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Frédéric Martinez, M. Valenza, Jimmy Armand. Numerical modeling of low frequency noise in ultrathin oxide MOSFETs. Noise and fluctuations : 20th International Conference on Noise and Fluctuations : ICNF 2009, Jun 2009, Pisa, Italy. pp.285-290. <hal-02052981>

HAL Id: hal-02052981

<https://hal.science/hal-02052981v1>

Submitted on 13 Dec 2024

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Numerical modeling of low frequency noise in ultrathin oxide MOSFETs

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Abstract. We present a numerical low frequency noise modeling related to oxide trapping/detrapping process, based on green's function formulation and its application to ultrathin oxide characterization. This model allows slow trap density profiles to be determined. The model was applied in the investigation of the validity of the flat band voltage fluctuation model in the case of thin oxides. Numerical gate current noise modeling was applied to the characterization of nitridation-induced traps. Finally, 2D model was applied in the investigation of low-frequency degradation of MOSFETs stressed by hot-carriers, and the generated slow oxide trap density profiles were deduced.

Keywords: Low frequency noise, MOSFET, Green's function, thin oxide .

PACS: 72.70.+m, 73.50.Td

INTRODUCTION

The downscaling of CMOS according to the historical law of Moore is achieved by the reduction of the dimensions. The scaling rules impose very thin oxide thicknesses of the order of one nanometer. The low frequency noise is known as an accurate tool to evaluate the quality of the interface region in MOSFETs. Within the carrier number fluctuation model, bulk oxide defects can be characterized from low frequency noise measurements [1]. Nevertheless, the aggressive reduction of the dimensions has made questionable the accuracy of simple analytical models used over past 15 years. Numerical noise modeling is an alternative that allows to take into account scaling effects. Scaling down induces a large number of new physical phenomena; among them, direct tunneling current increases exponentially and leads to modifications in the normal device operation and to degradations of the device performance. This gate current induces additional noise sources.

In this paper, we present numerical low frequency noise modeling related to oxide trapping/detrapping process, based on green's functions formulation and its application to ultrathin oxide characterization.

FLAT BAND VOLTAGE FLUCTUATION CONCEPT

A very popular formulation of McWhorter based models was proposed by Ghibaudo [2], who introduces the concept of an equivalent flat-band voltage fluctuation. The flat band voltage fluctuation technique has been used extensively for

the last 15 years to study and model the LFN in MOS transistors. The advantage is that one can extract the slow oxide trap density with I-V and LF noise measurements, without having to model of the drain current. However, the initial formulation of the flat band voltage fluctuation was established under approximations which no longer hold true with ultrathin oxide devices. In this first section, we present a numerical LFN model for ultrathin oxide MOSFETs.

In order to describe the static behaviour of the device, a one-dimensional formulation is used, taking into account poly-depletion effects in the gate material as well as quantum-mechanical effects. The physical model is based on a self-consistent Poisson-Schrödinger numerical resolution which includes a polysilicon gate.

For the noise analysis, charge fluctuations are introduced in the oxide, and a Green's function approach is used to calculate the spatial cross-spectrum of potential fluctuations.

$$S_V(x, x', f) = \int_{\text{Oxide}} G_V(x, x_a) S_{\Delta V, n_t}(x_a, f) G_V(x', x_a) dx_a \quad (1)$$

where $G_V(x, x_a)$ is the Green's function of the potential $V(x)$, defined as the response of the potential V at a point x due to a δ function in the oxide at a point x_a . The spectral density of the fluctuation of the number of occupied traps in a volume ΔV is given by [3]:

$$S_{\Delta V, n_t}(x, f) = \frac{4\tau(x)}{1+2\pi f^2\tau(x)^2} \frac{f_t(1-f_t)N_t(x)}{\Delta V} \quad (2)$$

where $\tau(x)$ is the trap time constant as a function of its depth, f_t is the trap occupation probability, and $N_t(x)$ is the trap density at a point x .

