Threshold Voltage Time-Variations in MOSFETs under Total Ionizing Dose Effects

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1.Abstract

Ionizing radiation modifies the characteristic parameters of an electronic device, and the threshold voltage is usually one of the most affected parameters. Therefore, assessment of the damage caused by ionizing radiation may be performed by checking the variation of the threshold voltage of the device. In order to do that, it is necessary to have well defined data analysis criteria. This paper describes the analysis of the filters Savitzky-Golay smoothing type (SG) and the Exponential Smoothing (ES) type, applied to determine the threshold voltage in a P and N type MOSFETs. The devices under test (DUTs) were analyzed before and after accumulating X-ray Total Ionizing Dose (TID). The results show the influence of the bias applied during characterization process and also the importance of a well-established methodology in the analysis of irradiated devices, especially for determining the threshold voltage shifts.

2. Introduction

2.1. Radiation Effects

CMOS is the technology most employed in MOSFET and integrated circuits (IC) used in space or in other environments where radiation is a major concern. Therefore, it is critical to characterize CMOS devices still at the ground to assess the damage from radiation exposure and develop a radiation hardened technology [1]. The effects may be observed by three different mechanisms: Total Ionizing Dose (TID), Single Event Effects (SEE) and Displacement Damage (DD). These effects can be either transient, such those due to SEE, or permanent, like TID. The generation of accumulated electrical charges in the gate oxide causes a shift of the threshold voltage and it is the main permanent damage due to TID effects [1]. Therefore, to observe the changes of the characteristic parameters of a device caused by accumulated ionizing radiation, the process of data analysis is extremely important.

When photons of 10 keV X-ray interact with the device oxides, they create electron-hole pairs in the material, mainly by photoelectric effect. In a typical oxide, electrons can escape swiftly to the positive electrode while holes move slowly towards the negative electrode by a hopping mechanism. The slow motion of the holes increases the probability that they are trapped by defects in the bulk of the oxide or near the oxide-semiconductor interface. This positive charge concentration may change the basic operating characteristics of the device [1]. Holes escape from the oxide by tunneling or in a thermally assisted way [2]. In thermal annealing, even when the room temperature, the thermal energy afforded to the holes stimulates their release from the traps, which can result in a stabilization of the electrical condition by accommodation the trapped charges [1,2].

Given the above, after reaching a equilibrium state of damage, it is possible to assess the effects of radiation on the devices due to the trapped charges in the oxide and at the oxide/Si interface.

2.2. Digital Filters

Practical systems used in characterizing a particular device or electronic system are subject to noise and random perturbations that can hamper the procedures of analysis and the parameters determination. To circumvent these problems, one may resort to digital filters that, ideally, would retain only the signal of interest, removing all the noise and only the noise [3]. It should be noted, however, that real filters applied on finite sets of data have limitations that could mask part of the signal that could bring important information about the Device Under Test (DUT).

Smoothing is important and necessary on various fields. In the Savitzky-Golay smoothing procedure, each successive subset of 2m+1 points is fitted by a polynomial of degree p (p≤2m) using a least squares method. The running least squares polynomial fitting can be simply and automatically performed by convolving the entire input data with a digital filter of length 2m+1. Convolution coefficients may be obtained for all data points, all polynomial degrees and all differentiation orders [3-5].

A low-pass filter eliminates high frequency oscillations due to noise and can be represented by the differential equation of first order, (1) and (2):

$$T_{\mathrm{f}}\frac{\mathrm{d}y(t)}{\mathrm{d}t}+y(t)=u(t) \tag{1}$$

where $u(t)$ is the measured value (filter input), $y(t)$ is the filtered value (the filter output) and T_{f} is the time constant of the filter. The value of T_{f} is selected to cut the high frequency noise without affecting the signal.
The equations that describe the exponential filter are given by:

$$y(k)=\beta_{\mathrm{F}}y(k-1)+\alpha_{\mathrm{F}}u(k) \tag{2}$$

$$\beta_F = 1 - \alpha_F = \frac{T_f}{T_f + T_s}; \quad \alpha_F = \frac{T_s}{T_f + T_s}$$

The equations indicate that the filtered measure is the weighted sum of the current measure *u*(*k*) and the filtered value at the instant of sampling before *y*(*k-1*). Limiting cases to α_F are:

$\alpha_F = 1$, there is no filtering;

$\alpha_F = 0$, the measure is ignored.

