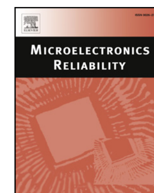
Microelectronics Reliability 84 (2018) 181–186

Contents lists available at ScienceDirect

Microelectronics Reliability

journal homepage: www.elsevier.com/locate/microrel



Physics-based modeling of TID induced global static leakage in different CMOS circuits☆

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ARTICLE INFO

Keywords:
CMOS
Radiation effects in devices
Total dose effects
Dose rate effects
Annealing
Modeling
Simulation
FPGA

ABSTRACT

Compact modeling of inter-device radiation-induced leakage underneath the gateless thick STI oxide is presented and validated taking into account CMOS technology and hardness parameters, dose-rate and annealing effects, and dependence on electric modes under irradiation. It was shown that proposed approach can be applied for description of dose dependent static leakage currents in complex FPGA circuits.

1. Introduction

The problem of radiation-induced leakage in CMOS circuits is a challenge which questions the main merit of the CMOS technology – its low consumption in the off-state regime [1]. It is well-known that the total ionizing dose (TID) induced supply current of the CMOS circuits is composed of the two components. First, it is the intra-device edge drain-to-source leakage currents through the narrow conductive paths near the transistor sidewall isolation which is proportional to the number of fingers [2]. Second, it is the inter-device leakage through parasitic conductive paths under the thick Shallow Trench Isolation (STI) oxides between, for instance (see Fig. 1), the n^+ source/drain region of an n-channel device and the n-well region of an adjacent p-channel device [3,4].

There is a large body of experimental evidence that radiation-induced supply current is not proportional to the finger number, which implies the importance of inter-device leakage, especially for sub-100 nm technologies [5,6,7]. This means that the IC supply leakage is not an additive sum of leakages in the separate local transistors, and it is more a global response of the whole circuit. One of the distinctive features of the effective parasitic transistor structure of inter-device leakage is a lack or remoteness of the conductive gate above thick STI oxide.

Despite the low values of electric fields E_{ox} in such oxides (typically $\leq 10^5$ V/cm), they are capable to accumulate a significant number of positively charged defects near the interface between the isolation oxide and the p-Si substrate, causing occurrence of the parasitic electron channels [8,9].

The objective of this study is to develop a physics-based analytical model for compact simulation of the dose dependencies of total IC supply current as functions of the total dose at different dose rates, assuming the dominance of inter-device component.

The rest of this paper is organized as follows. The Sec. 2 focuses on a concise description of the physics-based model and its features. The model validation and radiation-oriented applications are presented in Sec. 3. Sec. 4 is devoted to simulation of the TID induced circuit leakage in FPGAs.

2. Parasitic leakage current modeling

2.1. Electrostatics of the gateless transistor structure

The positive charge accumulated in the oxide leads to the surface potential changing underneath the thick oxide. The surface potential shift depends on the thickness of the oxide, concentration of charged traps and doping of the p-*epi* substrate. The electric neutrality condition without the gate is described by the equation $N_{ox} = N_S$. Here, N_S is the total (negative) charge density in the silicon substrate, which can be represented using the charge-sheet approximation as a sum of the channel n_S and the depletion layer densities [10]

☆ This work was supported by the Competitiveness Program of the NRNU MEPHI.
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https://doi.org/10.1016/j.microrel.2018.03.014
Received 12 December 2017; Received in revised form 6 February 2018; Accepted 15 March 2018
Available online 04 April 2018
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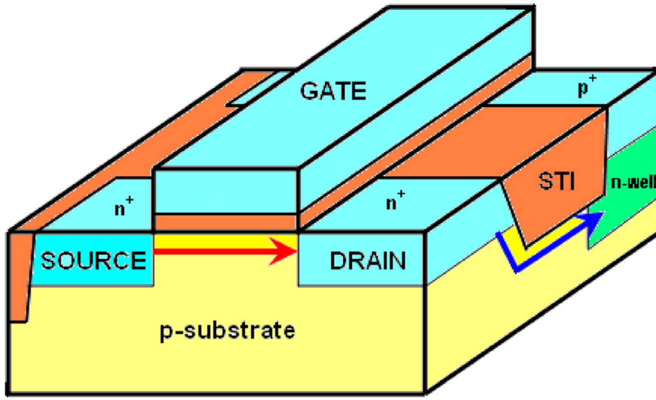

Fig. 1. Cross-sectional diagram indicating: (1) drain-to-source leakage and (2) leakage between the n^+ source/drain region of an n-channel device and the n-well region of an adjacent p-channel device.

$$N_S = N_A x_d(\varphi_S) + n_S, \tag{1}$$

where $x_d(\varphi_S)$ is the depletion layer width, N_A is the Si substrate acceptor concentration. On other hand, we have from the Poisson equation solution [11]

$$N_S = N_A L_D \left(\exp\left(\frac{\varphi_S - 2\varphi_F}{\varphi_T}\right) + \frac{\varphi_S}{\varphi_T}\right)^{1/2}, \tag{2}$$

where $\varphi_F = \varphi_T \ln N_A/n_i$ is the Fermi level position marker, where $\varphi_T = k_B T/q$ is the thermal potential, $n_i \cong (N_C N_V)^{1/2} e^{-E_G}/2k_B T$ is the silicon temperature-dependent intrinsic concentration ($\sim 10^{10}\,\text{cm}^{-3}$ at 300 K), $N_C(N_V)$ is the effective conduction (valence) band density, E_G is the Si bandgap.

