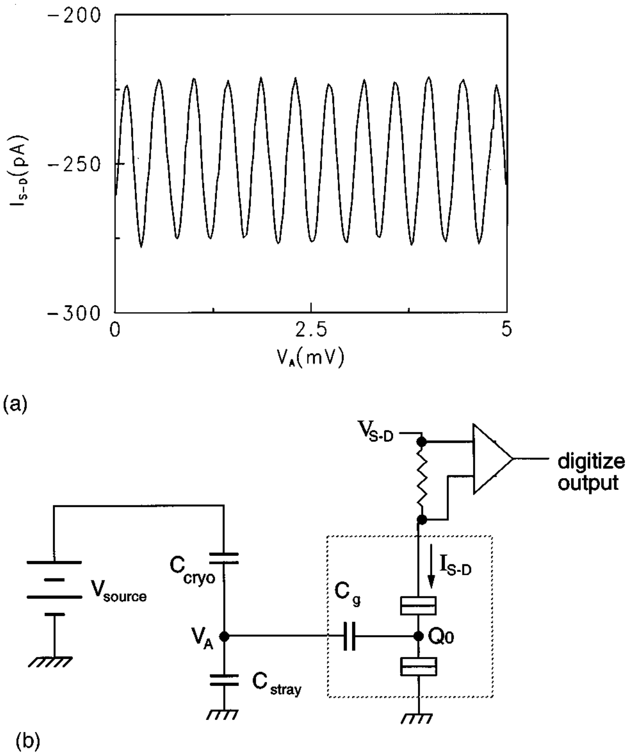

FIG. 1. (a) Source-drain current I_{SD} at $V_{SD}=-0.80$ mV as a function of gate voltage V_A, showing the standard SET oscillations, with a period of $1e/C_g$. (b) Circuit diagram of the experiment. The island charge is Q_0. Elements inside the dotted box are on the substrate.

inferred from the value of C_g, measured separately. The tunnel junction resistances were about 0.5 MΩ each.

After about two weeks of operation, the device developed a large TLF-type noise, as shown in Fig. 2. The sudden onset or turnoff of TLF noise is a common observation in small electrical devices, both metal and semiconducting.[9] Figure 2 shows the time dependence of I_{SD} at fixed V_{SD}. Each trace corresponds to a different fixed value of V_A, with expanded time scales as shown; as V_A increased, we digitized I_{SD} at an increasing rate, so as to maintain roughly the same number of points per fluctuation for all measurements. This set of noise measurements was made over the course of two days; over the course of weeks, the noise as a function of V_A was reproducible and stable as we swept repeatedly through the range of values. We made a sparse set of measurements at negative V_A, which appeared qualitatively similar (rate seemed to increase as V_A became more negative). It was not possible experimentally to measure the dependence on temperature.

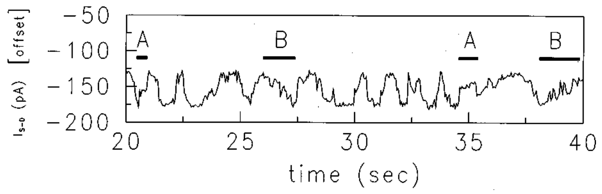

FIG. 3. An expanded view of the trace in Fig. 2 with $V_A = 0.30$ V, showing examples of (A) midlevel states and (B) cascading behavior.

We can immediately see several features of this noise: (1) the duty cycle[10] was always about 50%, (2) the amplitude ΔI_{SD} over which the current fluctuates stayed the same, and was the same value (about 60 pA) as the size of the SET oscillations I_{SD} (V_A) [see Fig. 1(a)]. Also, (3) this noise is clearly not a single clean TLF. Rather, there are many levels, often cascading over large excursions in the island charge Q_0. Figure 3 shows some particular examples of both stable levels in the middle of the I_{SD} range (A), as well as cascading behavior (B).