Savitzky-Golay (SG) filter is very similar to the exponential filter. The SG – filter is essentially a method of weighted average in the form:

$$x_i = \frac{1}{2m+1} \sum_{j=-m}^{m} w_j \, x_{i+j} \tag{3}$$

When applying this filter, the goal is to find the correct weights w_j in equation (3) by means of polynomial regression. Savitsky-Golay filter uses the equation (4) to fit the first data and then finds all weights by least squares technique for:

$$x_j^i = a_0 + a_1 j + a_2 j^2 + \cdots + a_k j^k \quad (j = -m, -m+1, \ldots, m-1, m; i = 1, \ldots, n) \tag{4}$$

where x_j^i and j are known. The least-squares technique can be applied to find a_R(R=0,1,2).

3. Methodology

Using a Shimadzu XRD-7000 X-Ray diffractometer, two commercial integrated circuits (IC) CD4007 were irradiated: 2.95 krad / s dose rate for the IC-17 and 96 rad / s dose rate for the IC-18. Each IC is composed by three nMOS and three pMOS. Total dose accumulated on IC-17 was 3 Mrad and 250 krad was accumulated on IC-18. The X-ray mean energy was 10 keV, corresponding to 20 kV applied on the copper X-ray tube. The ICs were kept at 10 cm from the X-ray source, which guaranteed the beam's homogeneity [2,6,7].

When photons interact with the device oxides, they create electron-hole pairs in the material, mainly by photoelectric effect. In a typical oxide, electrons can escape swiftly to the positive electrode while holes move slowly towards the negative electrode by a hopping mechanism. The slow motion of the holes increases the probability that they are trapped by defects in the bulk of the oxide or near the oxide-semiconductor interface. This positive charge concentration may change the basic operating characteristics of the device. Holes can, however, escape from the oxide by tunneling or in a thermally assisted way [7].

In order to analyze the influence of the radiation, characteristic I_D x V_{GS} curves of drain current I_D versus gate voltage V_{GS} with low source-drain voltage V_{DS} were extracted using a Precision Semiconductor Parameter Analyzer PXI National [8]. From the I_D-V_{GS} curves, threshold voltage (V_{TH}) was extracted using the second derivative method. The value of V_{TH} is taken as the maximum point of the curve obtained with the derivative of the transconductance (g_m), which is shown in equation (5).

$$g_m = \frac{\partial I_{DS}}{\partial V_{GS}} = \frac{W\, C_{OX}\, V_{DS}}{L} \, \mu_N \tag{5}$$

where *W* is the width of the channel of the device , C_{OX} is the capacitance of the gate oxide , V_{DS} is the voltage applied to the transistor drain, *L* is the length of the channel and μ_N is the mobility of carriers in [9, 10].

This method originates on the premise that to lower voltages the V_{TH}, I_{DS} equal to zero and to V_{GS} greater than or equal to V_{TH}, I_{DS} has linear relationship with V_{GS}. Thus, the first derivative of I_{DS} x V_{GS} generates a step function in V_{GS} equals V_{TH} and the second derivative results in an impulse in V_{GS} equals V_{TH}. In practice this does not occur, but a relatively narrow pulse can be identified and its maximum point and provides the V_{TH} value [9,10].

Characteristic curves were obtained after at least one week after the ICs have been irradiated, in order to establish a damage steady-state by thermal annealing at room temperature.

Data acquisition concerning the current I_{DS} depending on the gate voltage V_{GS}, was performed for a period of time necessary to stabilize the value of V_{TH}. The value of V_{TH} for a particular DUT changed during the characterization, due to the effect of the electric field polarizing the device on the charges trapped in the shallow border traps.

4. Experimental Results

Figure 1 shows the second derivative curves of current between source and drain, I_D, as a function of the gate voltage, V_{GS}, for a pristine, non-irradiated, CD4007 device. The curves were analyzed with the two filters; SG and ES. In both cases the device showed a threshold voltage V_{TH} of 1.13 (2) V. The responses were obtained through a series of consecutive measurements, giving reproducible results. The values of V_{TH} extracted from these curves showed no dependence on the filter used in the analysis.

The V_{TH} values extracted from the curves shown to be independent of the filter used in the DUT.

