Observing sub-microsecond telegraph noise with the radio frequency single electron transistor

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Telegraph noise, which originates from the switching of charge between meta-stable trapping sites, becomes increasingly important as device sizes approach the nano-scale. For charge-based quantum computing, this noise may lead to decoherence and loss of read out fidelity. Here we use a radio frequency single electron transistor (rf-SET) to probe the telegraph noise present in a typical semiconductor-based quantum computer architecture. We frequently observe micro-second telegraph noise, which is a strong function of the local electrostatic potential defined by surface gate biases. We present a method for studying telegraph noise using the rf-SET and show results for a charge trap in which the capture and emission of a single electron is controlled by the bias applied to a surface gate.

The presence of 1/f noise, which is characterized by a spectral density inversely proportional to frequency, has been observed in many diverse fields of physics \([1]\). In solid state devices the origin of this noise is generally believed to be the weighted sum of many independent noise sources that physically correspond to fluctuating charge traps or defects. In the limit of strongly coupled charge traps, where the occupation of a single trap has a significant effect on the output signal, telegraph or switching noise is observed \([2]\). In this instance the frequency dependence of the noise resembles a Lorentzian, deviating significantly from the usual 1/f form. Owing to the importance of both 1/f and telegraph charge noise for the operation of nano-scale devices, there has been a recent resurgence of interest in this phenomena including its influence on decoherence rates in coherent quantum systems \([3,4,5]\). In particular, quantum computer (QC) architectures based on the charge degree of freedom \([6,7]\) are especially sensitive to charge noise, which has the potential to affect both phase coherence and qubit mixing times.

Here we present charge noise measurements made on metal-oxide-semiconductor (MOS) devices cooled to mK temperatures using a high bandwidth and sensitive electrometer: the radio frequency single electron transistor (rf-SET) \([8]\). The purpose of our work is to firstly study both the magnitude and frequency to which telegraph noise persists in these structures and secondly, to investigate how it can be activated and controlled by the voltage biases applied to surface gates. Our method makes use of the rapid sample rate of the rf-SET detector to quickly locate regions of high telegraph switching in the parameter space defined by the gate voltage biases. Although the dependence of telegraph noise on gate voltage has been extensively studied at lower frequencies (typically <1kHz) we note that the increased bandwidth of the rf-SET permits us to uncover large additional noise with switching times on the sub-microsecond scale \([8,11]\).

Our interest is in devices that resemble architectures proposed for solid state QC, although these investigations also hold importance for classical nano-scale device operation. In particular our devices have a similar material structure to silicon-based QC proposals \([11,12]\) and consists of a high resistivity silicon substrate \((5-7\text{ k}\Omega\text{cm})\) with a 5nm oxide, grown thermally at \(T = 800\degree\text{C}\). The quality of the oxide and silicon oxide interface were characterized using both capacitance profiling and by measuring the threshold voltage in a MOSFET configuration. Separate measurements indicate an interface trap density of \(\sim 10^{12}/\text{cm}^2\) \([13]\). Al-SETs and surface gates were fabricated on top of the oxide layer.
in a shadow mask process \[\text{[14]}\]. In contrast to conventional SETs, which are limited by the large shunting capacitance of the wiring, the rf-SET makes use of an impedance matching LC network to transform the SET resistance towards the 50Ω characteristic impedance of a transmission line. In this mode rf-SETs have demonstrated bandwidths greater than 100MHz by mapping changes in resistance to the amount of reflected rf power from the LCR network. The sensitivity of the rf-SET used in the experiments reported here (in the absence of telegraph noise) is $\delta q \sim 8\mu e/\sqrt{Hz}$ at 1.1MHz (the details of our rf-setup can be found in \[\text{[15]}\]).

As indicated by the white circles in Fig.1a, we identify several key locations within this device structure that are likely to harbor charge traps. With the exception of deep substrate traps, we believe that most trapping sites are located at the interface regions where the amorphous oxide forms bonds with either the silicon \[\text{[16]}\] (below the SET) or aluminum (in the SET tunnel barriers) \[\text{[17]}\].

Turning now to our results, Figs.1b-d show the response of the rf-SET as a function of time on several different time-scales. Each trace is taken in succession, with some adjustment in offset charge between each trace. The data exhibits discontinuous switching of the rf-SET output signal corresponding to changes in induced charge on the SET island of order $\Delta q \sim 0.1e$, with the exception of Fig.1c which is of order $\Delta q \sim 0.2e$. This telegraph noise is associated with charge capture and release events from traps in the surrounding material that are strongly coupled to the SET. We see RTSs on all time-scales observable within the bandwidth of our detector (~10MHz in this case). As is evident by comparing data taken on different time-scales (e.g. Fig1.b & c), the detector bandwidth is crucial in quantifying the amplitude of charge noise in these devices. In this way fast telegraph signals, such as those shown in Fig1.d would remain undetected by conventional dc SETs.

