Single Election Trapping in Nanoscale Transistors; RTS(Random Telegraph Signals) and l/f Noise

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ABSTRACT

Noise signals can be equivalently represented in either the frequency domain or the time domain. The representation or modeling in the frequency domain gives the mean square noise current of a transistor as a function of frequency. The representation or modeling of the RTS or l/f noise of nanoscale devices that is easiest to understand is that done in the time domain. The capture and emission of a single electron in a nanoscale NMOS transistor with be equivalent to a change in threshold voltage. Modern devices are now small enough that we can see RTS noise signals associated with single electron trapping.

***Keywords**:* random telegraph signals, noise, l/f noise , single electron noise

1 INTRODUCTION

Random telegraph signal, RTS, noise[1] is most obvious in submicron devices with traps, for example in nanoscale MOS transistors, MOSFET's, with a low number of carriers. RTS is sometimes an indicator of poor device quality in larger devices and indicative of giant traps capturing and emitting many electrons at one time. RTS is however present in all devices and in particular MOSFET's, RTS is easily observed in small submicron MOSFET's as individual steps in the drain current associated with the capture and emission of single electrons. For a single type of trap the power spectral density is a Lorentzian spectrum, Fig. 1, and depends on the number of traps, N, and occupancy of the traps, <N>^{2}. For strong asymmetric RTS noise <N>^{2} approaches zero. and there is no noise. Symmetric traps can become asymmetric in a MOSFET, by applying switching bias, but asymmetric ones without bias switching can become symmetric after bias switching[1].

$$\frac{S_I}{I^2} = \frac{S_N}{N^2} = \frac{1}{N^2}\,\frac{4\,\tau\,\Delta N^2}{1+(2\pi f\tau)^2}$$

$$\overline{\Delta N^2} = \frac{\tau_e\tau_c}{(\tau_e+\tau_c)^2} \le \frac{1}{4}$$

$$\overline{\Delta N^2} = \frac{1}{2+\tau_e/\tau_c+\tau_c/\tau_e}$$

$$\tau = \frac{\tau_e\tau_c}{\tau_e+\tau_c}$$

$$\frac{\tau_e}{\tau_c} = K > 1 \text{ or } K < 1$$

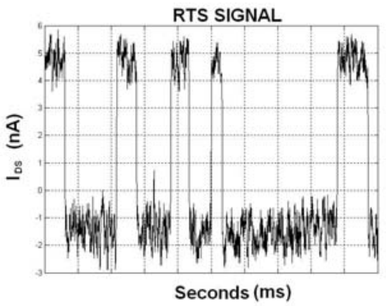
$$\Rightarrow S_I^{RTS} \rightarrow 0$$

Fig. 1 Single electron trapping noise[1].

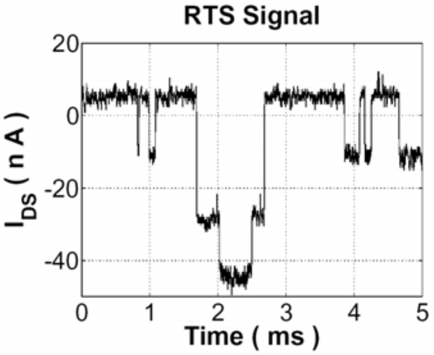
McWorter has shown how a combination of these individual trapping events over many different traps with different time constants can result in l/f noise[2].

2 RTS ON NANOSCALE DEVICE

Fig. 2 illustrates the measured RTS noise in a submicron or nanoscale size MOSFET due to single electron and multiple electron traps.



(a) Single electron trapping noise.



(b) Multiple electron trapping RTS signal.
Fig. 2 RTS noise due to electron trapping.

RTS is however present in all devices and in particular MOSFET's and can result in transients in the measured noise and long term transient effects in the noise of large MOSFET's.