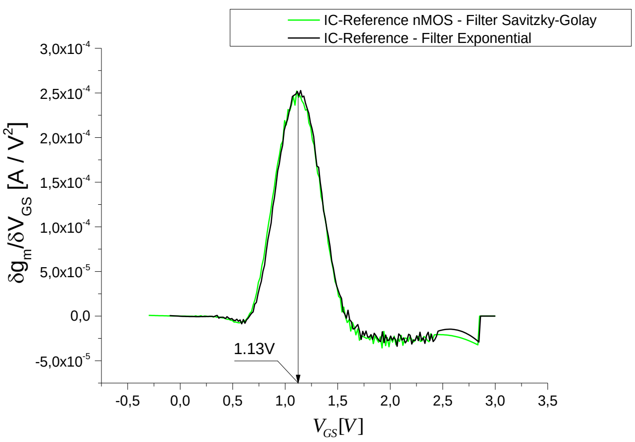

Fig.1. *$\partial g_m / \partial V_{GS}$ curve for IC-Reference nMOS device.*

Since the two filters produced the same results, we opted for the SG filter in order to follow the same method of analysis for the device characterization process.

In Figure 2 the V_{TH} determination is shown for IC-17, irradiated by 10 keV X-ray, accumulating up to 3 Mrad. It was observed that the IC-17 presented V_{TH} = 1.65 V immediately after irradiation, and V_{TH} =1.76 V after 7 days of annealing at room temperature.

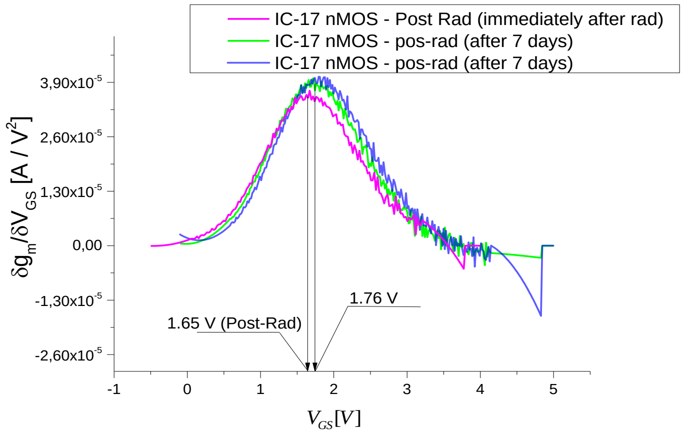

Fig.2. *$\partial g_m/\partial V_{GS}$ as a function of the V_{GS} for DUT IC-1, after 3 Mrad..*

Figure 3 shows V_{TH} determination for an nMOS transistor in IC-18, with 250 krad accumulated. It is possible to observe that V_{TH} = 1.67 V immediately after irradiation, and V_{TH} =1.61 V after 7 days of annealing at room temperature.

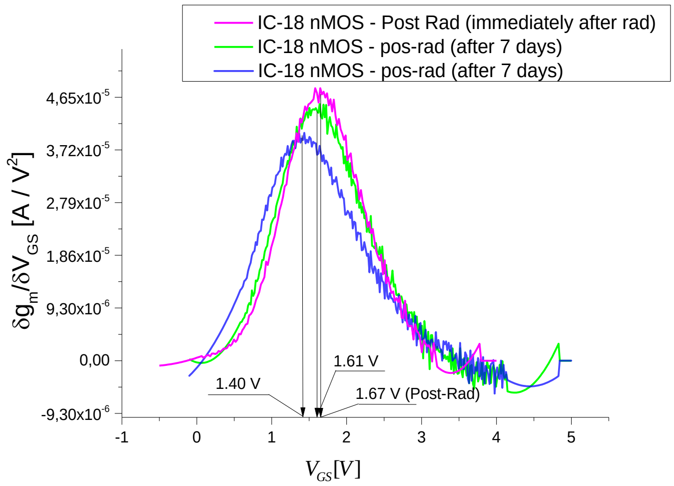

Fig.3. *$\partial g_m/\partial V_{GS}$ curve IC-18 compared for nMOS device.*

It is important to remark that several consecutive measurements were performed in order to characterize the devices after the annealing period. The green and the blue curves shown in Figures 2 and 3 represent some of these measurements, signaling a time-variation of the threshold voltage.