In order to study how the magnitude and switching time of the telegraph signals depends on the local electrostatic potential, we make use of the large bandwidth of the rf-SET to quickly vary the bias potential and search for bias configurations that activate trap switching. Our characterization technique is outlined as follows. Firstly, biases applied to two surface gates define the local potential. Secondly, at each gate bias the response of the rf-SET is monitored for 2.0 ms with a resolution of 200ns and the average, variance, signal histogram and trap capture time are computed from the time-domain data. This procedure is repeated to cover a wide range of gate bias over which the degree of charge noise may be mapped. Fig.2a is an intensity plot of the variance of each 2ms time-domain trace as a function of the two gate biases, taken on a different device to the data shown in Fig.1. The variance of the data (represented as an intensity) is a measure of the degree of telegraph noise present during the measurement time. The intensity plot reveals a distinct zone, mutually defined by each gate bias, where strong telegraph noise is evident (contoured region moving diagonally across the plot). In addition, the variation in sensitivity of the rf-SET can be seen as light regions also moving diagonally across the plot and corresponding to the edges of the Coulomb blockade oscillations. Although fast feedback techniques \[\text{[18]}\] can be used to eliminate such variations in sensitivity by maintaining a constant potential at the SET, we refrain from using such methods in order to study how telegraph noise is affected by changes in the potential near the SET.

Figs.2b-d are examples of the information that can be extracted at each point in the intensity plot. Fig.3b is a 100μs long segment of the 2ms time-domain data taken at the bias point indicated by the star in Fig.2a. The data shows telegraph switching between two trapping sites on
microsecond time-scales, with the dynamic range of the SET (~0.5e) indicated by the dashed lines. Fig. 2c and 2d show signal probability histograms of the two distinct states and trap capture- and emission-time histograms respectively, computed from a fit to the 2ns of time-domain data (the fit is shown in Fig. 2b). For the fluctuator examined here an electron spends equal time (decay time of 3.4µs) in both the up and down trapped states. Of further interest the diagonal zone in Fig. 2a where a high degree of switching is evident follows a Coulomb blockade peak edge, where the potential at the SET is kept constant. This suggests that the trap we observe here is located in or very close to the SET.

Having presented our technique for mapping telegraph noise we now turn to discuss the presence of submicrosecond switching. Fig. 3 compares the SET output spectra (obtained with a spectrum analyzer over several minutes) at different gate biases (data taken from the same device as data in Fig. 2). For the case where the SET is in blockade (spectra and time trace I)) the data represents the intrinsic system noise and not the input charge noise detected directly by the SET electrometer. For frequencies < 100kHz, there is little difference between the traces as the output is dominated by the intrinsic 1/f noise of the measurement system. Above 100kHz however, we find a significant increase in charge noise between spectra II and III), which were obtained at two different (but near equally sensitive) gate bias settings. The black spectra is clearly associated with rapid telegraph noise of order ~ 0.1e (see inset III)) and fits the high frequency ‘tail’ of the Lorentzian distribution (dashed line is a Lorentzian fit) expected for a two level fluctuator strongly coupled to the SET. [2, 3]. Under this condition the spectral density of the noise exceeds the intrinsic shot and thermal noise of the detector for frequencies up to ~2MHz, well above the typical corner frequency of 10-100kHz generally associated with 1/f charge noise. Although we present data here for a fluctuator that exhibits microsecond switching we have also observed switching on faster time-scales (up to 70ns - the bandwidth of our rf-SET), consistent with counting errors seen in experiments on single electron pumps [19].

Finally we present data in which the state of a two-level charge trap can be reversibly switched by the bias applied to surface gates [20]. Here we study the same device from which data was taken for Figs. 2 & 3. Fig. 4 shows the rf-SET signal (left y-axis) while a differential voltage ramp is applied between two gates (right y-axis). When the differential bias is small the electron is predominately in the up (left) state, as shown schematically in inset I). As the bias increases, occupation of the trap switches between the two equilibrium levels until the electron is captured and maintained in the down (right) state for increased differential gate bias as shown in inset III). The differential bias changes by only ∆V = 3.8mV across the plot. In contrast to the measurements presented in Fig. 2, the results shown here were taken using a compensation technique in which the potential at the SET is held constant while the potential away from the SET is varied. As a result we believe that this two-level trap is located in either the substrate or at the silicon-oxide interface away from the SET island, where the trap can be switched as the potential changes with the differential gate bias. Of further note, no qualitative change in behavior of the trap was observed with increasing temperature to T ≈ 500mK (or B-field to 2T), consistent with the notion that the fluctuations are likely associated with tunneling between two trapping sites (as indicated in the
insets) and not over-barrier thermal activation \[21\].

Taken together with the characterization technique shown in Fig.2, the ability to find and control charge traps on fast time-scales, opens up the possibility of studying the noise properties of \textit{single} two-level fluctuators, including their quantum dynamics \[22\]. Although here we have only shown preliminary data, these results demonstrate the capability of the rf-SET to investigate telegraph noise in nano-scale devices on time-scales previously inaccessible. Future efforts will focus on combining the charge mapping technique presented here with a source of microwave photons to provide insight into the mechanisms driving fluctuations on these time-scales. In particular, the interplay of microwave photon assisted tunneling and thermal activation of charge switching will be crucial to the study and control of decoherence in quantum systems.

In conclusion, we have shown that telegraph noise in Silicon MOS devices, occurs on all time-scales observable within the bandwidth of our rf-SET. We have presented a technique for the characterization of this noise as a function of the local potential and demonstrated gate-bias controlled switching of a single charge trap on fast time-scales, an ideal platform in which to explore the feasibility of charge based quantum computation.

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