Reduction of 1/f Noise by Switched Biasing: an Overview

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Abstract— **MOSFETs are notorious for having strong low frequency noise (1/f noise or flicker noise). In the late 90's we discovered that this noise can be reduced if you periodically switch the bias on and off. This lead to a STW research project "Reduction of 1/f Noise in MOSFETs by Switched Bias Techniques" (TEL.4756), in which we tried to model the effect of large signal excitation on LF noise and explore its application perspective. This paper gives an overview of the main results obtained during this project. We found that the reduction of LF noise is related to capture and emission of electrons in traps, which renders Random Telegraph Noise (RTS noise). The effect of large signal excitation on LF noise can be modeled by making capture and emission time-constants dependent on the instantaneous bias voltage. We were able to show that the energy distribution of traps in the band-gap determines whether there will be significant noise reduction or not.**

Keywords— **Low frequency noise, 1/f noise, flicker noise, RTS noise, noise reduction, CMOS, MOSFET, Switched Biasing**

I. INTRODUCTION

Low Frequency (LF) noise in MOSFETs is a topic of growing concern, especially in small devices. LF noise in MOSFETs has been studied for a long time: already in 1969, Hooge [1] showed that homogenous semiconductor samples suffer from bulk 1/f noise. Though MOSFETs probably suffer from bulk 1/f noise in the same way, it has since become clear that the dominant mechanism in MOSFETs is Random Telegraph Signal (RTS) noise caused by traps at the Si-SiO_2 interface [2].

In 1991, it was noted for the first time [3,4] that MOSFET LF noise is reduced when the device is subjected to large signal excitation (LSE). In other words, turning a MOSFET 'off' for some time before turning it 'on' reduces its noise when it is 'on'. This means that the LF noise of the device not only depends on the present bias state of the device but also on the bias history of the device. Soon afterwards this effect was associated with the emptying of traps that cause RTS noise [5]. In 1996, the effect was independently rediscovered by Hoogzaad and Gierkink at the University of Twente [6,7], leading to a demonstration of the LF noise reduction effect by LSE in a ring oscillator [8] and in a coupled sawtooth oscillator [9].

During the STW research project "Reduction of 1/f Noise in MOSFETs by Switched Bias Techniques" (TEL.4756), the effect of switched biasing on LF noise in general, and RTS noise in particular was studied in detail. The two main aims of the project were:

1) MOS Device characterization and modeling, to unveil and model the properties of the low frequency noise under switched bias conditions.

2) To explore applications of switched biasing in circuits.

This paper presents an overview of the main results obtained during the project. In section II we will give a summary of the main measurement results obtained from a multitude of MOSFET devices with several newly developed measurement techniques. Section III will address the modeling of the observed noise reduction behavior, while section IV addresses the practical application perspective of switched biasing in circuits. Section V finishes with conclusions.

II. LOW FREQUENCY NOISE MEASUREMENTS

Measuring LF noise under LSE is challenging, because the LF noise is small compared to the change in bias; the dynamic range requirements of the measurement setup are high. One might be tempted to conclude that LF noise therefore does not play a significant role in the operation of circuits, but this is not the case. For example in VCO's, the LF noise of the active devices is up-converted to become problematic close-to-carrier phase noise, and in many sampling circuits, the LF noise immediately following device turn-on is of critical importance (e.g. CMOS imagers).

New measurement techniques have been developed for characterization of LF noise, not only in the frequency domain, but also in the time domain. There are several ways in which the dynamic range requirements of the measurement setup can be solved: one can apply a common mode bias signal to two MOSFET and measure the noise differentially [10], one can separate the bias signal and the noise in frequency [12], or one can separate the bias pulse and the noise in time, by first applying a bias pulse to the device and subsequently measuring its LF noise [15,16, 26]. All three measurement techniques have been used as appropriate to obtain results. More details about the measurement techniques can be found in [10,15,16, 20,21,22,23,26].

We will now present an overview of the most important measurement results. At the start of the project, we gathered noise data from commercially available devices, mainly HEF4007 devices, which are produced by many different companies. Later, we got access to deep submicron devices from 0.35 micron down to 0.18 micron CMOS processes.

A. *Large Devices from old technologies (HEF 4007)*

Figure 2 shows a typical plot of the Power Spectral Density (PSD) of the drain current of large HEF4007 NMOS device (estimated dimensions: 144µm/8µm). For steady state bias a -10dB/decade roll-off is found, as we expect for 1/f noise.