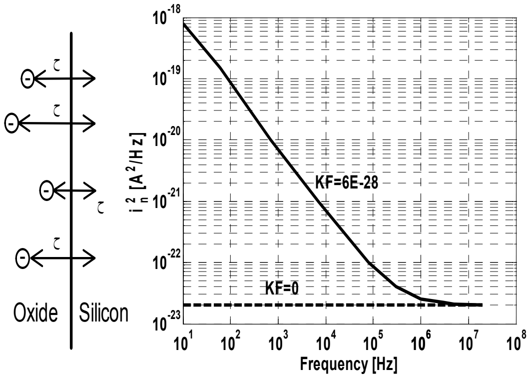


Fig. 3 l/f noise due to electron trapping.

3 SWITCHED BIAS ON LARGE DEVICES

We have also observed and investigated these trapping effects on very large micron size MOSFET's. Klumperink et al. [3] used a differential circuit, here we have used a transistor substitution technique as shown in Fig. 3 to reduce the large switching transients that can occur in previous circuits [3, 4-7]. Simple RC filtering is also introduced before the amplifier which follows and the spectrum analyzer to reduce the switching transients that occur due to differences in transistor gain and stray capacitances. Here we always have one transistor on so there is no 6dB difference in the noise at low frequency as in the previous circuit by Klumperink et al.[3] where the transistors are off one half the time.

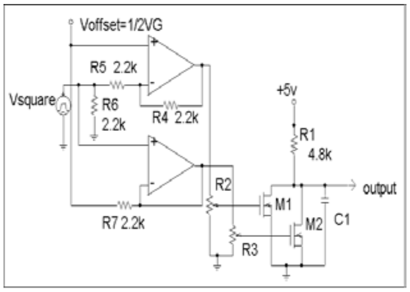


Fig. 4 Transistor substitution circuit.

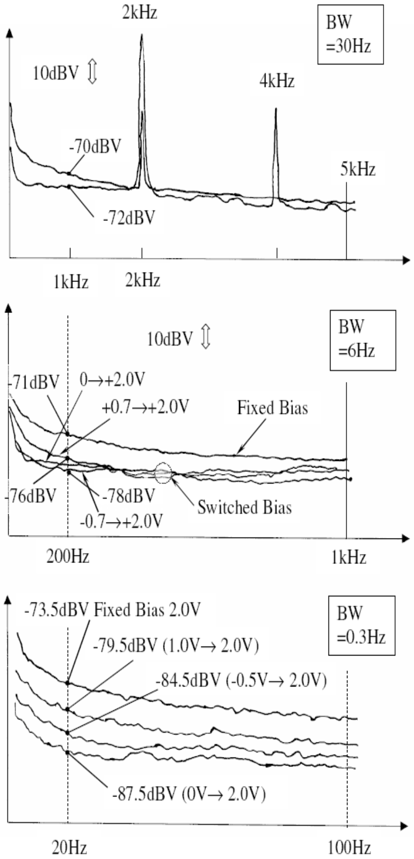


Fig. 5 Switched bias noise measurements.

Following the application of switched bias the noise at 1kHz, Fig. 5, is reduced due to accumulation of the surface and holes collecting at the surface of the transistor channel. This results in many surface states and oxide traps capturing holes and changing charge states and remaining in a fixed charge state over an extended period of time, Fig. 6. As such the charge state can not fluctuate and contribute to noise.

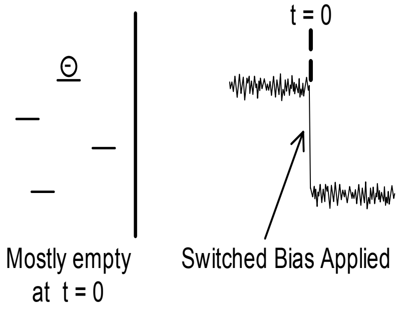


Fig. 6 Switched bias noise at 1 kHz.

What is new and different here in the time domain, Fig. 7, is that there are long term transients in the l/f noise after the application of switched bias. A variety of different types of transient behaviors have been observed on devices from two different manufacturers obtained over different time periods years apart. In some case the l/f noise will decrease after the application of fixed bias and stay at a lower level for long periods of time, however, the next time switched bias is applied it will recover from this lower level.

