Modeling of RTS Noise in MOSFETs under Steady-State and Large-Signal Excitation


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Abstract

The behavior of RTS noise in MOSFETs under large-signal excitation is experimentally studied. Our measurements show a significant transient effect, in line with earlier reports. We present a new physical model to describe this transient behavior and to predict RTS noise in MOSFETs under large-signal excitation. With only three model parameters the behavior is well described, contrary to existing models.

Introduction

With shrinking device dimensions, low-frequency (LF) noise in MOSFETs is dominated by Random Telegraph Signals (RTS), limiting the achievable circuit performance in analog and RF CMOS (e.g. LF noise in amplifiers and filters for radio receivers and phase noise due to up-converted LF noise in oscillators).

The steady-state behavior of an RTS has been extensively studied [1-2]. Although it is known that RTS noise changes significantly under large-signal periodic excitation, (Fig.1) [3-5], which is beneficial for oscillators and PLLs, current circuit simulators do not model this behavior [6]. Even circuit simulators that support time-variant noise sources (e.g. periodic steady-state analysis of Spectre RF), do not adequately model the observed effects.

Experimental

NMOS transistors with W/L=1/0.13 fabricated in a 0.18 μm CMOS process, have been used for this study. The RTS is characterized in the time-domain by three parameters: 1) the mean low time; 2) the mean high time; 3) the amplitude (Fig. 2), using a differential measurement setup [5]. Fig. 3 shows the steady-state bias dependence of the mean capture time (τc), and the mean emission time (τe), on the gate-to-source voltage (VGS) for a given drain voltage. Fig. 4 shows the steady-state bias dependence of the RTS amplitude (∆I) on VDS for a given VGS.

In steady-state when the device is ON, the trap-occupancy is given by: τe on / (τc on + τe on). When the device is in the OFF state for a long period, with no charge carriers in the channel, the trap-occupancy is almost zero (τc off / (τe off + τc off)).

To overcome these shortcomings, we have performed extensive measurements on RTS under large-signal excitation and we present a simple, physical model giving a realistic description of the observed effects.
the steady-state occupancy). It is determined by averaging the state of the RTS (high or low) over many successive RTS time-domain records, for a given time instant during the ON period (Fig. 5). Measurements on three different RTS on three different devices show that the instantaneous trap-occupancy does not follow the instantaneous step-voltage but increases exponentially from the steady-state OFF value to reach the steady-state ON value (Fig. 6). Existing circuit simulators implicitly assume an instantaneous change in the trap-occupancy with changing gate-bias, thus giving erroneous noise predictions under periodic bias excitation.

The study of instantaneous trap-occupancy during biasing transients is extended to the large-signal periodic excitation case. Under periodic large-signal excitation, the device is alternating between an ON state and an OFF state. The excitation frequency is well above the corner frequency of the RTS. Under these conditions the cyclo-stationary RTS parameters (obtained by sampling the drain-current in the ON states [7]) are significantly different compared to the RTS parameters in the steady-state, resulting in a changed RTS noise spectrum (Fig. 1).

Steady-State RTS Modeling

Fig. 7 shows a block representation of our model. The model is primarily based on the Shockley-Read-Hall statistics of capture and emission [1]. Three physical parameters are used to characterize a trap: the trap energy in silicon band-gap at flat-band \((E_n)\), the location of the trap (distance from the \(Si/SiO_2\) interface) in the oxide \((X_t)\), and the intrinsic cross-section of the trap \((\sigma_t)\) [2]. The RTS amplitude is calculated by assuming an elementary electron charge in the channel that changes the channel conductivity [8]. In steady-state, the trap-occupancy function follows the Fermi-Dirac statistics and is a function of the trap energy \((E_t)\), and the Fermi-level for traps \((F_t)\) [1]. In steady-state, the Fermi-level for the trap \((F_t)\) is equal to the Fermi-level for the charge carriers in silicon \((F_n)\) [1]. \(F_n\) changes with \(V_{GS}\), and the steady-state trap-occupancy is a function of \(V_{GS}\). The number of charge carriers in the channel depends on the band-bending in Silicon and thus \(V_{GS}\). The slope of \(\tau_e\) as a function of \(V_{GS}\), is used to extract \(X_t\) [2]. Together, the variation of \(\tau_e\) and \(\tau_i\) as a function of \(V_{GS}\), are used to extract the trap parameters: \(E_n, X_t, \) and \(\sigma_t\).
Dynamic RTS Modeling (Periodic large-signal excitation)