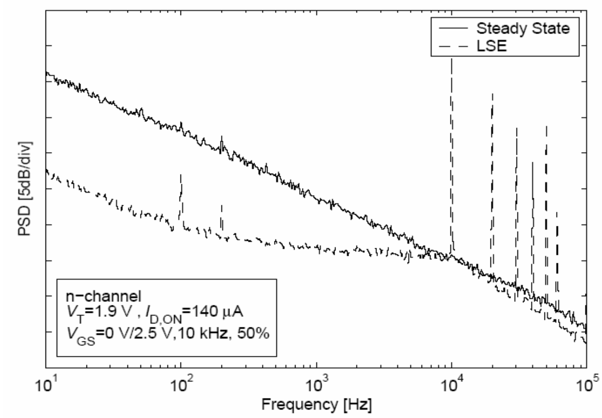

Figure 1: Power Spectral Density of the noise of HEF4007 devices at constant bias (top line) and Large Signal Excitation (LSE) at 10kHz (low line): below the switching frequency noise reduction is observed.

For large signal excitation at 10kHz (dashed LSE line) with a 50% duty cycle square wave, a significant reduction of the PSD is found below the switching frequency. For 50% duty cycle we expect 6dB noise reduction because the device is off half of the time (3dB less noise power), while the switching effectively up-converts half of the noise to the switching frequency and its harmonics [9]. However we see more than 6 dB noise reduction and a much more flat PSD which resembles "white" (thermal) noise. A white PSD corresponds to a Dirac-like autocorrelation function. In other words, LSE reduces the long-term correlation of LF noise which leads to the characteristic 1/f spectrum.

B. *Dependence on off-voltage*

Figure 2 shows the PSD for different values of the off-voltage (the on-voltage is kept the same). When the off-voltage is equal to the threshold voltage (1.5V in this case), the expected 6dB noise reduction is observed as predicted by signal theory. However, further reduction of the off-voltage renders more noise reduction. For low off-voltages the noise reduction saturates at some value well above 6dB, e.g. 12dB in figure 2.

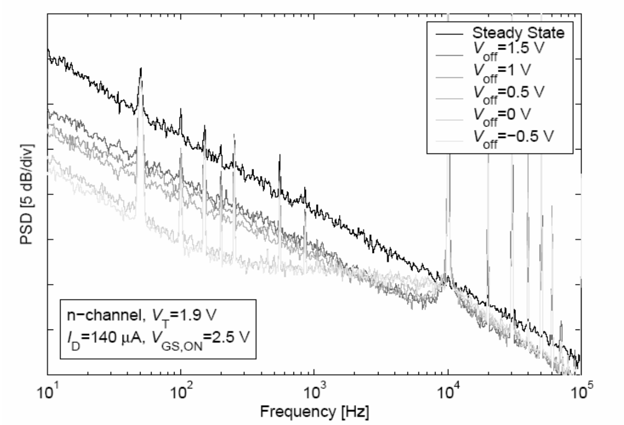

Figure 2: LF noise spectrum for various off-voltages. Whereas 6dB is expected, more noise reduction is found if the off-voltage is lowered below the threshold (V_{TH}=1.5Volt in these old devices)

C. *Effect of the Switching Frequency*

As 1/f noise is a low frequency process, one might expect a strong effect of switching frequency. Figure 3 shows the PSD of one device cycled to a sufficient off-voltage to obtain significant noise reduction, while the switching frequency is varied. As can be seen, the PSD lines converge at low frequency. This means that the noise reduction *at a sufficiently low frequency* well below the switching frequency is independent of the switching frequency.

Figure 3 shown this for frequencies up to 1MHz, which is about the maximum frequency attainable with discrete HEF devices. With integrated devices and a more advanced measurement setup using an RF sine-waves as LSE signal, we were able to show that this insensitivity to switching frequency holds for frequencies up to at least 3GHz [12].

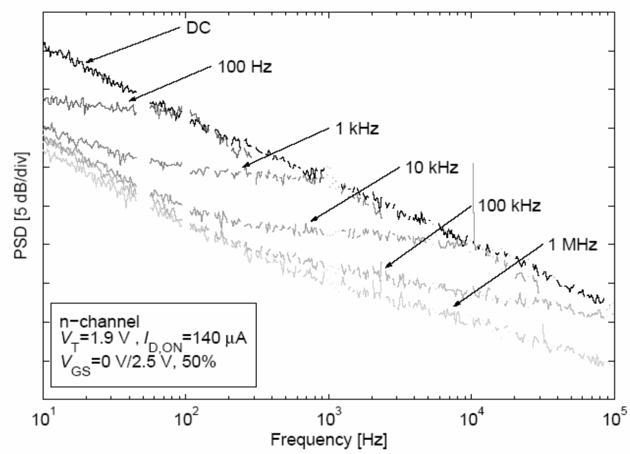

Figure 3: Effect of switching frequency on noise reduction: all lines converge at low frequency so the switching frequency is irrelevant for the LF noise reduction.