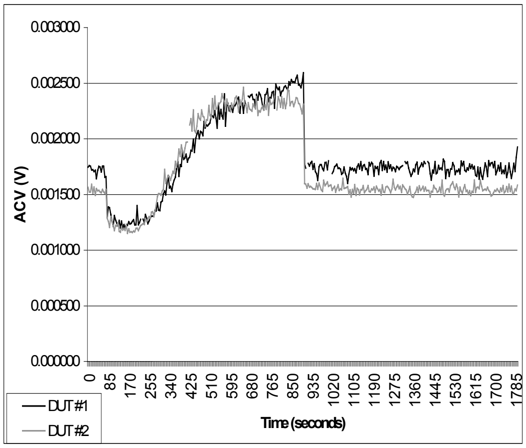


Fig. 7 Measured switched bias noise at 1 kHz.

In other cases the l/f noise will initially decrease with switched bias but recover in shorter periods of time.

The results shown in Fig. 7 demonstrate the time dependence of the noise at 1kHz with a 100 kHz switching frequency. The biasing circuit is initially set at fixed bias with no input signal and allowed to reach steady state. A 100 kHz switching frequency was then applied to the biasing circuit and allowed to reach steady state. This followed by reverting back to the fixed bias state and allowing the circuit to reach steady state. The demonstrated behavior is repeatable as shown in Fig. 7 for two devices.

As the circuit transitioned from fixed bias to switched bias, the noise dropped from the respective steady state fixed bias level down to the switched bias level. The noise at 1kHz with switched bias will gradually increase and settles to another steady state condition. A long term transient is evident over a time period of 15 minutes in the noise at 1kHz after the application of switched bias as illustrated in Fig. 8.

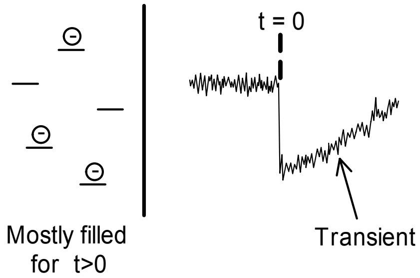


Fig. 8 After switched bias applied for some time.

Annealing or wear out effects are observed in the long term transients as illustrated in Fig. 9. Fig. 9 shows the noise at lkHz, with fixed bias, then switched bas for 100 minutes, fixed bias for 15 minutes, then switched bias for 50 minutes, and finally fixed bias. Note the wear out or annealing in the second switched bias sequence and faster recovery from the lower initial noise level for two different devices. There are a variety of different transients observed over long time periods on devices from two manufacturers.

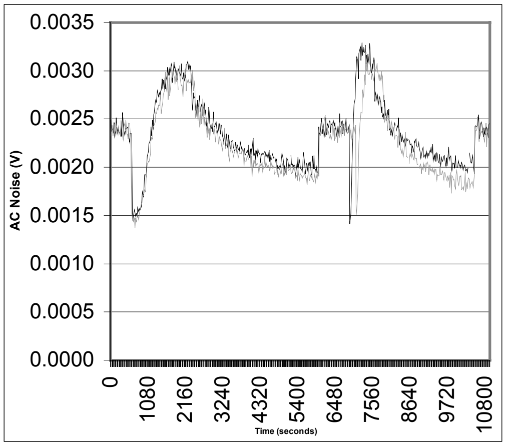


Fig. 9 Fatigue or wear out in switched bias effects.

Fatigue and wear out is also commonly observed in the tunneling phenomena in flash memories which have a limited endurance or number of cycles at about one million. [9] Fifty minutes of switched bias results in about one hundred million cycling or tunneling events.

4 CONCLUSIONS

A unified model for the trapping and emission at the oxide silicon interface is described which makes it possible to relate RTS noise signals on nanoscale devices to l/f noise on large MOSFET's. Switched bias effects in larger MOSFET's are a consequence and natural result of the trapping and emission of many single electrons in these larger devices.

Wear out or fatigue phenomena have also been observed to be associated with these tunneling events.

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