Large Signal Excitation Measurement Techniques for Random Telegraph Signal Noise in MOSFETs

Abstract— **This paper introduces large signal excitation measurement techniques to analyze Random Telegraph Signal (RTS) noise in MOSFETs. RTS noise originates from capture and emission of mobile carriers in traps in the oxide and at the interface and manifest itself as low frequency noise. The paper concentrates on the trap-occupancy that a) depends strongly on the bias history, as derived from Shockley-Read-Hall theory, and b) relates directly to the generated noise. The proposed measurement technique makes trap-occupancy observation possible for every bias-situation, including the OFF-state of the transistor. It provides crucial information for modelling of RTS noise under Large Signal Excitation.**

Keywords— **MOSFET, Random Telegraph Signal (RTS) noise, LF noise, Large Signal Excitation, Transient.**

I. Introduction

All electronic devices suffer from noise, limiting the minimum signal level that a circuit can process reliably. There is a trade-off between signal to noise ratio, power dissipation, speed and linearity. In order to design optimal systems adequate noise models are required. Therefore, research is needed to understand the origin of noise and the mechanisms behind it.

In a MOSFET, thermal noise noise is a dominant factor at higher frequencies of the drain current Power Spectral Density (PSD). This noise is caused by scattering of carriers with the lattice, due to thermal motion [1]. For 'large' MOSFETs (active area above $\approx 1\ \mu\text{m}^2$), at lower frequencies the MOSFET drain current PSD is dominated by $1/f$-noise, which is caused by fluctuation in the conductivity. The conductivity σ is given in Eq. 1, where n is the number of carriers, μ the mobility and q the electron charge.

$$\sigma = \mu\, n\, q \tag{1}$$

Fluctuations in σ can be explained by either a change in the number of carriers n as described by the number fluctuation model [2], or by a fluctuation of the mobility μ according to the mobility fluctuation model [3]. A correlated combination of both the number fluctuation model and the mobility fluctuation model is suggested as well [4]. In bulk material like metals and semiconductors, the mobility fluctuation model describes $1/f$-noise correctly. For $1/f$-noise observed in MOSFETs, the number fluctuation model and the correlated combination of both models provide a better fit. According to the number fluctuation model, $1/f$-noise arises from the summation of Random Telegraph Signal (RTS) noise, which originates from capture and emission of charge carriers in traps in the gate oxide and the interface. The correlated combination of both models [4] takes into account the influence of the captured carriers on the local electric field, resulting in a change in mobility.

For 'small' devices (active area below $\approx 1\ \mu\text{m}^2$) RTS noise is directly observed in the MOSFET drain current. The trend in the IC-Industry is to reduce device dimensions, which increases the dominance of RTS noise. The associated noise behavior in not yet included in circuit simulator noise models. In large signal applications, the noise may depend on the bias situation, as well as on the bias-history [5–9]. Circuit simulators do not take the bias history into account, which results in incorrect noise predictions in large signal excitation situations.

The behavior of RTS noise in steady state is described by Shockley-Read-Hall (SRH) theory [2]. The influence of large signal excitation on RTS noise is also investigated [7,8]. This paper introduces new measurement techniques to investigate RTS noise under large signal excitation. In the new measurement techniques, the occupancy of the trap from which the RTS noise originates plays a central role for two reasons. Firstly, the trap-occupancy depends strongly on the bias history, as is derived from SRH-theory and confirmed by measurements. Secondly, the trap-occupancy is directly related to the noise. In most bias-conditions the trap-occupancy can be measured directly. For bias situations where direct measurement is not possible, because the device is OFF or the RTS is not dominant over the other sources of noise, an indirect occupancy extraction method is proposed. By combining the extracted transient trap-occupancy with SRH theory, the RTS is characterized.

With the introduced measurement techniques a single trap can be characterized over the whole bias-range, which is of great importance as in large signal excitation applications the noise depends strongly on the bias-history.

This paper is organized as follows: Section II involves the RTS theory. Section III describes the devices under test, together with the measurement method. The trap-occupancy is investigated in Section IV. Section V introduces the indirect measurement method. Finally, in Section VI, conclusions are drawn.

