Long-Term Charge Offset and Glassy Dynamics in SET Transistors

Neil M. Zimmerman and William H. Huber
National Institute of Standards and Technology[1]
Gaithersburg, MD 20899-8112

Abstract

We report long-term measurements of the charge offset Q_0 in SET (single-electron tunneling) transistors, made of Al/AlO$_x$/Al tunnel junctions. In one case, we saw a Q_0 which was constant (within 0.1 e) over a twelve-day period, except for one excursion of short interval. In most cases, we see a transient (since cooldown) relaxation of the rate of wandering of Q_0 over one to two weeks, which is very reminiscent of the non-equilibrium heat evolution observed in glasses. We propose that this mechanism drives both the initial high level of noise in SET transistors, as well as the high error rate in SET pumps.

Introduction

Several groups have measured the charge offset noise in SET transistors in the sub-audio (typically 0.1 Hz to 1 kHz) frequency range. This noise forms the noise floor for sensitive electrical measurements. However, the static charge offset, and its long-term drift, have not been systematically studied before. The drift is of importance because it precludes integration of SET devices, both for memory/logic applications as well as for parallelization of a large number of SET pumps (to provide a larger current). This provides one motivation for performing systematic, quantitative measurements of Q_0 over longer time scales.

In addition, another motivation is provided by the puzzle concerning the high error rate in SET pumps.[1, 2] The error rate (ie, extra electrons or deficit electrons passed) in pumps has been quantitatively shown [2] to be many (2 to 12) orders of magnitude higher than the error predicted by orthodox theory. There is a speculation[2] that the high rate is due to extra cotunneling that results from energy being released by relaxation of states upon cooling. In the next section, we will present results from the literature of non-equilibrium heat evolution in glasses, which is in rough quantitative agreement with the measured level of the error rate.

An additional prediction from the heat evolution results is that the rate should fall as $1/t$, where t is time since the cooldown. Unfortunately, a time-dependent measurement of the error rate in a pump is quite difficult to perform[4]. Thus, we hope that by performing time-dependent measurements of the charge offset $Q_0(t)$, we may be able to confirm or refute this speculation; in the next section, we will also discuss differences between the coupling of the error rate versus Q_0 to the heat evolution hypothesis.

Low-Temperature Dynamics in Glasses: Prediction for Error Rate/Charge Offset

One common observation in amorphous materials is that there is a transient, non-equilibrium evolution of heat from the material at low temperatures, after a quench. This evolution has a $1/t$ time dependence after the quench (this long-time tail persists after a crystal of the same geometry and material would reach thermal equilibrium), and has a larger magnitude for higher "annealing" temperatures.

In one particular study[3], the heat evolution was measured in a silica glass, for a quench temperature of 0.2 K, and for annealing temperatures between 0.3 K and 3.5 K. Using the results of this work, we can make a rough prediction of the frequency of errors in a pump, with the following assumptions:

1) Amount of glass is the volume of the barrier in one tunnel junction, estimated as $(0.3\ \mu m)^2$ (2 nm).
2) AlO$_x$ (SET pump barrier material) is identical in heat evolution to SiO$_x$ (glass studied in [3].
3) Amount of heat evolution is proportional to volume.
4) "Annealing" temperature is 3.5 K.
5) All heat is released as phonons/photons of energy equivalent to 3 K (the energy barrier in the pump [2]), and all of those energy packets are captured by electrons in the pump, and all are thus successful in causing one error each.
6) The error rate measurement was done at a time equivalent to one week delay since the quench.

From [3], the rate of heat evolution for a sample of volume 18 cm^3, held at 3.5 K and then quenched to 0.2 K for one week, was $dQ/dt = 7 \times 10^{-5}$ erg/s (1 week/t). Scaling by the relative volumes, and dividing by the energy equivalent to 3 K yields a final rate of release of 3 K phonons/photons of about 6×10^{-6} (t^{-1}) s^{-1}, or about one error event every few hours. This prediction is about one order of magnitude slower than the observed rate of errors in the hold mode (every 1/5 hour [1]); given the crudeness of the approximations, this agreement is quite suggestive. To confirm this hypothesis, one would need to measure the time dependence of the error rate. As noted above, however, such a measurement is quite difficult.

Thus, we have chosen to observe the rate of wandering of the charge offset $Q_0(t)$ as a function of time since the cooldown, both to test the hypothesis, as well as to see whether various device geometries/materials modifications can improve the long-term performance, necessary for integration/parallelization.

As mentioned above, there are several possible differences between the coupling of the dynamical entities in the glass (two-level systems or TLS) to the electrons in a SET pump, versus the coupling of the TLS to $Q_0(t)$ in a SET transistor. These include:

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1) a) TLS couples to electrons via energy packets

b) $Q_0(t)$ is believed to arise from structural defects (in tunnel barriers or in other insulating regions) which carry an effective charge; thus, the TLS could either be these charged defects, or could induce fluctuations in the charges via energy coupling.