D. NMOS and PMOS Devices

Measurements on PMOS devices revealed that they exhibit similar behavior to NMOS devices. Also devices with different oxide thickness were measured. In all cases noise reduction was found [13].

E. Small Deep-submicron Devices: RTS noise

MOS devices from many different IC processes were characterized with respect to LF noise [10,11,13,22,23]. When measuring small deep submicron devices, results are much less consistent. Figure 4 shows an example of a PSD of a small deep-submicron device.

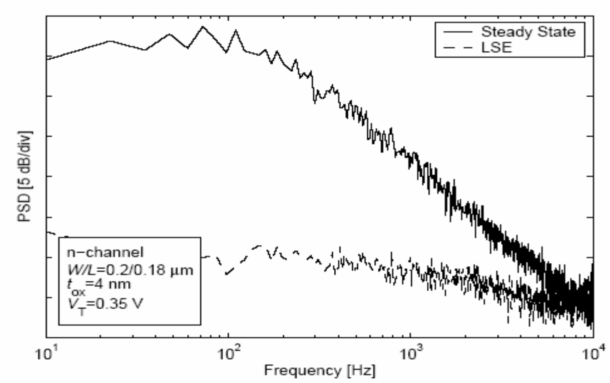

Figure 4: PSD of the drain current for a device dominated by RTS noise: a flat LF part and -20dB/decade HF roll-off are found. For LSE the noise is strongly reduced.

The steady state noise is no longer 1/f like, but rather flat at low frequencies, followed by a -20dB/decade roll-of at higher frequencies. With LSE the noise reduction is impressive: more then 25dB noise reduction is found! Examining the drain current of this MOSFET at constant biasing via direct current measurements results in a plot similar to figure 5. The drain current shows discrete steps in current. This is known as random telegraph noise [2] and is typically observed in transistors with a small gate area, in which one trap dominates the noise behavior. Under LSE the RTS signal disappears as first reported in [5].

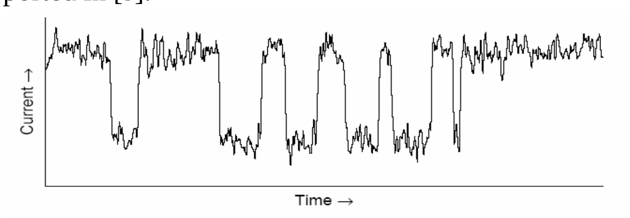

Figure 5: Time domain measurement of the drain current: discrete constant amplitude current steps occur, known as a "Random Telegraph Signal" (RTS)

F. Small devices and spread

For small devices the LF noise may spread significantly [17]. In order to examine the spread in switched bias noise reduction, we measured many devices of nominally identical size. Figure 6 gives an overview for small 0.2/0.18 micron devices with 4nm gate thickness.

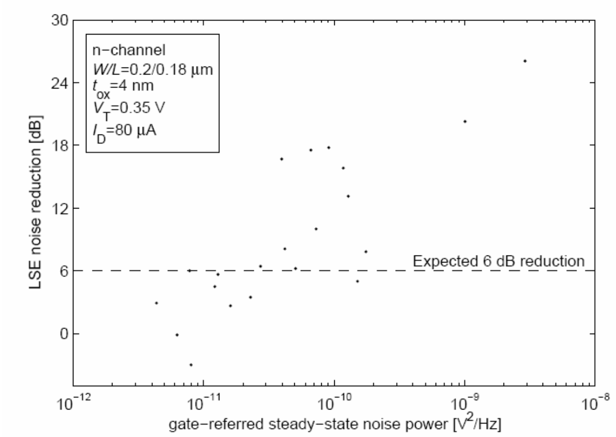

Figure 6: Noise reduction found under LSE versus the noise for steady state biasing: large reductions up to >20dB are found, but also sometimes increased noise (below 6dB line)

Vertically the noise reduction under LSE is shown, while horizontally the noise power for steady state biasing is shown. Clearly the spread is large, where high steady state noise seems to correlate with high noise reduction. However, note that not all devices have a LSE noise reduction of more than 6dB. This means that there are also devices which show a noise increase under LSE.