II. RTS in the time domain

An RTS is characterized by three parameters: the mean capture time $\bar{\tau}_\text{c}$ (mean time to capture when the trap is empty), the mean emission time $\bar{\tau}_\text{e}$ (mean time to emission when the trap is filled) and the amplitude (Fig. 1). The chance that the RTS is in the high state (the trap is filled) is equal to the occupancy of the trap. The relation between the steady state trap-occupancy $P_{f-\text{ss}}$ and the mean time constants (Eq. 2) is derived in the Appendix.

$$P_{f-\text{ss}} = \frac{\bar{\tau}_\text{e}}{\bar{\tau}_\text{c} + \bar{\tau}_\text{e}} \tag{2}$$

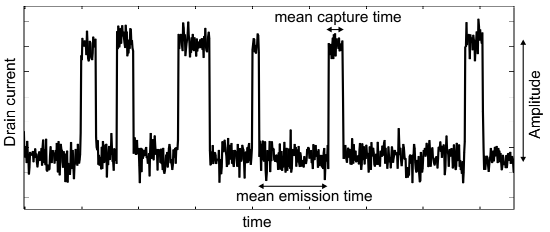

Fig. 1. Time domain sample of the drain current of a MOSFET (W/L = 1/0.13μm).

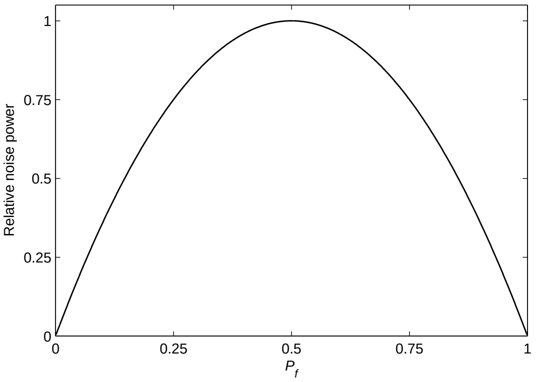

Fig. 2. Relation of trap-occupancy with RTS noise power.

A change in bias of the MOSFET results in a new steady state occupancy of the trap, which results in a different $\bar{\tau}_{\rm c}$ and $\bar{\tau}_{\rm e}$. Shockley-Read-Hall (SRH) theory assumes that the change in the mean capture and in the mean emission time is instantaneous with the bias, as $\bar{\tau}_{\rm c}$ and $\bar{\tau}_{\rm e}$ depend only on the instantaneous bias condition [10]. In the Appendix, the transient trap occupancy behavior is derived from SRH-theory. According to the derivation (Eq. 3), the trap-occupancy cannot change instantaneously; it experiences an exponential transient $P_f(t)$ from the old occupancy $P_f(0)$, towards the new steady state situation $P_{f-\rm ss}$. The time constant of occupancy change $\tau_{\rm r}$ (Eq. 4) is the exponential decay constant.

$$P_f(t) = P_{f-\rm ss} + \big(P_f(0) - P_{f-\rm ss}\big)\exp\big(-\mathrm{t}/\tau_{\rm r}\big) \tag{3}$$

$$\frac{1}{\tau_{\rm r}} = \frac{1}{\bar{\tau}_{\rm c}} + \frac{1}{\bar{\tau}_{\rm e}} \tag{4}$$

For long times t ($t >> \tau_{\rm r}$), the instantaneous occupancy $P_f(t)$ (Eq. 3) reduces to the steady state occupancy $P_{f-\rm ss}$ (Eq. 2). Note that, if the initial occupancy $P_f(0)$ is not equal to the steady state occupancy, the mean time constants $\bar{\tau}_{\rm c}$ and $\bar{\tau}_{\rm e}$ can be calculated from the instantaneous occupancy and vice versa (Eq. 2, 3, 4).

The noise power of an RTS depends directly on the occupancy of the trap [11]. The noise is maximal when P_f is $\frac{1}{2}$ and decreases when P_f deviates from this value (Fig. 2).