Under periodic large-signal excitation our model assumes $F_n$ changing instantaneously with changes in $V_{GS}$. During transients, the capture rate is not equal to the emission rate. The RTS behavior under transient biasing conditions shows that the instantaneous trap-occupancy increases exponentially from the OFF state occupancy to the ON state occupancy (Fig. 5). Although the trapping behavior cannot be observed in the OFF state, we expect the OFF transient to be exponential as well. The increase (and decrease) of the trap-occupancy is modeled using $\tau_{\text{occRlx}}$ (time-constant for the occupancy relaxation) as a model parameter for the exponential fit. $\tau_{\text{occRlx}}$ is not a new trap parameter, but the mean time before the trap-occupancy reaches its steady-state value. It can be shown that $1/\tau_{\text{occRlx}}$ is the sum of $1/\tau_{\text{on}}$ and $1/\tau_{\text{off}}$ during the ON state transience and similarly: $1/\tau_{\text{occRlx}} = 1/\tau_{\text{c}} + 1/\tau_{\text{e}}$ during the OFF state transience [9]. When the frequency of the applied gate-bias is much higher than the corner frequency of the RTS, the averaged trap-occupancy is somewhere between the steady-state trap-occupancy in the ON and OFF state (Fig. 8).

![Fig 8: Instantaneous occupancy under periodic large-signal excitation](image)

Intuitively, this makes sense, as it is clear that slow traps cannot adapt quick enough to fast changes in the biasing, resulting in relaxation effects. Our model calculates the instantaneous capture and emission rates from the instantaneous trap-occupancy and the instantaneous $\tau_{\text{c}}$ and $\tau_{\text{e}}$. The cyclo-stationary RTS parameters needed for comparison with the measurement data, under periodic large-signal excitation, are calculated in our model using the instantaneous $\tau_{\text{c}}$, $\tau_{\text{e}}$, and the duty-cycle and frequency of periodic excitation (Fig. 9). Fig. 10 and 11 show this cyclo-stationary RTS parameters $\tau_{\text{c}}$ and $\tau_{\text{e}}$ as a function of the duty-cycle and frequency of the large-signal periodic excitation.

Fig. 12 shows the variation of $\tau_{\text{c}}$ and $\tau_{\text{e}}$ as a function of the OFF voltage of the applied periodic large-signal. $\tau_{\text{e}}$ decreases rapidly as the OFF voltage goes deeper below the threshold voltage. Physically, this can be visualized as the trap cross-section for emission ($\tau_{\text{e}}$) increasing as the OFF voltage goes deeper below threshold. This behavior is not modeled by assuming a simplistic bias independence of $\tau_{\text{e}}$. Thus, in our model, the trap cross section decay constant ($X_0$) [10] is
empirically modeled as a function of $V_{GS}$, to fit our measurement results.

![Graph showing cyclo-stationary RTS time constants $\tau_c$ and $\tau_e$ as a function of $V_{GS}$ for $V_{GS_{on}} = 0.6$ V, $V_{DS} = 50$ mV, duty-cycle = 50%, $f_{sw} = 31.6$ kHz.]

Fig 12: Cyclo-stationary RTS time constants $\tau_c$ and $\tau_e$ as a function of $V_{GS}$ for $V_{GS_{on}} = 0.6$ V, $V_{GS_{off}} = -0.5$ V, duty-cycle = 50%, $f_{sw} = 31.6$ kHz.

| TABLE I | EXTRACTED PHYSICAL MODEL PARAMETERS FOR 3 DIFFERENT RTS ON 3 DIFFERENT DEVICES |
|---------------------|-------------------------------|---------------------|
| $E_t$ (eV) | $X_t$ (nm) | $\sigma_0$ ($\text{cm}^2$) |
| RTS1410        | 0.126 | 1.5 | $1.0 \times 10^{-17}$ |
| RTS1613        | 0.120 | 2.0 | $4.0 \times 10^{-16}$ |
| RTS0611        | 0.015 | 0.2 | $2.2 \times 10^{-23}$ |

Fig 13: LF RTS noise spectra under steady-state and large-signal periodic excitation (cyclo-stationary RTS). $f_{sw} = 31.6$ kHz, $V_{GS_{on}} = 0.6$ V, $V_{GS_{off}} = -0.5$ V, duty-cycle = 50%.

We use our model to simulate the RTS parameters under various biasing conditions (steady-state and periodic large-signal excitation) and match them with measured data by using the same set of extracted trap-parameters (Fig. 3, 4, 6, 10, 11, and 12 show measurements and our model simulation on a device RTS1410). The markers in the figures indicate measurement data and solid lines represent our model simulation. Table 1 shows the extracted model trap-parameters for 3 different traps. Finally, Fig. 13 shows the measurement and simulation of the RTS noise spectrum under steady-state and under large-signal periodic excitation (cyclo-stationary RTS).

Conclusions

For the first time we investigate single trap behavior under transient biasing conditions that is not observable in steady-state, thus providing more insight in trapping and de-trapping mechanisms. We present a simple physics based analytical model to accurately predict the RTS parameters and noise spectra, in steady-state as well as under large signal excitation. All our model parameters have a physical significance and the model shows excellent agreement with measured data on a single RTS. Given a distribution of traps in energy and location, it is possible to extend our model to accurately predict the LF noise in MOSFETs, under varying bias conditions, leading to better optimization of analog and RF designs.

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References