However, the increase in noise is only modest and there are only a few devices exhibiting such increase. On average, noise reduction is observed.

In order to see whether this average noise reduction is always observed, we characterize devices from several processes. Figure 7 shows the average amount of noise reduction above the expected 6dB due to LSE. It turns out that on average always noise reduction is found, but that the amount varies from process to process.

Device	Averaged Amount of Noise Reduction > 6dB
HEF 4007	≈ 8 dB
0.35 μm n-channel	1.4 dB
0.25 μm n-ch (0V)	0 dB
0.25 μm n-ch (-0.6V)	2.9 dB
0.18 μm n-ch	8.2 dB
0.18 μm p-ch	5.7 dB

Figure 7: Table summarizing the average noise reduction observed for different IC processes

G. Source versus Gate switching

From an analog circuit designer's point of view, switching a device off can be done with the gate, but also with the source voltage. Thus one might wonder whether source switching is as effective in reducing LF noise as gate switching. Figure 8 shows the results: vertically the amount of noise reduction due to gate-switching is shown, while horizontally the effect of source switching is shown.

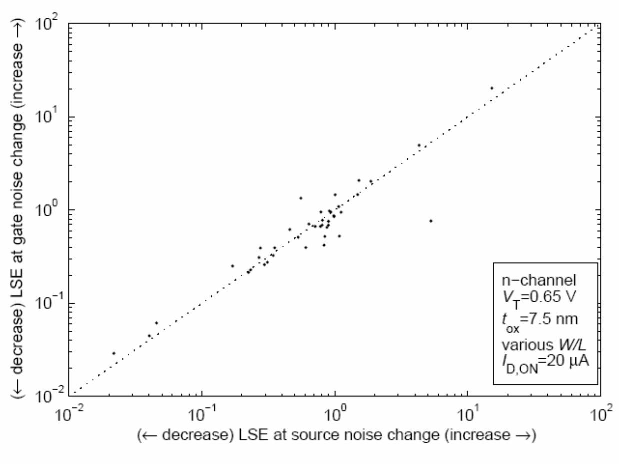

Figure 8: Noise reduction found for gate switching and for source switching. Their effect is strongly correlated, i.e. source switching has almost the same effect.

A very strong correlation is evident, which shows that it is not necessary to cycle a device to accumulation to obtain noise reduction, although this is a sufficient condition.

H. Summary

Summarizing the measurement results discussed above, we observed that for large signal excitation:

- In large devices, LF noise goes down
- In small devices, the *average* LF noise goes down
- Cycling well below V_T maximizes the LF noise reduction
- Reduction occurs in both n and p channel devices
- Noise reduction varies with process
- Varying V_G is equivalent to varying V_S
- high switching frequencies > 3.5GHz can be used.

III. MODEL: BIAS DEPENDENT RTS

Based on the experimental material presented in the previous paragraphs, there is little doubt that the observed noise reduction is due to RTS noise behavior. In order to model the observed effects, we looked for a simple model, building as much as possible on existing models. This was partly done top-down, via a "macro-model" approach focusing on the macroscopically observed behavior, and bottom-up from physical models, especially the Shockley-Read-Hall (SRH) model. In this section we will briefly describe the key assumptions in modeling the LSE noise reduction, and describe the main results. For a more detailed discussion we refer to [14,20,22, 23,28].

A. PSD of an RTS

A Random Telegraph Signal (RTS) is defined as a 2-valued signal, which is time-continuous, but amplitude-discrete. The conditional probability of a transition from one state to another (i.e. given that it is in that one state), per unit time, is constant. This makes the time spent in each state exponentially distributed. An RTS can be characterized by three parameters: the amplitude, mean time spent in the low state and the mean time spent in the high state. Trapping/de-trapping behavior can be described as RTS activity, where the average time spent in the trapped state is the average "time to emission" τ_e, while the average "time to capture " is τ_c.

Due to trapping and detrapping discrete current steps ΔI are observed in the drain current. These steps occur because trapping withdraws an electron from the channel, but also may cause a correlated mobility variation as the trapped charge introduces local variation in the mobility ("Coulomb scattering").