2) Energy cutoff of 3 K for the pump; no obvious cutoff for $Q_0(t)$.

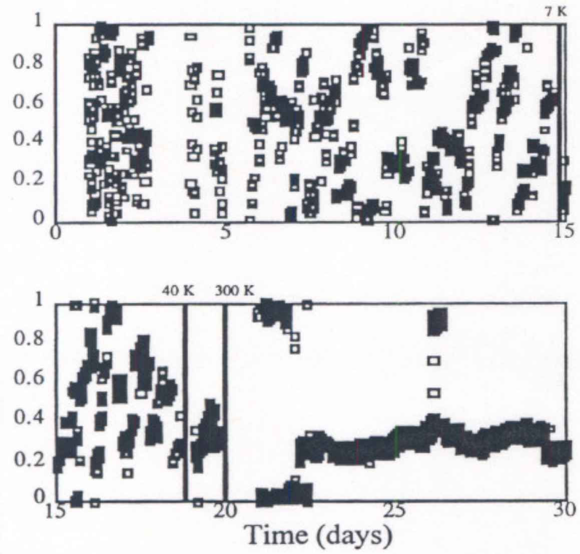

Fig. 1: Charge Offset Q_0 versus time

Data

Fig. 1 shows the time dependence of the charge offset $Q_0(t)$, measured over about the first four weeks since the cooldown (which occurred at –1 days). These data were obtained by repeatedly measuring the $I_{S\text{-}D}(V_G)$ oscillations (at fixed bias voltage), and then force-fitting the oscillations to a cosine curve, with the phase offset used as a fit parameter to yield Q_0. (Here, $I_{S\text{-}D}$ and V_G are the source-drain current and gate voltage, respectively, and gaps in the data correspond to times when experimental problems precluded measurement; vertical lines correspond to thermal cycles to 7K , 40 K, 300 K).

Two main features are immediately obvious. Firstly, for the period starting at day 22, Q_0 was essentially constant (except for one excursion) for a long period; this is the best result (most stable Q_0) we have achieved. Secondly, for the first ten or so days, the wandering of Q_0 has a transient relaxation, from very fast fluctuations, to being stable for fractions of a day. This is the qualitative signal reminiscent of the non-equilibrium heat evolution in glasses.

We note that, *in contrast to the results of the glass studies*, the transient does not repeat upon cycling to temperatures as high as 730 K in vacuum, N_2, or H_2 (not all cycles shown). In addition, this transient relaxation does not appear for all devices, but seems to be associated with time since fabrication; we are presently investigating this further. We believe that these differences are due to a difference in the disorder of thin films (possibly nano-crystalline) versus bulk, amorphous glasses.

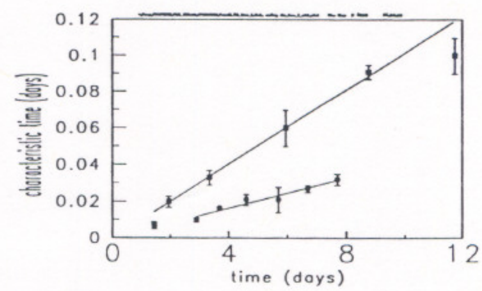

Fig. 2: Inverse of $Q_0(t)$ wandering rate versus time. Upper set from Fig. 1; lower from similar, unshown set.

Quantitative analysis of the transient relaxation (Fig. 2) yields a relaxation of the rate of wandering which, within the scatter in the data, is roughly inversely proportional with time, in agreement with the prediction from the previous section.

Conclusions

1) The long-term measurement of $Q_0(t)$ showed at least one occasion when the charge offset was stable enough to allow possible parallelization of SET pumps, to form a current standard.

2) Thermal cycling and annealing in N_2 or H_2 did not improve long-term stability.

3) The static charge offset has a transient relaxation which qualitatively is very similar to the relaxation of heat evolution in glasses when quenched. We believe that this, plus the estimate of the rate of 3 K phonons/photons from this energy release, suggests that:

a) The excessive error rate in pumps is due to this heat evolution.

b) The initial high level of noise in SET transistors is also due to this mechanism, and may be avoided by annealing of the device.

References

[1] Mark W. Keller, John M. Martinis, Neil M. Zimmerman and Andrew H. Steinbach, "Accuracy of Electron Counting Using a 7-Junction Electron Pump", Appl. Phys. Lett., Vol. 69, pp. 1804-6, 1996.

[2] Mark W. Keller, John M. Martinis and R. L. Kautz, "Rare Errors in a Well-Characterized Electron Pump", Phys. Rev. Lett., Vol. 80, pp. 4530-3, 1998.

[3] J. Zimmerman and G. Weber, "Thermal Relaxation of Low-Energy Excitations in Vitreous Silica", Phys. Rev. Lett., Vol. 46, pp. 661-4, 1981.

[4] Mark W. Keller, private communication.