VARIABILITY OF CHARGE NOISE IN Al-BASED SET TRANSISTORS

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Abstract

We measured the charge noise of four Al-based SET transistors on multiple cooldowns. We found a consistent *1/f* component independent of thermal cycling and other treatments, but large variations in the total noise spectrum due to two-level fluctuators.

Introduction

Devices based on the manipulation and detection of individual electrons flowing through nanoscale tunnel junctions, known generally as single-electron tunneling (SET) devices, offer a number of advantages for fundamental electrical standards [1]. A major limitation for most applications of SET devices is noise caused by the motion of charged defects in or near the devices. Typically this noise is studied in an SET transistor configuration, as described for example in [2]. Despite many investigations over the past 15 years, several questions remain about the origin of the noise and the possibility of reducing or eliminating it. The reported noise spectra vary considerably in both amplitude at a given frequency and in the frequency dependence over the range of roughly 1 mHz $< f <$ 1 kHz. This may be due in part to different device designs, but there is also variability among devices with the same design and often significant variability with thermal cycling of a given device. To further understand and quantify this variability, we have measured the noise of four SET transistors on several cooldowns. Some of the cooldowns involved special treatments such as slow cooling or application of a large electric field.

Device Fabrication and Measurement

Fig. 1 shows the geometry of our transistors. They were fabricated at NIST/Boulder on Si substrates with 118 nm of oxide using electron-beam lithography and 2-angle evaporation of Al. They had total resistances of 95 kΩ to 460 kΩ, gap voltages of 0.4 mV to 0.9 mV, and gate capacitances of 16 aF to 30 aF. Transistors A1 and A2 were made on one chip, and transistors B2 and B3 were made on a separate chip. The chips were attached to headers with vacuum grease and held at 45 °C for ~ 1 h during wire bonding. Measurements were done in a dilution refrigerator at METAS with microwave filters, made from lossy coax or a mixture of metal powder and epoxy, on each lead. A permanent magnet under the header suppressed superconductivity in the Al. The measurement system noise was at least an order of magnitude smaller than the transistor noise for $f <$ 100 Hz. The transistors were voltage-biased at the point of maximum modulation with gate voltage and a feedback circuit held the gate voltage at the point of maximum sensitivity on the modulation curve. Measuring the noise of the feedback voltage and dividing by the modulation period gives the charge noise S_Q in units of $e/\mathrm{Hz}^{1/2}$.

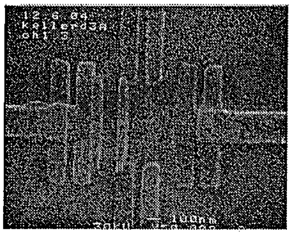

Fig. 1: Electron micrograph of transistor geometry.

Separation of Noise into Components

In looking for systematic behavior it is useful to consider each spectrum as consisting of two components (other than the white noise background from the measurement system): 1) a component that is *1/f* throughout the measurement bandwidth and 2) a component (or possibly more than one) that has a more complicated frequency dependence. The most common example of the latter is a Lorentzian that exceeds the *1/f* component over some range of frequency. This is generally attributed to a single charged defect switching between two states, a system known as a two-level fluctuator (TLF).

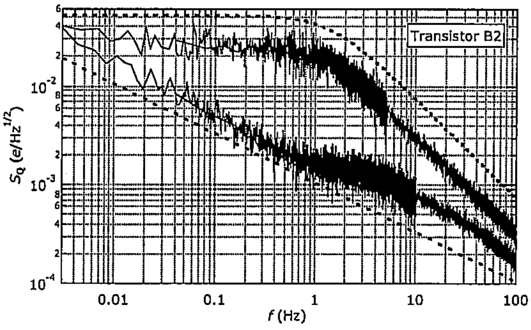

Fig. 2: Noise for transistor B2 on two cooldowns. The upper and lower dashed lines illustrate the shapes for Lorentzian and *1/f* spectra, respectively.

Fig. 2 shows two spectra illustrating the variability seen for one transistor on different cooldowns. In the lower trace the noise is mostly *1/f* with a small TLF near 5 Hz. In the upper trace there is a large TLF near 1 Hz which exceeds the 1/*f* component even at 100 Hz, and in such cases we extended the measurement to as low as 10^{-4} Hz in order to measure the 1/*f* component. Nearly all the spectra we measured contained both components.