The PSD of the RTS can be calculated by the Fourier transforming its autocorrelation function [18,23], resulting in a so-called "Lorentzian" spectrum S_{RTS}. Ignoring the DC term, S_{RTS} can be expressed as follows:

$$S_{RTS}(\omega) = 2(\Delta I)^2 \frac{\beta}{(1+\beta)^2} \frac{1}{\omega_{RTS}} \frac{1}{1+(\omega/\omega_{RTS})^2} \quad (1)$$

where ω_{oRTS}, the RTS corner frequency and parameter β depend on the capture and emission times via:

$$\beta = \frac{\tau_c}{\tau_e} \quad (2) \qquad \omega_{0RTS} = \frac{1}{\tau_c} + \frac{1}{\tau_e} \quad (3)$$

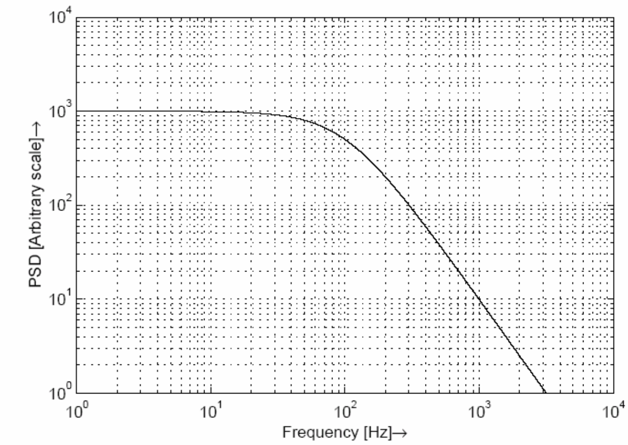

Figure 9: PSD of a Random Telegraph Signal (RTS)

Figure 9 shows a Lorentzian spectrum. The final term in S_{RTS} defines the frequency dependence of the PSD: flat at low frequencies and decaying as $1/\omega^2$ above the RTS corner frequency. At low frequencies we see a plateau in figure 9, where the PSD is inversely proportional to the RTS corner frequency and dependent on β. The β-dependent "plateau level" is symmetrical with respect to emission and capture times. The power of the PSD depends on the 'asymmetry factor' β, as shown in figure 10. If $\beta = 1$, i.e. capture and emission times are equal, an RTS will have a maximum contribution to the LF noise.

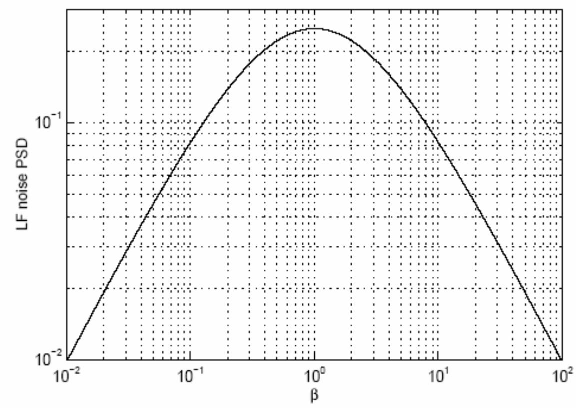

Figure 10: PSD "plateau" at low frequency of an RTS signal as a function of β : if the ratio is 1 ($\tau_e = \tau_c$), power is maximized

B. Relation between 1/f noise and RTS noise

As discussed in the previous section, the PSD of an RTS decays with $1/\omega^2$ instead of $1/\omega$, as for 1/f noise. Figure 11 shows how the addition of many Lorenzians can lead to a 1/f spectrum. Theoretically, the RTS corner frequencies should be uniformly distributed along a logarithmic frequency axis to obtain a 1/f spectrum. In practice, the addition of only a few RTSs with different corner frequency already renders a 1/f-like spectrum.

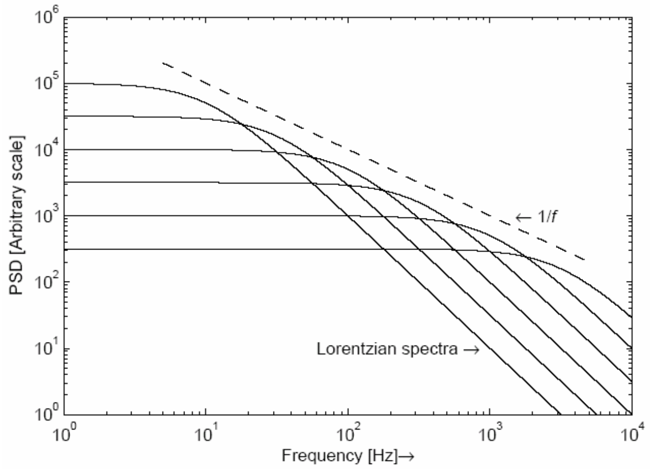

Figure 11: Adding several Lorenzian spectra can result in a spectrum that closely resembles 1/f noise