The Debye length is defined here as follows

$$L_D = \left(\frac{2\varepsilon_S \varepsilon_0 \varphi_T}{q N_A}\right)^{1/2}, \tag{3}$$

where $\varepsilon_S \varepsilon_0$ is the Si permittivity. Eq. (2) is valid on a condition $\varphi_S > \varphi_F$ when the electron inversion layer underneath the thick STI has already formed.

2.2. Surface potential as functions of oxide trapped charge

Then the electric neutrality condition can be written as follows

$$\exp\left(\frac{\varphi_S - 2\varphi_F}{\varphi_T}\right) + \frac{\varphi_S}{\varphi_T} \cong a^2, \tag{4}$$

where $a \equiv N_{ox}/N_A L_D$. When one can neglect the exponential term in (4), i.e., at $2\varphi_F > \varphi_S > \varphi_F$ (depletion mode), we have

$$\varphi_S \cong \frac{q N_{ox}^2}{2\varepsilon_S \varepsilon_0 N_A}. \tag{5}$$

This as a usual form of the expression for surface potential has a square dependence on concentration of the charge in the oxide [12]. The exact solution of this equation can be written generally in a following form

$$\begin{aligned}\varphi_S &= \varphi_T a^2 - \varphi_T W\left[\exp\left(a^2 - \frac{2\varphi_F}{\varphi_T}\right)\right] \\ &= \frac{q N_{ox}^2}{2\varepsilon_S \varepsilon_0 N_A} - \varphi_T W\left[\frac{n_i^2}{N_A^2}\exp\left(\frac{q N_{ox}^2}{2\varepsilon_S \varepsilon_0 N_A \varphi_T}\right)\right],\end{aligned} \tag{6}$$

where $W(s)$ is the Lambert function, defined as a solution of the equation $W(se^s) = s$, and also known as the ProductLog function in *Mathematica* [13].

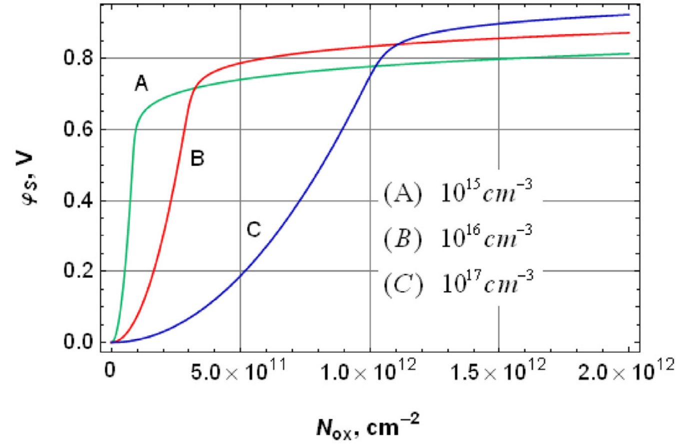

Fig. 2. Surface potential simulated as a function of positive oxide-trapped defects density at different doping levels of the p-type substrate, the oxide thickness t_{ox} = 500 nm.

Fig. 2 shows the surface potential underneath the thick STI oxide as a function of external oxide charge, calculated with (6) at different doping levels of the p-type Si substrate.

Note that increase of substrate doping hinders the band bending at moderate N_{ox} (i.e., at $N_{ox} < N_A x_D(2\varphi_F)$), since we have $\varphi_S \propto 1/N_A$ in (5), and, at the same time, it provides the larger maximum values of φ_S because of an increase in φ_F.

2.3. Electron density as a function of the oxide trapped charge

Then, the parasitic electron density as a function of N_{ox}, N_A, and temperature can be calculated using the charge-sheet approximation

$$\begin{aligned}n_S &= N_S - N_A x_d(\varphi_S) = N_{ox} - N_A L_D(\varphi_S/\varphi_T)^{1/2} \\ &= N_{ox}\left\{1 - \left[1 - 2\frac{\varepsilon_S \varepsilon_0 N_A \varphi_T}{q N_{ox}^2} W\left(\frac{n_i^2}{N_A^2}\exp\left[\frac{q N_{ox}^2}{2\varepsilon_S \varepsilon_0 N_A \varphi_T}\right]\right)\right]^{1/2}\right\}.\end{aligned} \tag{7}$$

This compact analytical formula with the clear physical parameters is the main result of this work.

General relations (6) and (7) have quite incomprehensible forms. To make them more physically transparent, it is instructive to consider some special cases. For the case $N_{ox} < N_A x_D(2\varphi_F)$, which equivalent to the depletion and weak inversion mode condition $\varphi_S < 2\varphi_F$, we have (5) and

$$n_S \cong \frac{n_i^2}{N_A}\frac{\varepsilon_S \varepsilon_0 \varphi_T}{q N_{ox}} \exp\left(\frac{q N_{ox}^2}{2\varepsilon_S \varepsilon_0 N_A \varphi_T}\right). \tag{8}$$

For the strong inversion case $\varphi_S \geq 2\varphi_F$ ($N_{ox} > N_A x_D(2\varphi_F)$) we have an asymptotic relation

$$n_S \cong N_{ox} - N_A x_d(2\varphi_F) \tag{9}$$

Fig. 3 shows the dependency of the parasitic channel electron densities as a function of the oxide-trapped charge density calculated at different substrate doping levels.

Notice that the calculated dependencies of n_S on N_{ox} have a threshold form which is caused by the deep physical reasons. Until the surface potential φ_S reaches the value φ_F, the electron conductive channel beneath the oxide is absent in principle. So, the substrate doping effectively suppresses the formation of parasitic electron channels under the oxides. A formal inclusion of the interface traps in this model does not significantly change the qualitative and even quantitative results but introduces additional uncertainties associated with the inability to determine their parameters.

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