Finally, we also see from Fig. 2 that as a function of V_A, the rates of switching speed up quite dramatically over the range shown; this range of V_A corresponds to between about 400 and 1300 extra electrons induced on the SETT island. We note that there was no dependence of the switching rates on the fine V_A scale seen in Fig. 1(a). To demonstrate the systematic dependence in a different way, Fig. 4 shows the power spectral density of three of the traces in Fig. 2; the

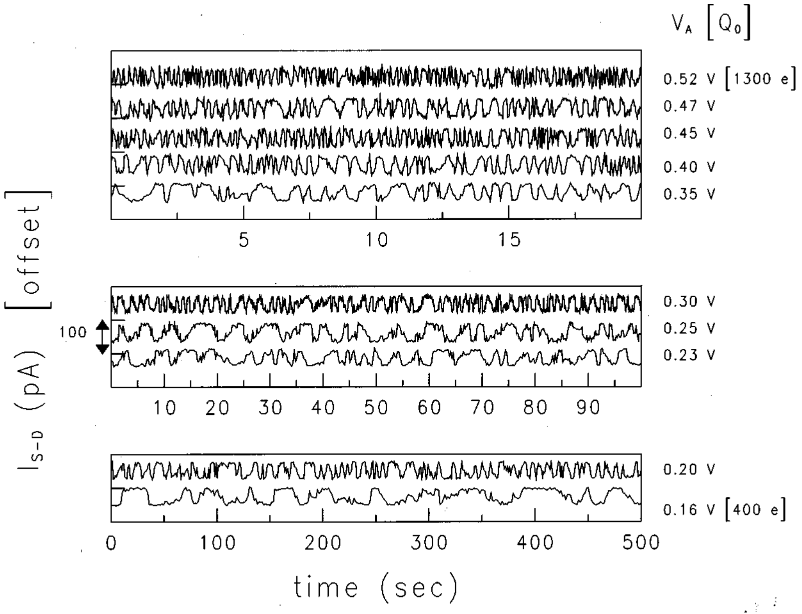

FIG. 2. I_{SD} as a function of time, at fixed source-drain voltage, and for fixed values of the gate voltage V_A, as indicated. Note (1) the constant duty cycle of 50%, (2) the constant amplitude of about 60 pA, equal to the size of the oscillation in I_{SD} (V_A) [Fig. 1(a)], and (3) the existence of multiple discrete levels and cascading behavior. Each successive panel is expanded by a factor of 5 in time; this shows the strong systematic dependence of switching rate on V_A.

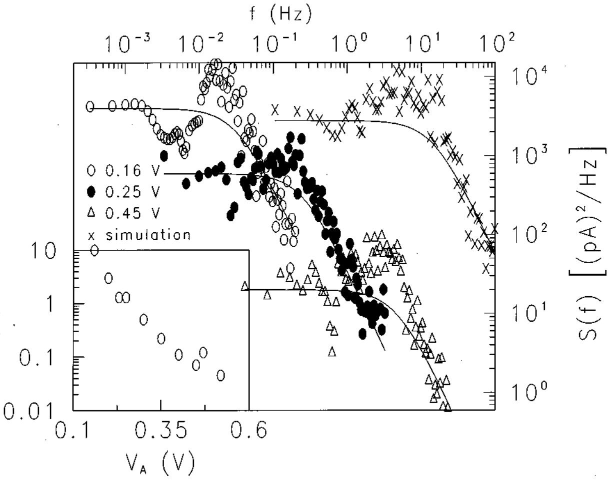

FIG. 4. Power spectral densities $S(f\ )$ of three of the traces in Fig. 2, as indicated. Each is fit by a Lorentzian (solid lines). The fourth $S(f\ )$ is from a simulation (as described in the text) using a triggered cluster of 100 TLF's, each with switching size randomly distributed between 0 and $0.1e$; also shown is a fitted Lorentzian. Note that the simulated $S(f\ )$ shows all of the features of the data, including the extra spectral weight near the knee frequency. Inset: Derived characteristic time τ from the fits, showing a roughly exponential dependence on gate voltage V_A.

other spectra are similar. We see quite clearly that the spectra all fit roughly to a Lorentzian $S(f\ )=S_0\tau/[1+(\pi\tau f\ )^2]$; we will discuss later the deviation (extra spectral density) near the knee frequency. To show the dependence of the rates on V_A, we have fit Lorentzians to the spectra; as a consistency check, we confirmed that the fit parameter S_0 varied by less than 30% over the full range of V_A, and agreed with the amplitude of the switching in Fig. 2. To show the strong dependence of the switching rates on gate voltage, we have plotted the fit parameter τ in the semilogarithmic inset to Fig. 4. We can see that τ is roughly exponentially dependent on V_A over 2 1/2 decades of time.