C. Bias dependent capture & emission time-constants

After this introduction on RTS noise and its PSD, we can now address the issue of noise reduction due to switched biasing. Experimentally it was observed that RTS capture and emission time constants change with the steady state biasing. For switched biasing we observed various types of behavior, as reported in figure 6. Most of the time the noise decreases, but sometimes there was not much effect of switched biasing, and in a few cases noise increases. When RTS signals were visible, the amplitude of the RTS signals didn't change, while the time constants did. Thus all experimental results indicated that the effect of switched biasing could be modeled as a change in the "effective" capture and emission time constants. As the capture and emission times changed with bias, we assumed that bias dependence of the capture and emission time was the cause of the noise reduction. From literature we gathered data on the bias dependency of capture and emission time constants. Monte Carlo simulations were done using a model with stochastic behavior similar to the real RTS. Using the results of this simulation we were able to empirically model measured PSD results, as for instance shown in figure 12.

In terms of the RTS parameters introduced in the previous section, the noise change can be understood as a change in the "effective β". E.g. if β changes from 1 in the constant bias case to a value much larger or much smaller than 1, a very large noise reduction is expected and this is confirmed by simulation in figure 12.

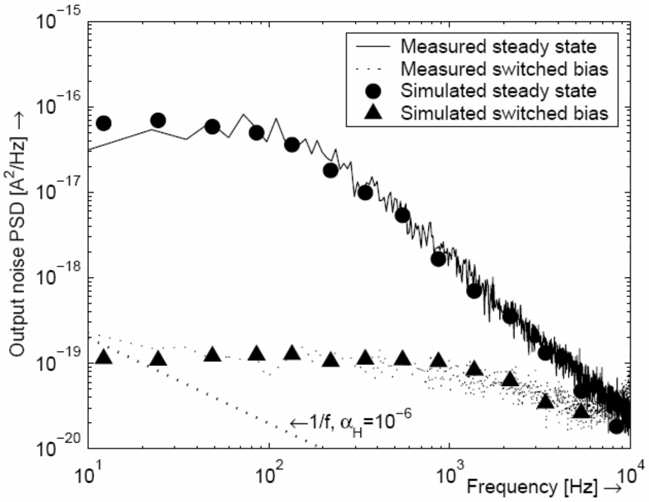

Figure 12: Measured and modeled (simulated) noise PSD

It turned out that by using capture and emission time-constants that depend on the instantaneous bias, various types of noise reduction behavior could be modeled. This macro-approach works well but doesn't say much about the link to the lower level physical parameters. This issue is addressed in the next section.

D. Relate Time constants to Physical Parameters

Shockley-Read-Hall theory [24], originally meant to describe the action of bulk states, has been generally adapted to describe the trapping-detrapping behavior of interface traps as well.

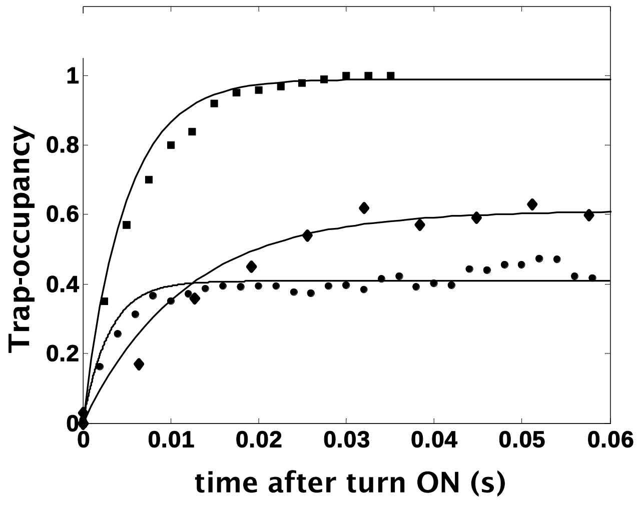

Figure 13: Measured and modeled trap occupancy

Traps located in the oxide can also be modeled, if tunneling via interface traps is assumed. We used this model to cover dynamic biasing conditions and model the trap-occupancy under transient biasing conditions. We developed a measurement technique to observe the occupancy under transient bias conditions and compared it to the model prediction, as shown in figure 13 [20,26]. In this figure the bias of a MOSFET device is switched on so the switch-on transient in the occupancy is observed. Using SRH theory, we expect a trap-occupancy that changes exponentially from an ‘off’ state value to an ‘on’ state value, and this is indeed observed in the measurements of figure 13. The final occupancy is equal to the occupancy calculated for steady state biasing from capture and emission time constants.