III. Experimental

The devices under test are nMOS matched pair MOSFETs fabricated in an industrial 0.18 μm process flow. The drain contacts are separate; the gate, source and substrate contacts are common. The gate length is 0.13 μm and the width is 1 μm. The noise is measured with a differential noise measurement setup [6]. This setup suppresses large common mode signals, enabling the measurement of the small uncorrelated noise currents of both MOSFETs. If an RTS is observed it is not known from which transistor it originates. Either the high or the low current state of the observed signal can be associated with the capture time. The trap will be empty after a long OFF-time (no charge carriers in the channel), which assures that the first state observed after turn ON is the capture time of the RTS.

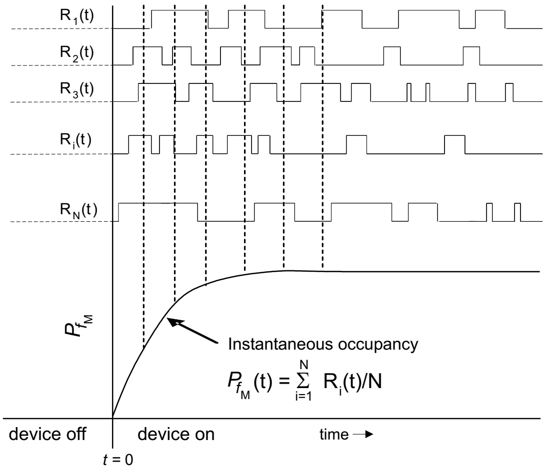

Fig. 3. Schematic representation of the instantaneous measured occupancy $P_{f_{\rm M}}(t)$.

A measurement method has been developed to measure the instantaneous trap-occupancy $P_{f_{\rm M}}(t)$ of a single trap. After an OFF-time, the MOSFETs are switched ON. Subsequently, the state of the trap (filled or empty) is recorded at each instant in time, for a large amount of time records N (Fig. 3). The measured instantaneous occupancy is the total number of times that the trap is filled, at each moment in time, divided by the total number of time records. Separately from the instantaneous occupancy, the steady state time constants are measured.

IV. Transient trap-occupancy

For short OFF-times the measured instantaneous occupancy does not change substantially (Fig. 4). Longer OFF-times appear to have reduced the occupancy considerably. This decrease is caused by the low capture chance in the OFF-state, due to the absence of charge carriers. By fitting the instantaneous occupancy (Eq. 3) with the measured occupancy (Fig. 4), the values of $P_{f-\rm ss}$ and $\tau_{\rm r}$ are derived. The initial occupancy $P_f(0)$ is selected for optimum match. From $P_{f-\rm ss}$ and $\tau_{\rm r}$ the mean capture time (9.5 ms) and the mean emission time (7.0 ms) are extracted (Eq. 2, 4), which agree with the mean time constants derived from steady state measurements, done under the same bias conditions.

Fig. 5 gives an example of a trap that is being filled when the MOSFETs are switched ON ($P_{f-\rm ss} = 1$) and becomes

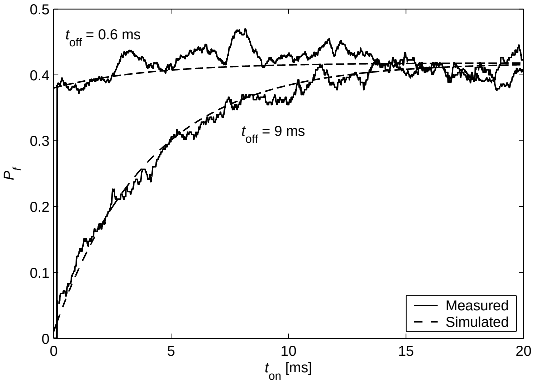

Fig. 4. Measured and simulated occupancy ($\bar{\tau}_{\mathrm{c}} = 9.5$ ms, $\bar{\tau}_{\mathrm{e}} = 7.0$ ms)