We now discuss three of the features noticeable in Figs. 2 and 3: the constant amplitude at the value of the SETT oscillations, the constant duty cycle (50%), and the multilevel and cascading behavior. The three features can all be consistently explained in the context of a single physical picture: that there is a *cluster* of TLF's, which change their configuration coherently (i.e., they are triggered in their up or down flips by a single TLF event). This picture has again been observed previously in other small devices; one particularly clean example is in Al/SiO$_2$/Si (MOS) tunnel junctions.[9]

A schematic picture of this model for our device is indicated in Fig. 5. Here, we have a cluster of five TLF's, each with a fluctuation amplitude a small fraction of $1e$, triggered to switch by a single event. This causes the island charge Q_0 to cascade up and down in time, with total excursions greater than $e/2$. When this $Q_0(t)$ is put through the periodic I_{SD} (Q_0), it turns into an $I_{\mathrm{SD}}(t)$ as shown. We have slightly exaggerated the flatness of I_{SD} (Q_0) for purposes of illustration, but the idea is clear: for a cluster of TLF's which have individual switch sizes small compared to $e/2$, but with total excursion comparable to or larger than $e/2$, the periodic nature of I_{SD} (Q_0) will yield a current fluctuation with amplitude the same as the SETT oscillations, a duty cycle of 50%, and occasional examples of intermediate levels or cascading behavior. Thus, this simple physical model of a triggered cluster, which has been observed before in tunnel junctions, results in the type of noise seen in Fig. 2, when viewed through the nonlinear prism of the SETT transistor action I_{SD} (Q_0).

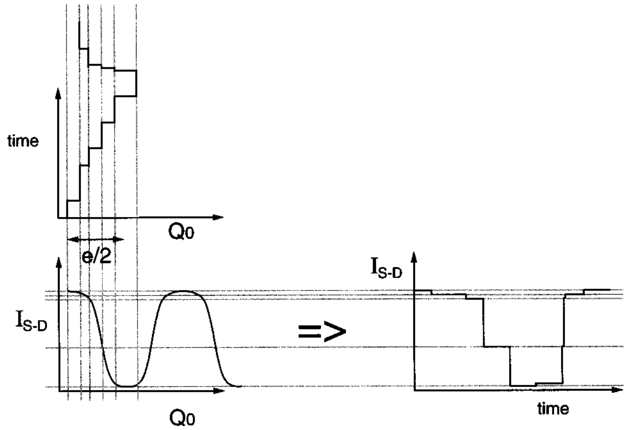

FIG. 5. Schematic depiction of the physical origin of the noise: a triggered cluster of five TLF's gives rise to a cascade up and then down of Q_0 (upper panel). As modulated by the SET transistor I_{SD} (V_A) (lower left), this yields a time trace I_{SD} (time) roughly switching between extremal values, but with midlevel states and some cascading (lower right).

We have also performed simulations of the events depicted in Fig. 5, allowing for random distributions of switch size and characteristic time for a variable number of triggered TLF's; only a subset of the TLF's trigger each time, so that the limits of Q_0 vary over time. We can produce time traces very similar in appearance to Fig. 2, for a fairly wide range of parameters. In addition, we can reproduce the spectra seen in Fig. 4, *including the extra spectral weight near the knee frequency*, with a narrower range of parameters: individual switch size of maximum size 0.1 e to 0.2 e, and total cluster number of order 50 or greater. For example, for the simulation shown (with 100 switchers total), the number switching between each trigger event varied between zero and about 25. Our conclusion is that, presuming that the noise does indeed arise from microscopic mobile charged defects (see below for a discussion of possible artifactual origin), a cluster of triggered TLF's is the origin of the noise seen in our device.

We now briefly discuss the roughly exponential dependence of switching rates or times on gate voltage, $\tau(V_A)$. In the absence of detailed knowledge about the identity of the mobile defects in SET devices, we can try to find useful information in studies of TLF noise in similar devices. The most studied TLF's have been in MOSFET's and bipolar transistors.[4] In all cases, one of the rates (up or down) uniformly and roughly exponentially increases with gate voltage, while the other rate can increase, have no dependence, or decrease with gate voltage. In many cases, both rates increase with gate voltage,[4,11] in agreement with our data.