The power spectral density (PSD) of the inversion charge fluctuations is expressed by taking into account the overall collection of potential fluctuations

$$S_{Q_{inv}}(f) = \iint J_V^{Q_{inv}}(x) S_V(x, x', f) J_V^{Q_{inv}}(x')^T dx dx' \quad (3)$$

where $J_V^{Q_{inv}}$ is the jacobian matrix of the inversion charge Q_{inv} with respect to the electrostatic potential $V(x)$. Finally, we calculate the equivalent flat-band voltage fluctuations that induce the same inversion charge fluctuation than the one evaluated by Green's functions.

$$S_{V_{FB}}^{Green}(f) = \frac{S_{Q_{inv}}(f)}{\iint F(x) \cdot F(x') dx dx'} \quad \text{with} \quad \delta n(x) = F(x) \cdot \delta V_g \quad (4)$$

A comparison of the classical formulation $S_{V_{FB}}^{CL}(f)$ and the Green's function approach to the flat-band voltage PSD $S_{V_{FB}}^{Green}(f)$ was carried out. Results are presented in Fig. 1, showing that for a given trap density, the new flat band voltage PSD $S_{V_{FB}}^{Green}(f)$ is smaller than the classical $S_{V_{FB}}^{CL}(f)$ for ultrathin oxides.

The classical formulation leads to an overestimation of the flat band voltage PSD in the case of ultrathin oxide devices. This result shows that the classical model is no longer suitable for characterization of advanced MOSFETs devices. The oxide trap density vs. equivalent oxide thickness is usually used as figure of merit of a process. This model has been used to correct the data for thin oxides, showing that trap density continues to increase even for ultrathin nitrided oxides (Fig. 2).

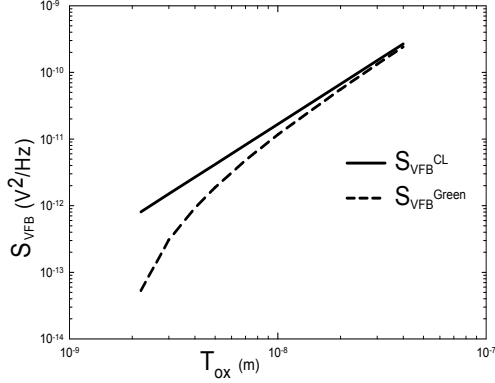


FIGURE 1 : Classical flat-band voltage fluctuations PSD $S_{VFB}^{CL}(f)$ and Green's function approach flat-band voltage fluctuations PSD $S_{VFB}^{Green}(f)$ for a metal gate at $f=1\text{Hz}$.

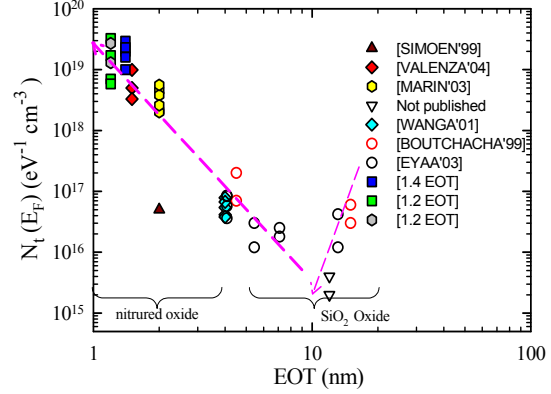


FIGURE 2 : Figure of merit N_t vs EOT extracted with corrections for ultrathin oxide.