E. Effective cyclo-stationary time constants

Let us now return to the case of periodic on/off switching. Figure 14 shows a model for the expected trap occupancy for a MOSFET subjected to a square wave switched biasing signal. In this case the "on" and "off" times are in the same order of magnitude as the capture and emission times of the trap. The response looks like the response of a RC network to a square-wave voltage.

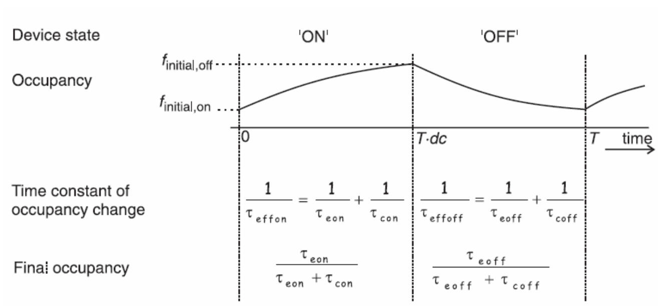

Figure 14: Model for the (time variant) occupancy of the traps. A exponential increase and decrease of the occupancy is predicted.

Based on this model, we can now examine the (practically relevant) case for which noise reduction is commonly observed (see section II): a switching frequency much higher than the RTS corner frequency. According to the model in figure 14, a constant average occupancy results, similar to the response of an RC network to a square wave (triangular waveform with a vanishing amplitude for high frequency). We have now a cyclo-stationary stochastic trapping process with a constant occupancy which is a function of the effective cyclo-stationary capture and emission times. These are again linked to the (stationary) bias dependent occupancies in the steady bias "on" and "off"-state as proposed in the previous paragraph [14]. Experimentally

[20,22] and mathematically [23,28] it can be shown that there is a relation between the duty cycle "dc" of the switched bias waveform, and the effective capture and emission time constants for the "on" and "off" state:

$$\frac{1}{\tau_{c,eff}} = \frac{dc}{\tau_{c,on}} + \frac{1-dc}{\tau_{c,off}} \quad (4)$$

and:

$$\frac{1}{\tau_{e,eff}} = \frac{dc}{\tau_{e,on}} + \frac{1-dc}{\tau_{e,off}} \quad (5)$$

Figure 15 shows measurement results of the effective cyclo-stationary capture and emission times (black dots and squares) and a model fit using our model. This model uses only parameters with a physical meaning. Measurements show that it is especially the mean emission time, which varies strongly with the off-voltage. This relation to the gate voltage can be modeled assuming that the trap are located in the oxide, and have a "capture cross-section" which decays exponentially with the gate-source voltage. We verified the model with measurements under various steady state and switched biased conditions [14,20,22,23].

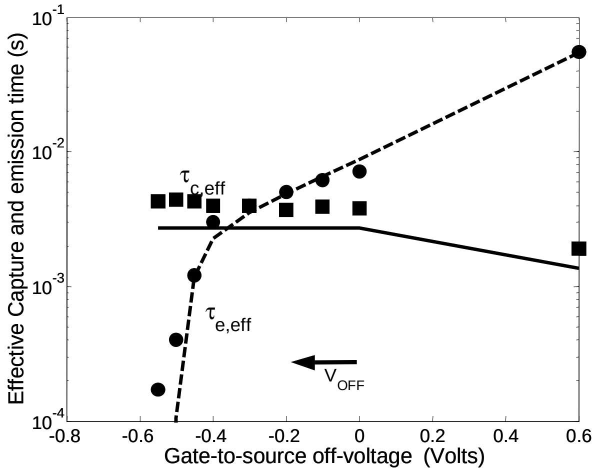

Figure 15: Measured and predicted effective cyclo-stationary capture and emission times versus gate-source off-voltage (V_{GSon} = 0.6V, V_{DS}=50 mV, duty-cycle = 50%).

