

Gate Voltage Dependent 1/f Noise Variance Model in n-Channel MOSFETs

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Abstract

1/f noise is one of the most important characteristics for designing analog/RF circuits such as operational amplifiers and oscillators. We have analyzed and developed a novel 1/f noise model based on SPICE2's. The model includes two noise generation mechanisms that are mobility and interface trap number fluctuations. Noise variability dependent on gate voltage is also implemented in the model.

1. Introduction

1/f noise in MOSFET is one of the important characteristics for analog/RF circuit design. For example, 1/f noise is up-converted in frequency domain and degrades phase noise performance of oscillators in wireless transceiver circuits. Since existing 1/f noise models including [1] and [2] are useful only for nominal simulations, we have developed a new model which can simulate noise variance dependent on the gate voltage of a MOSFET. Although the model is modified from simple SPICE2 MOSFET 1/f noise model integrated in any SPICE simulator, it is based on two 1/f noise generation mechanisms that are McWorter's [3] and Hooge's [4].

In this paper, we present the model derivation, implementation in BSIM4 model on our SPICE3 circuit simulator (MDW-SPICE), and verifications with 1/f noise measurements. The 1/f noise level and the deviation dependencies of gate bias voltages (i. e., as the gate voltage increases, 1/f noise level increases but its variance decreases [5]) are successfully simulated and agreed with measurements. Note that the modeling of the 1/f noise deviation (or statistical modeling) is important to estimate yield of analog/RF circuits.

2. MOSFET 1/f noise model derivations

1/f noise is generated in MOSFET. Fig. 1 shows the tunneling transitions from the Si to the gate oxide and between interface traps. 1/f noise is caused by these traps in energy. Also it is inversely proportional to the frequency so that noise power is dominant at low frequency.

McWorter suggested 1/f noise generation model in eq. (1) based on energy level fluctuation caused by interface trap number.

$$S_{I_D} = S_V \left(1 + \frac{\alpha_H \mu_{eff} C_{OX} I_D}{g_m} \right)^2 g_m^2. \quad (1)$$

Hooge also showed 1/f noise generation model in eq.

(2) and (3), which are considered as mobility fluctuations.

$$\frac{S_{I_D}}{I_D^2} = \frac{\alpha_H \cdot \mu_{eff} \cdot 2kT}{fL^2 I_D}. \quad (2)$$

$$S_{I_D} = \frac{\alpha_H \cdot \mu_{eff} \cdot 2kT \cdot I_D}{fL^2}. \quad (3)$$

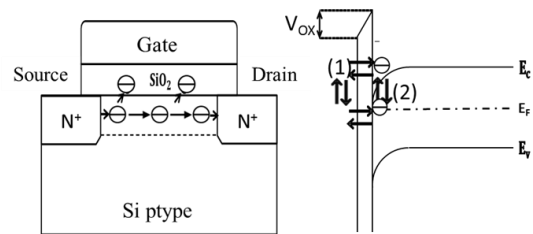


Fig. 1. Schematic illustration and the energy band diagram represent the tunneling transition of electrons between the conduction band and traps in the gate oxide, (1) related to direct tunneling and (2) to indirect tunneling through interface traps.

α_H is a coefficient caused by phonon scattering and related to mobility fluctuations. Accordingly, it is expected that 1/f noise vary because α_H varies.

SPICE2 model, which is used for most MOSFETs of SPICE model as a selection, is based on McWorter's model with precision to 1/f noise generation mechanism. We also include Hooge's model in SPICE2 model by replacing a noise coefficient parameter, KF , with a mobility fluctuation equation. Then we try to get a new 1/f model which includes both of mobility fluctuations and interface trap number fluctuations.

Here we show SPICE2 model in (4) as follows:

$$S_{id}(f) = \frac{KF \cdot I_{ds}^{AF}}{C_{OX} L_{eff}^2 f^{EF}}. \quad (4)$$

We compare Hooge's in eq. (3) with SPICE2 models in eq. (4). Assuming of $AF = EF = 1$ as ideal 1/f noise to simplify the derivations, we obtain eq. (5)

$$\alpha_H \cdot \mu_{eff} \cdot 2kT = \frac{KF}{C_{OX}}. \quad (5)$$

Then, we have the following:

$$KF = C_{OX} \alpha_H \cdot \mu_{eff} \cdot 2kT. \quad (6)$$

Where, KF is a parameter which shows mobility fluctuations.