GATE LEAKAGE CURRENT LF NOISE MODELING

In this section, we present a numerical model of the gate current LFN adapted to ultra-thin oxides. The aim is to relate the gate current LFN to a slow-trap density profile in the oxide. Gate leakage current has been implemented in the one dimensional solver presented in the previous section. The tunnelling transmission coefficient for electrons is expressed by:

$$T(\psi) = \exp\left(-2\sqrt{\frac{2 \times m_{ox}}{\hbar^2} \int_0^{T_{ox}} (\chi_b - q(\psi_s - \psi(y)) - E) dy}\right) \quad (5)$$

where \hbar is the reduced Planck constant, m_{ox} is the effective mass of the electron in the conduction band in the oxide, T_{ox} is the oxide thickness, χ_b is the barrier height, ψ_s is the surface potential, $\psi(y)$ is the potential at point y , and E is the energy of the tunnelling electron. The gate leakage current is expressed as:

$$I_G = q N_{inv}(\psi) C(\psi) T(\psi) f_i(\psi) \quad (6)$$

Where N_{inv} is the inversion charge, C is the correction coefficient due to reflections at the interface, and f_i is the frequency impact. The spectral density of the gate current fluctuation is given as:

$$S_{I_G}(f) = \iint J_{\psi}^{I_G}(x) S_{\psi}(x, x', f) J_{\psi}^{I_G}(x')^T dx dx' \quad (7)$$

with

$$S_{\psi}(x, x', f) = \int_{Oxide} G_{\psi}(x, x_1) S_{\Delta V, n_t}(x_1, f) G_{\psi}(x', x_1) dx_1 \quad (8)$$

where $J_{\psi}^{I_G}$ is the Jacobian matrix of the gate current I_G with respect to the electrostatic potential $\psi(y)$, $G_{\psi}(x, x_1)$ is the Green's function of the potential $\psi(x)$ defined as the response of the potential ψ at a point x due to a unit charge in the oxide at a point x_1 .

Results and discussion

In this study, n-type MOSFETs with a 1.2 nm equivalent oxide thickness (EOT) targeted value and featuring a polysilicon gate were investigated. The nitridation of the dielectric films was carried-out using either a Decoupled Plasma Nitridation (DPN) or

a Rapid Thermal Nitridation (RTN). The devices were processed on 200 mm diameter silicon wafers. The gate current noise was investigated on isolated nMOS transistors with source, drain and substrate tied together with V_{GS} varying from 0.4 to 1 V.

The main feature observed is the slope of the spectra. For RTN devices, a power factor $\alpha \approx 0.8$ was observed (i.e. the LFN level varies as $1/f^{0.8}$). For DPN devices, we observed $1/f$ spectra and lorentzian spectra with a cut-off frequency of about 1-2 Hz. In order to fit this experimental data, our new gate current LF noise model was used. In particular, the slow oxide trap density profile for each nitridation technique was extracted. Fig. 3 shows the results of the power spectral density simulations for different gate voltages and for both nitridation techniques.

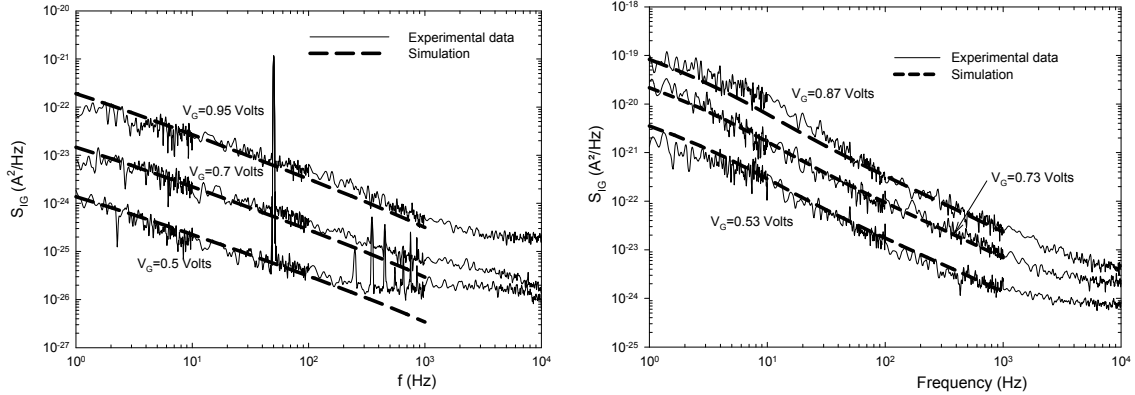


FIGURE 3 : (a) Transistor ($W/L=10 \mu\text{m}/0.34 \mu\text{m}$), with an RTN oxide. The best fit is obtained with a constant trap density profile. (b) ($W/L=10 \mu\text{m}/10 \mu\text{m}$), with an DPN oxide. The best fit is obtained with a Gaussian profile.