For MOSFET's and bipolar transistors, the TLF's are identified as electron traps, with the rates corresponding to capture and emission; if the rates have opposite dependence on gate voltage, the one which increases with gate voltage is identified as the capture rate. Without a knowledge of the temperature dependence of the TLF-type noise reported in this paper (and thus without knowledge of the identity), we can do no more than speculate about the physical meaning of the dependence of switching rates on gate voltage. However, we must emphasize that, *independent of the origin of the dependence of τ on V_A, we believe that the basic picture of a cluster of triggered TLF's must be the explanation of the amplitude, duty cycle, and multilevel-cascading behaviors seen in Fig. 2.*

The most significant finding in the data is the *systematic, nonperiodic* gate voltage dependence of the switching rates on V_A. This dependence gives us information about the location of the charged defects: we know that the voltage across the tunnel junctions depends periodically on V_A (with period $e/C_g = 0.4\,\mathrm{mV}$) (Ref. 1) as in Fig. 1(a); thus, if the defects were in the tunnel barriers their only rate dependence on V_A would be with the same period, but with no large-scale monotonic dependence. The fact that the data are opposite to this tells us *unambiguously that these defects, which clearly modulate Q_0 by a significant fraction of $1e$, are not located in the tunnel barriers*, in contrast to some previous suggestions,[6] but in agreement with the indirect work of Zorin *et al.*,[7] looking at noise correlation measurements.

Finally, we consider the possibility of an artifactual origin of all of these data. In particular, we consider the effect of the significant capacitance C_{cryo} in series between the voltage source and C_g. If there is leakage of the voltage V_A through either C_{cryo} or C_{stray} (for instance, through the substrate to ground), this will manifest as a drift in Q_0, and thus a periodic fluctuation in I_{SD}. If this leakage is not a smooth current, but rather stochastic tunneling, it will appear as a drift made of discrete steps in Q_0 and, similarly to the picture of Fig. 5, would reproduce the data in Fig. 2.

We first make a qualitative observation that bears on this surmise: After the TLF noise arose, at times we slowly ramped V_A [similar to Fig. 1(a)], and saw a simple superposition of the SET I_{SD} (V_A) oscillations and the TLF noise; *the rate of the latter depended only on the magnitude of V_A, while the period of the SET oscillations remained fixed, with the same value as in Fig. 1(a).* This strongly suggests that the TLF noise is not due to a slow drift in V_A.

We can also make a simple quantitative argument to refute the possible artifact explanation, based on the observation that such leakage would change V_A by a large amount, easily observable in the time traces. Measurements of I_{SD} (t), of which portions are shown in Fig. 2, encompass a total of between 50 and 300 ''switches.'' If this were due to drift, Q_0 would thus have changed by between $50e$ and $300e$ over the course of a single measurement. For the dependence of rates on V_A shown in Fig. 4, this would correspond to changes in the rates, over the course of a single time trace, of factors between 1.3 (for a change of $50e$) and 6 ($300e$). We see no such change in the time traces we have observed, with an uncertainty of less than a factor of 1.3. We note briefly that this same argument holds for V_{source}-V_A (the voltage across C_{cryo} alone).

Finally, there is also a possibility that both C_{cryo} and C_{stray} are simultaneously leaking, with leakage resistances such that V_A remains fixed. This would require the ratio of the two leakage resistances be equal to the ratio of the capacitances at all values of V_A. We consider this unlikely, since such leakage resistances would not be Ohmic, and also because of the observed lack of history dependence of the noise on V_A.

In conclusion, we have observed time-dependent noise in a particularly noisy SET transistor. We have clearly shown that the amplitude, duty cycle, and multilevel-cascading behaviors can all be naturally explained by a triggered cluster of TLF's, as observed by others in similar materials systems.[9,4] We speculate that this is due to a highly defected ''patch'' somewhere on the surface of the substrate or device, near the SET island; one specific possibility is electron traps on a surface of the island. Our most important finding is that the reproducible, large-scale dependence of switching rates on gate voltage, with no periodic one-electron dependence, clearly demonstrates that, *even though the TLFs are not in the tunnel barriers, they are capable of modulating the SET island charge by significant fractions of $1e$ (less than or about $0.2\ e$).* We note that this last finding is independent of the microscopic nature of the TLF's in our particular devices.

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