Consistency of 1/*f* Component

Despite the dramatic difference in total noise between the two curves in Fig. 2, they have the same 1/*f* component: $(1.4 \times 10^{-3}\ e)/f^{1/2}$, which is within the range typically reported for Al-based SET transistors. The 1/*f* component was remarkably consistent for all our measurements, as shown in Fig. 3. Furthermore, the 1/*f* component of the noise was independent of

- Time after cooldown, for durations from 5 days up to 6 weeks.
- Rate of cooling to 4 K, which was varied between 2.5 h and 58 h.
- Application of 10 V to both gates during cooldown (normally the gates and bias leads were grounded).
- Application of relatively large gate voltages after cooling, as long as the relaxation threshold was not exceeded (see below).

We note that some investigations have reported charge noise that did depend on the first two items above; thus the results of our study should not be considered universal.

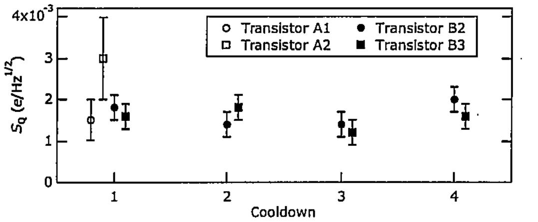

Fig. 3: 1/*f* component of the charge noise at 1 Hz. Some cooldowns involved different cooling rates or application of large gate voltages, but the 1/*f* component remained the same.

Variability of TLF-like Components

In contrast to the 1/*f* component, the TLF-like components of the noise were highly variable. TLFs were found with corner frequencies across the entire range from $f < 0.001$ Hz to $f > 100$ Hz. Thus the frequency dependence near any given *f* can vary from white noise (just below a TLF) to 1/*f* (far away from a TLF) to $1/f^2$ (just above a TLF). The TLF(s) for a given transistor always changed with thermal cycling. Some TLFs disappeared abruptly after the device had been cold for a few days, while others remained unchanged for weeks. In a few cases a modest change in gate voltage, corresponding to a charge of order 10*e* to 100*e*, caused a TLF to appear or disappear. In general, the variability of the TLFs makes it difficult to draw conclusions about systematic effects on SET noise from the total noise spectrum.

Effect of Large Gate Voltages

Since the moving defects that are thought to cause both the 1/*f* and TLF components of the noise are charged, we attempted to affect their motion by applying a large electric field near the transistor. For the gate closest to the island in Fig. 1, a crude estimate shows that a voltage of 10 V will produce a field of 10 V/100 nm = 10^8 V/m in the region between the gate and the island. This field is one to three orders of magnitude larger than the fields applied in previous studies of SET transistor noise, and it is reasonable to expect that it can affect the motion of defects in the substrate or in the native oxide on the surface of the island, and thus affect the noise.

We were able to apply 30 V to the gates of our devices without causing measurable leakage current or irreversible changes in the transistors. However, above a threshold of between 1.5 V and 2.5 V we observed relaxation, *i.e.*, the transistor signal drifted in time at fixed gate voltage. Below the relaxation threshold the noise spectrum did not change, while above the threshold it became $1/f^2$ at all measured *f*, as expected for non-stationary noise. Once the gate voltage was returned to zero, the spectrum returned to normal after ~ 10 h. The threshold for a given gate was repeatable upon thermal cycling within ±0.25 V. The origin of the relaxation is not known, but the fact that the threshold voltage was similar for gates with very different capacitance to the transistor island seems to indicate a substrate effect. A truly insulating substrate such as quartz or sapphire might allow larger voltages to be applied without relaxation.

Conclusion

While we saw considerable variations in the total noise spectrum of SET transistors between devices, and with thermal cycling of the same device, our study of multiple transistors and cooldowns reveals a remarkable consistency in the 1/*f* component of the noise. Comparisons of different device designs, fabrication recipes, and treatments during or after cooling may become clearer if the TLF-like components of the noise spectrum are excluded.

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References

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