The time-variations observed along consecutive measurements occurred because the charges that were trapped by TID, especially those trapped in the shallow border traps near the oxide/silicon interface may be untrapped relatively easily by the action of the electric field that polarizes the device. The release of these charges during the process of measurement causes a variation in the characteristic curve, leading to a variation in the threshold voltage of the device. Eventually, after performing several consecutive measurements, the characteristic curve stabilizes, signaling that the border traps have reached a new equilibrium state.

Table 1 shows the different threshold voltage V_{TH} obtained before irradiation, immediately after irradiation and 7 days after irradiation for IC-17 (3 Mrad) and for IC-18 (250 krad).

Table 1*- Threshold Voltage for an accumulated dose and after 1 week.*

	Threshold Voltage (V)	
	IC-17 (N type)	IC-18 (N type)
Pre rad	1.16 (1)	1.15 (1)
Immeadiately after irradiation	1.65 (1)	1.67 (1)
After 7 days of annealing	1.76 (1)	1.61 (1)

Figures 4 and 5 show the characteristic curves that are obtained after the time-variations reported earlier stabilize. This analysis suggests that, after irradiation and annealing V_{TH} should be determined only after several consecutive measurements are made, in order to allow the border traps to achieve an equilibrium state.

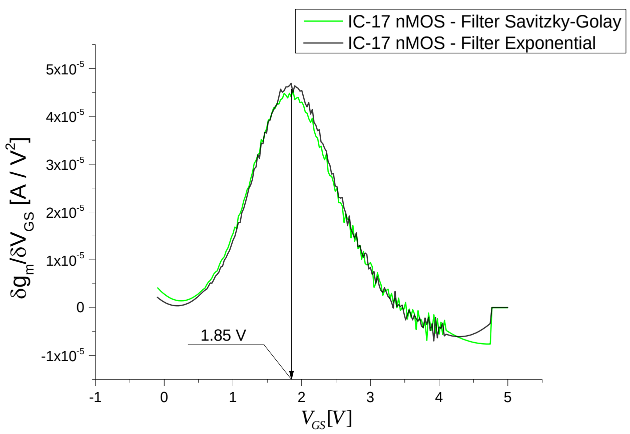

Fig.4. *$\partial g_m/\partial V_{GS}$ curve IC-17 compared for nMOS device.*

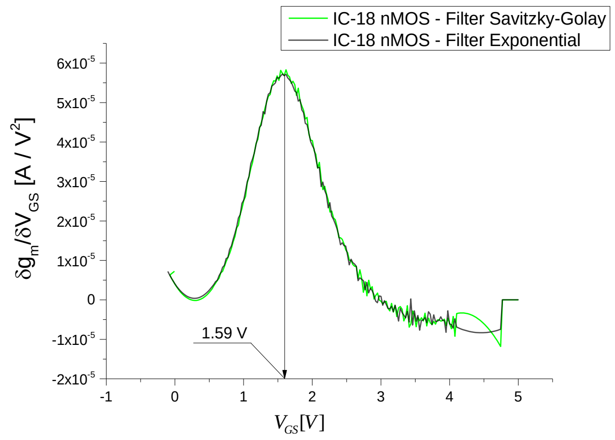

Fig.5. $\partial g_m/\partial V_{GS}$ *curve IC-18 compared for nMOS device.*

4. Discussion and Conclusions

Smoothing the data sets with an exponential filter or with a Savitsky-Golay filter led to essentially the same values of the threshold voltage after irradiation and thermal annealing in the case reported. However, we cannot discard the possibility that the change of a digital filter for another may produce spurious results, affecting thus the whole analysis.

The results obtained for the irradiated devices when compared to the reference IC, showed significant variations in the determination of V_{TH} as time went by. It was possible to verify that these time-variations were not due to the use of different digital filters. Instead, we believe that they are caused by the fact that even a small electric field may perturb the equilibrium state of shallow border traps after irradiation followed by an annealing period.

A fraction of the charges trapped in the border traps may escape from their traps with the application of an electric field in the device during the measurement process, in the transition to a new equilibrium. When the new equilibrium is achieved, after several characteristic curves measurements, the time-variations observed came to an end, and a reliable determination of the threshold voltage could be performed.

In conclusion, this study indicates that the underlying dynamics of trapping and untrapping in the shallow border traps may affect the electric characterization of devices submitted to total ionizing dose of radiation and annealing. Although further work is needed to completely address these issues, it is possible to recommend that the electric characterization of irradiated devices should contain a phase in which several consecutive measurements are performed until the variations of the parameters of interest becomes acceptably small.

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