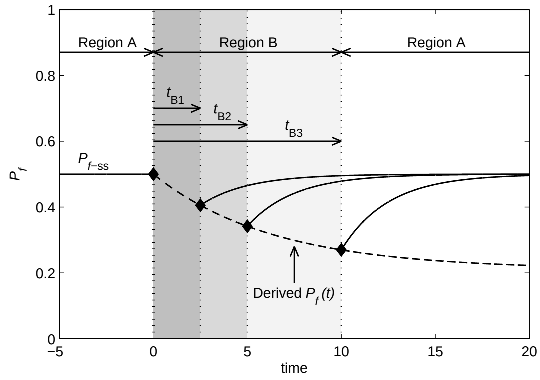

Fig. 6. Extraction method for the occupancy of regime B.

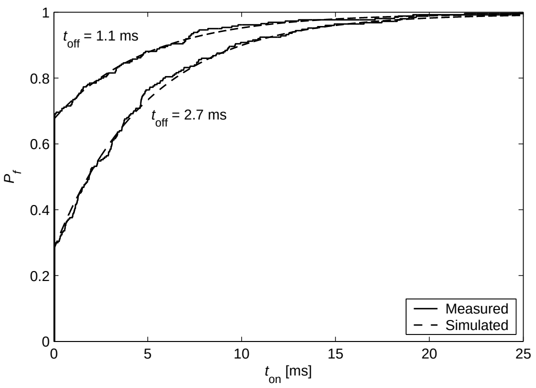

Fig. 5. Measured and simulated instantaneous occupancy ($\bar{\tau}_{\mathrm{c}} = 5.0$ ms, $\bar{\tau}_{\mathrm{e}} >> \bar{\tau}_{\mathrm{c}}$).

empty when the MOSFETs are switched OFF. This RTS is only visible, and thus dominant, during the first instants after turn ON. As a result, the mean time constants cannot be derived from steady state measurements. From the measured occupancy the mean capture time (5.0 ms) and a large mean emission time ($\bar{\tau}_{\mathrm{e}} >> \bar{\tau}_{\mathrm{c}}$) are extracted.

Existing circuit simulators assume that the noise is changing *instantaneously* with bias conditions. This is clearly *not true* as the occupancy, which depends on bias-history (Fig. 4, 5), is directly related to the noise (Fig. 2). Therefore, the noise modelled by circuit simulators in case of large signal excitation is erroneous.

With the introduced method, the mean time constants can be extracted after a bias-change by matching the measured trap-occupancy with the on SRH based transient occupancy behavior.

V. Indirect extraction method

When the MOSFETs are switched OFF, biased in the sub-threshold regime, or biased in a regime where the RTS is not dominant, the RTS time constants and the trap-occupancy can not be measured directly. An indirect extraction method has been developed to derive the parameters $P_f(t)$, $\bar{\tau}_{\mathrm{c}}$ and $\bar{\tau}_{\mathrm{e}}$. For these cases parameter extraction is important, because noise depends on the bias-history, and only with an indirect extraction method a single RTS can be characterized over the whole bias-range. The method concentrates on the trap-occupancy, because the trap-occupancy does not change instantaneously with the bias condition, as do the time constants. Two bias regimes are defined: regime A, where the occupancy can be measured and regime B, where the parameters can only be determined indirectly. First, steady state occupancy is reached in regime A. Subsequently, the devices are biased in regime B, after which the devices return to regime A (Fig. 6). The occupancy does not change instantaneously (Eq. 3); the occupancy measured immediately after the bias change is equal to the occupancy just before the bias change. Here, the sampling time must be chosen much higher than the involved mean time constants. By varying the time spend in regime Bm the occupancy is acquired at different time instants (Fig. 6). From these values the theoretical occupancy of regime B is derived (Eq. 3). Subsequently, the mean time constants of regime B are calculated (Eq. 2 and 4). Thus, by clever usage of the trap-occupancy dependence on bias history, the trap-occupancy and the mean time constants can be extracted for a different bias-condition.