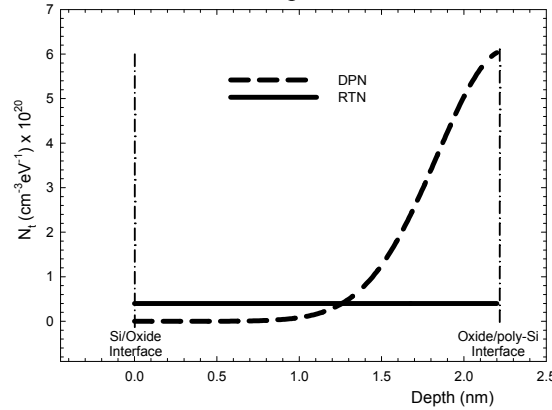


FIGURE 4 : Slow oxide trap density profiles extracted from DPN and RTN devices using gate current low frequency noise as a function of the physical oxide thickness.

As reported on Fig. 4, the best fitting profiles are a constant profile for the RTN devices and Gaussian profile for DPN ones. These results confirm the strong correlation between low frequency noise and Nitrogen related traps [4]. For thermal nitrated gate oxides, nitrogen profiles show that the nitrogen concentration is greater at the SiO_2/Si interface, and constant when approaching the poly/ SiO_2 interface. The DPN process induces a peak in the nitrogen concentration at the PolySi/ SiO_2 interface to preserve the Si/SiO_2 interface. Extracted profiles are in agreement with the typical distribution of nitrogen atoms.

HOT ELECTRON INDUCED DEGRADATIONS

Electrical Stress and DC characterization

Throughout this work, we used NMOS transistors obtained from a 65 nm CMOS technology. The tested devices had $W=5\ \mu\text{m}$, $L=0.3\ \mu\text{m}$ and $T_{\text{ox}}=5\ \text{nm}$.

The effects of a hot carrier electrical stress on the transconductance and the threshold voltage are well described in literature. [5]. The threshold voltage variation is caused by the creation of interface state and/or fixed charges in the gate oxide. The devices are stressed by Channel Hot Carrier injection with $V_{\text{GS}}=1.75\ \text{V}$ and $V_{\text{DS}}=4\ \text{V}$. In these condition (maximum of substrate current), an electron can achieve a sufficient energy for create an electron/hole pair by impact ionization. Thus, a “lucky” electron is injected into the gate oxide and create oxide or interface defects.

The interface state creation is confirmed by the subthreshold slope variation between the fresh and the stressed devices during $t=240\text{s}$. The effective density of interface states extracted from the subthreshold slope is proportionnal to the threshold voltage shift. Then we assume that no significant fixed charges are creating in the oxide during the hot carrier stress.

Low frequency noise results and discussion

Fig. 5 presents the low frequency noise level at 1 Hz for fresh devices ($t=0$) and devices stressed during a short time (10s and 30s). For fresh devices, we assume the trap density is uniform and we extract $N_t=10^{17}\ \text{cm}^{-3}\ \text{eV}^{-1}$. We don't observe any change in the subthreshold LFN level, whereas we observe an increase (about 3 times) of the noise level in strong inversion. This noise behavior can't be explain with classical analytical models, and may point out a non uniformity of the oxide trap profile. Fig. 6 presents the LFN level at 1Hz for fresh device ($t=0$) and devices stressed during longer times (90s and 240s). In that case, we observe an increase of the noise level in both subthreshold and strong inversion regimes (about 5 times) for the 90 s and 240 s stress times. This noise behavior can be interpreted as an increase of the average slow oxide traps in the oxide.