α_H decreases with a function of the effective gate-to-source voltage, which is written as eq. (7).

$$\alpha_H \propto e^{-(V_{gs}-V_{TH})}. \quad (7)$$

The variability is caused mainly by the device process variation [5]; therefore, it can follow Gaussian distribution. As described above, α_H has some variability, so that we use D as Gaussian Normalized Random Number, which fluctuates from 0 to 1. If we modify it to $D - 0.5$, it means that α_H takes a value between -0.5 and 0.5 , and then its mean is 0. α_H is now completed as eq. (8)

$$\alpha_H = (2 \cdot \alpha_{H_{nominal}} \cdot (D - 0.5) + KFN) \cdot e^{-(V_{gs}-V_{TH})}. \quad (8)$$

Eq. (8) means α_H is distributed from $-\alpha_{H_{nominal}}$ to $\alpha_{H_{nominal}}$, and its mean is KFN (see Fig. 2). Substituting α_H of eq. (8) into eq. (6) gives the model shown in eq. (9).

$$KF = C_{OX} \cdot \mu_{eff} \cdot 2 \cdot k \cdot T \cdot (2 \cdot \alpha_{H_{nominal}} \cdot (D - 0.5) + KFN) \cdot e^{-(V_{gs}-V_{TH})}. \quad (9)$$

By substituting eq. (9) into eq. (4), we have finally obtained the $1/f$ noise variability model incorporated in mobility fluctuations. The value of KFN is tuned to increase as the gate-source voltage V_{gs} increases.

3. Comparisons with simulation and measurement

The proposed model has been implemented in BSIM4 model with our MDW-SPICE for simulations. Also, $1/f$ noise measurement (under the condition equivalent to gate voltage change) has been performed by using a set of $1/f$ noise measurement system [6]. An n-channel MOSFET with the channel length of 90 nm, the channel width of 10 μm , and the EOT of 5 nm was measured after drain current measurements for parameter extractions.

Fig.3 shows simulation and measurement results. We see clearly that the center simulation curves of both gate voltages, which are nominal simulations, agree with measured results accurately. Also for $1/f$ noise variability with gate voltage, the variance is decreased with increasing gate voltage. Proposed model can accurately simulate the $1/f$ noise voltage density characterization.

4. Conclusions

In this paper we have presented the model derivation of $1/f$ noise, its implementation in BSIM4 model on our SPICE3 circuit simulator, and verifications with $1/f$ noise measurements. Our $1/f$ noise model includes two noise generation mechanisms that are using mobility and interface trap number fluctuations. Noise variability dependent on gate voltage is also implemented in the model.

We have performed simulation using the proposed model and confirmed that our model accurately agreed with measurement results of 90 nm n-channel MOSFET.

Acknowledgements

We would like to thank Semiconductor Technology Academic Research Center (STARC) for supporting our research.

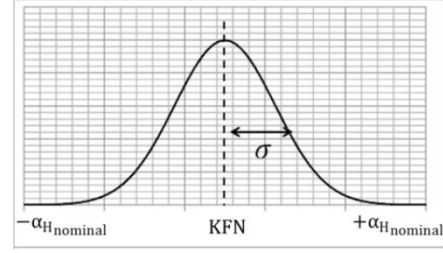


Fig. 2. Gaussian distribution with mean KFN and standard deviation σ

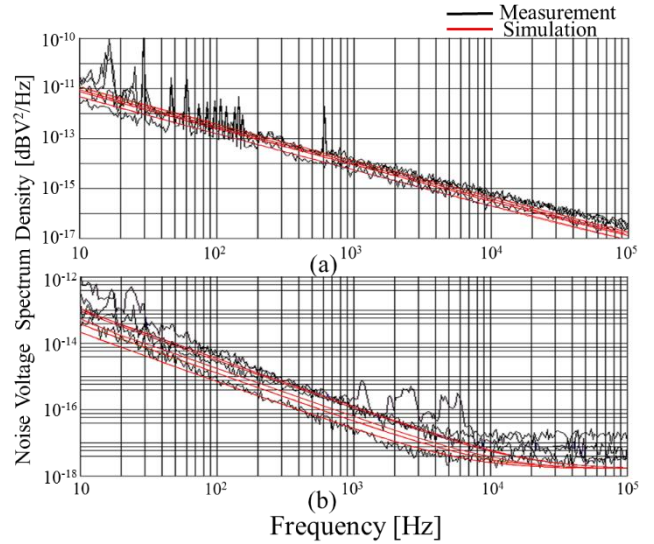


Fig. 3. Simulation and measurement results of drain output $1/f$ noise voltage density with (a) $V_{GS} = 1.41$ V and (b) $V_{GS} = 0.45$ V. V_{DS} was set to 1.0 V for (a) and (b). Where, $1/f$ noise parameters of the proposed model for simulations in (a) and (b) are $AF = 0.3$, $EF = 1.45$, $KF = 2.0 \times 10^{-3}$, $\alpha_H = 8.0 \times 10^{-4}$, and $KFN = 4.0 \times 10^{-3}$.

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