As an example, the occupancy and the mean time constants of the two earlier discussed traps are derived for a situation in which the MOSFETs are switched OFF (Fig. 7). In both cases the steady state occupancy (Eq. 2) approaches zero. This is because in the OFF-state, the probability for a capture is much lower than the probability on emission ($\bar{\tau}_{\mathrm{c}} >> \bar{\tau}_{\mathrm{e}}$). Due to this the time constant of occupancy change (Eq. 4) is dominated by the emission time. Thus, for the OFF-state, the instantaneous trap-occupancy (Eq. 3) reduces to a simpler form (Eq. 5). The initial OFF-state occupancy $P_{f_{\mathrm{off}}}(0)$ is equal to the steady state occupancy of the ON-state. The mean emission time constant of the OFF-state is extracted by matching the measured occupancy with the derived OFF-state occupancy (Eq. 5).

$$P_{f_{\mathrm{off}}}(t) = P_{f_{\mathrm{off}}}(0)\exp\big(-\mathrm{t}/\bar{\tau}_{\mathrm{e_{off}}}\big) \tag{5}$$

Note that, despite the fact that the MOSFETs are OFF for gate voltages below the threshold voltage, the occupancy still varies with the gate OFF-voltage (Fig. 8). The

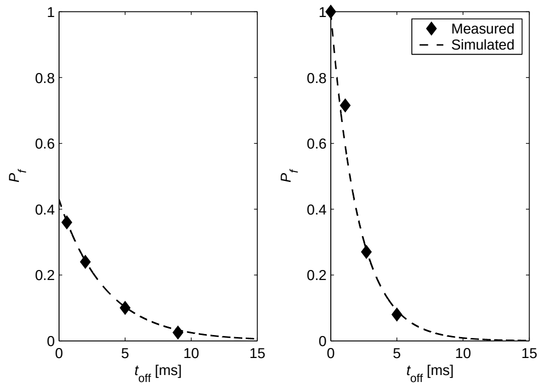

Fig. 7. Measured and simulated OFF-state occupancy. Extracted time constants: a) $\bar{\tau}_{\mathrm{e}} = 3.5$ ms, $\bar{\tau}_{\mathrm{c}} >> \bar{\tau}_{\mathrm{e}}$. b) $\bar{\tau}_{\mathrm{e}} = 2.0$ ms, $\bar{\tau}_{\mathrm{c}} >> \bar{\tau}_{\mathrm{e}}$.

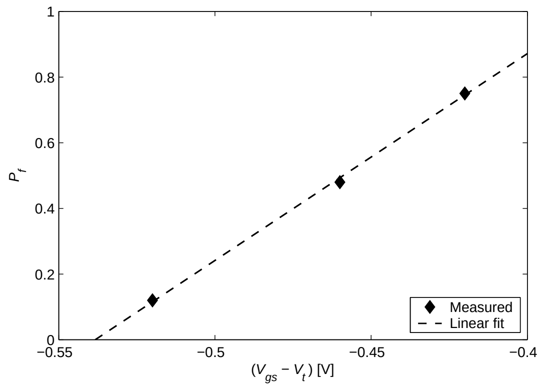

Fig. 8. Measured OFF-state occupancy at different gate OFF-voltages, after a constant OFF-time ($t_{\mathrm{off}} = 5$ ms).

emission time dominates in the OFF-state (Eq. 5), which indicates that the mean emission time decreases with the gate OFF-voltage, as reported in [8].

VI. Conclusions

For 'small' MOSFETs, the low frequency noise is dominated by Random Telegraph Signal (RTS) noise, originating from the capture and emission of charge carriers in gate oxide traps. Shockley-Read-Hall (SRH) theory relates the mean capture and the mean emission time to the instantaneous bias condition. The transient trap-occupancy, derived from SRH theory, predicts that the trap-occupancy changes exponential in time after a bias change, towards a new steady state occupancy. This paper presents new measurement techniques which allows observing the transient trap-occupancy under arbitrary bias conditions, including the OFF-state of the MOSFET. The introduced measurement techniques confirm the bias dependency of the trap-occupancy.