In order to characterize the non homogeneous oxide trap profiles induced by hot carrier stress, we have developed a two dimensional MOS model. The low frequency noise analysis is carried out using a local oxide charge fluctuation as noise sources and Green's functions approach to compute the power spectral density of the drain current fluctuations. With this model, we can take into account slow oxide traps in the oxide overlap region (oxide over the LDD), which is degraded by hot electron stress. The Fig. 7 presents the two oxide traps profiles used to explain the noise level behavior presented in Fig. 5 and Fig 6. These Gaussian profiles correspond to a short stress time and a long stress time. We have reported on Fig. 8 the stressed device noise level normalized to fresh device noise level from subthreshold to strong inversion regime and for the two trap profiles. In the case of the short stress time profile, we observe an increase of the noise only for strong inversion biases. We attribute this trend to the influence of the traps of the LDD region. A quasi constant increase of the noise level

is observed when computing noise with long stress time profile, which indicates that traps created in the channel by the hot carrier stress are the origin of the 1/f noise level increase. We conclude that degradation of defects related to 1/f noise level at 1 Hz (at a depth of around 2 nm in the oxide) follows the classical scheme of interface state degradation under Hot Carrier regime [5].

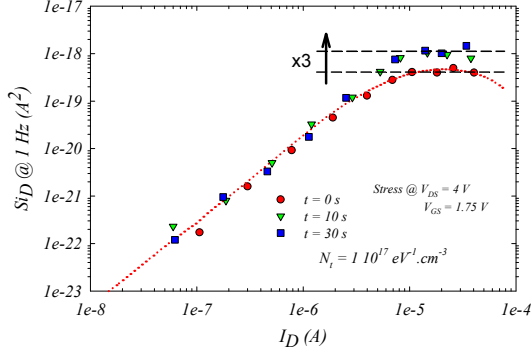


FIGURE 5 : 1/f noise level @ 1Hz vs. I_D before and after stress short stress time.

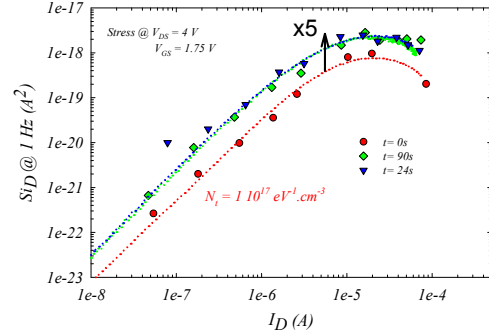


FIGURE 6 : 1/f noise level @ 1Hz vs. I_D before and after long stress time.

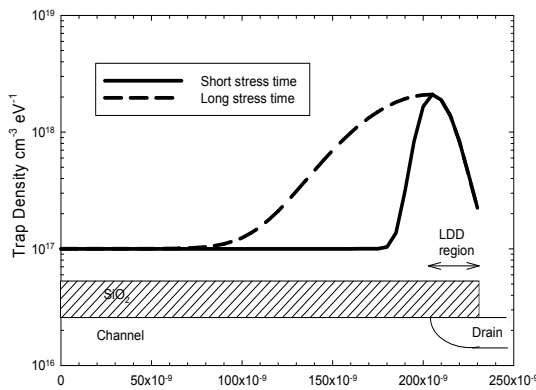


FIGURE 7: Slow oxide trap density profiles used for simulation of LFN of the drain current.

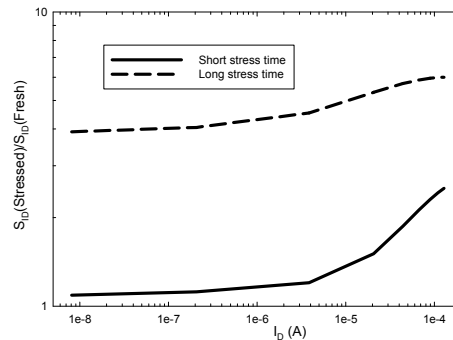


FIGURE 8: Simulation of the stressed device noise level (at 1Hz) normalized to fresh device noise level for from subthreshold to strong inversion regime.

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