F. Effect of Trap Energy Distribution

As discussed in the previous section, we are able to predict the behavior of a single RTS under constant and switched bias conditions [28]. For practical devices, we usually deal with a multitude of traps, and thus the question arises how the ensemble behaves. Based on our physical model, we know that this depends on the number of traps, the location of the traps in the oxide, and their energy level. Using this insight it is possible to predict the effect of switched biasing on a group of traps: For constant biasing in strong inversion, traps close to the conduction band play a dominant role, while for switched biasing traps located closer to the middle of the bandgap become important. If there is a *uniform* distribution of traps in energy all over the bandgap, our model predicts *no change* in noise spectrum. However, in accordance with reports in literature, a U-shaped distribution with a lower trap density in the middle of the bandgap is common. Assuming this U-shaped distribution, our model predicts a reduction in noise, as observed experimentally. This crucial insight is the subject of a recently accepted APL paper [23,28].

Figure 16 shows a device subjected to hot electron stress, and compares its noise behavior before and after radiation. Whereas there is significant noise reduction for the unstressed device, this reduction vanishes for stressed sample. Radiation experiments give similar results, which might be explained by the introduction of a more uniform trap distribution due to damage.

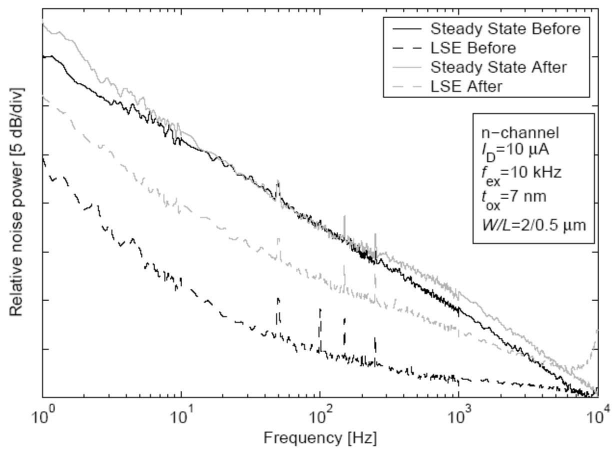

Figure 16: Effect of hot electron damage on the constant and switched bias noise spectrum: before damage the noise reduction is well above 6dB. After damaging the device there is just 6dB (as expected from signal theory)

IV. APPLICATION POTENTIAL

Existing circuit techniques for noise reduction like chopping and correlated double sampling give reliable low frequency noise reduction, and such techniques are generally more effective than switched biasing [23]. Still, for applications like RF circuits, where chopping and correlated double sampling are difficult to apply, switched biasing might be useful. We showed that the noise reduction effect exists up to high switching frequencies of at least a few GHz [12]. Other researchers of the University of California at San Diego and Stanford University have used the technique to obtain 6-8dB noise reduction in oscillators, PLLs and DLLs [31,32,33]. However, results on spread are not given.

Another application of the technique lies in CMOS imagers sensors. In co-operation with TU Delft, effects on CMOS imagers were studied [25]. Arnoud van der Wel showed in his PhD thesis that it is important to keep the bias history for correlated double sampling identical to reduce the RTS noise [23]. According to a report of Prof. A. Theuwissen, this is applied in high performance CMOS image sensors for digital photo cameras.

Looking back at all device measurements, we see that on average switched biasing gives a significant noise reduction. Unfortunately, however, individual devices show large spread, with strong variation in the amount of reduction, and there are even a few cases with increased noise [11,23,29]. This spread limits the practical application perspective of the technique. Another issue in this respect is the poor state of modeling of RTS behavior.

V. CONCLUSIONS

This paper described the main results of an STW project addressing low frequency noise reduction in MOSFETs due to large signal excitation (LSE).

We summarized the most important measurement results obtained with various newly developed measurements setups. It turns out that large devices consistently show a LF noise reduction, while small devices show large spread and might even show a small increase in LF noise.

The key to understanding this behavior lies in modeling the RTS noise in MOSFETs. By making capture and emission time constant dependent on the instantaneous biasing, good predictions of noise behavior under LSE can be made.

The relation between RTS noise and physical properties has been explored in detail, and the RTS noise was related to the Fermi level, trap energy, trap capture cross section and depth in the oxide.

Finally, the relation between trap energy distribution and the presence or absence of noise reduction was developed. This can for instance explain why devices with hot electron damage or radiation damage hardly show RTS noise reduction, while undamaged device do.

This dependence on trap energy distribution is likely to limit the practical applications of the noise reduction effect to well-controlled well-characterized MOS processes.

There is a trend to use different oxide materials in new CMOS processes, for instance to reduce gate leakage current. The effect of such oxides on noise might prove very important. We think that our characterization methods and noise models will prove to be valuable in this context.

VI. ACKNOWLEDGEMENTS

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