The trap-occupancy is directly related to the noise, which indicates that the generated RTS noise depends strongly on the bias history, and not only on the instantaneous bias condition, as is currently modelled in circuit simulators.

By applying the proposed measurement techniques, RTS behavior can be characterized in steady state and under large signal excitation situations. This is essential for the development of noise models.

Appendix

In this Appendix, the transient trap-occupancy behavior for an n-channel MOSFETs is derived from SRH-theory. For p-channel MOSFETs, an analogous derivation can be made. The mean capture time $\bar{\tau}_{\mathrm{c}}$ and the mean emission time $\bar{\tau}_{\mathrm{e}}$ are defined as [10]:

$$\frac{1}{\bar{\tau}_{\mathrm{c}}} = \sigma_t v_{th} n \tag{A-1}$$

$$\frac{1}{\bar{\tau}_{\mathrm{e}}} = \sigma_t v_{th} N_c \exp\big(E_t/kT\big) \tag{A-2}$$

where σ_t is the capture cross section of the trap, v_{th} the thermal velocity of the electrons, n the electron density in the conduction band, N_c the effective density of electrons states in the conduction band, E_t the energy of the trap below the conduction band edge, k the Boltzman constant and T the temperature. The net rates of capture $r_{\mathrm{c}}(t)$ and emission $r_{\mathrm{e}}(t)$ are given by:

$$r_{\mathrm{c}}(t) = \frac{1 - P_f(t)}{\bar{\tau}_{\mathrm{c}}} \tag{A-3}$$

$$r_{\mathrm{e}}(t) = \frac{P_f(t)}{\bar{\tau}_{\mathrm{e}}} \tag{A-4}$$

where $P_f(t)$ is the instantaneous trap-occupancy, the probability that the trap is filled at time t. The net rate of capture is given by:

$$\frac{dP_f(t)}{dt} = r_{\mathrm{c}}(t) - r_{\mathrm{e}}(t) \tag{A-5}$$

This first order differential equation is valid in steady state as well as during transients, and can be solved to [12]:

$$P_f(t) = \frac{\bar{\tau}_{\mathrm{e}}}{\bar{\tau}_{\mathrm{c}} + \bar{\tau}_{\mathrm{e}}} + K\exp - \big(\frac{1}{\bar{\tau}_{\mathrm{c}}} + \frac{1}{\bar{\tau}_{\mathrm{e}}}\big)t \tag{A-6}$$

where K is the integration constant, which value is chosen such that the occupancy at $t = 0$ equals the initial occupancy $P_f(0)$:

$$P_f(t) = \frac{\bar{\tau}_{\mathrm{e}}}{\bar{\tau}_{\mathrm{c}} + \bar{\tau}_{\mathrm{e}}} + \big(P_f(0) - \frac{\bar{\tau}_{\mathrm{e}}}{\bar{\tau}_{\mathrm{c}} + \bar{\tau}_{\mathrm{e}}}\big)\exp - \big(\frac{1}{\bar{\tau}_{\mathrm{c}}} + \frac{1}{\bar{\tau}_{\mathrm{e}}}\big)t \tag{A-7}$$

For steady state situations ($t \to \infty$) the trap-occupancy is:

$$P_{f-\mathrm{ss}} = \frac{\bar{\tau}_{\mathrm{e}}}{\bar{\tau}_{\mathrm{c}} + \bar{\tau}_{\mathrm{e}}} \tag{A-8}$$

$$\frac{1}{\tau_{\mathrm{r}}} = \frac{1}{\bar{\tau}_{\mathrm{c}}} + \frac{1}{\bar{\tau}_{\mathrm{e}}} \tag{A-9}$$

Substituting the steady state occupancy $P_{f-\mathrm{ss}}$ (Eq. A-8) and the time constant of occupancy change τ_{r} (Eq. A-9) into Eq. A-7 gives the transient trap-occupancy:

$$P_f(t) = P_{f-\mathrm{ss}} + \big(P_f(0) - P_{f-\mathrm{ss}}\big)\exp\big(-\mathrm{t}/\tau_{\mathrm{r}}\big) \tag{A-10}$$

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