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A simple model of the accumulation of trapped ionization charges for RADFET Dosimeters

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1. Introduction

The response parameter of a RADFET dosimeter to the total accumulated dose of ionizing radiation (TID), that can be used for dosimetry, is the gate threshold voltage (Vth) variation [1,2], as this voltage variation is easily measured by using a simple measuring circuit [3,4]. In modeling the response of a P-type MOS transistor to dose accumulation, we based on the free charges (electron-hole pairs) generated by ionizing radiation, whose part was trapped in gate isolation oxide. This type of modeling has already been successfully applied to describe the opacity of optical fibers exposed to ionizing radiation in a previous work coordinated by one of the authors of the present work [5].

The main cause of accumulated dose effects (TID) in MOS transistors is the accumulation of trapped charges in the gate oxide and in the insulation oxide between neighboring transistors, in their body and in their interface with silicon lattice. So, many parameters, such as leakage current, threshold voltage, etc., will vary with the accumulated dose following the variation of these trapped charges with the accumulated dose [6, 7, 8, 9, 10].

In this work, the modeling of the response variation to the accumulated radiation dose of a RADFET dosimeter is presented and its experimental verification in one irradiation test of the PMOS transistor IRF4905PBF with gamma radiation from a ^{60}Co irradiator up to the accumulated dose of 310 krad(Si) is presented, also.

2. Methodology

To describe the dynamics of charge trapping in the gate oxide of a MOS transistor, let us consider a very simplified model that relates the charge capture rate by unoccupied traps (dN/dt) with the number of unoccupied traps (N_0 - N) and the charge flow generated by the ionizing radiation, which moves under the effect of the existing electric field. Under these conditions, the charge trapping rate in the traps in gate oxide is given by:

$$\frac{dN}{dt} = \lambda(N_0 - N) \tag{1}$$

where N_0 is the number of traps available and N is the number of traps occupied in the gate oxide. In a simplified model based on the theory of collisions in nuclear physics, the probability of capture per trap per unit of time (λ) is done by the product of the capture center cross section (σ) and the fluence rate (ϕ) of the charges that migrate through the oxide by driving by electric field applied to the transistor gate:

$$\lambda = \sigma\phi \tag{2}$$

It must be pointed out that in this modelling long live traps are considered only, as their decay constant is much smaller than the trapping rate of charges created by radiation.

Considering that at the time $t' = 0$ the number of occupied traps is null and at any time $t' = t$ the number of occupied traps is $N(t)$, the solution of the differential equation (1) is:

$$N(t) = N_0(1 - e^{-\lambda t}) \tag{3}$$

The irradiation time t can be expressed as a function of the accumulated dose (D) up to this moment and the dose rate (D') at which the device is being irradiated:

$$t = \frac{D}{D'} \tag{4}$$

Then, the accumulated charge in the traps, $Q(t) = N(t).q$ (where q is the elementary charge), as a function of the dose (D) will be:

$$Q(D) = Q_0(1 - e^{-\mu D}) \tag{5}$$

where $\mu = \lambda/D'$ is a constant, when a constant dose rate D' is used in irradiation, and Q_0 is the accumulated charge of trap occupancy in the saturation (long irradiation times).

This equation holds for each type of trap, as the parameters λ and Q_0 depends on the type of the trap. For the gate oxide, considering only one type of trap for the oxide body (indicated by the index "*ox*") and only one type of trap for the oxide/silicon interface (indicated by the index "*it*"), the total accumulated charge will be expressed by:

$$Q(D) = Q_0^{ox}\left(1 - e^{-\mu^{ox} D}\right) + Q_0^{it}(1 - e^{-\mu^{it} D}) \tag{6}$$

The change in transistor threshold voltage (ΔVth) will be proportional to the change in the trapped charge $Q(D)$ divided by the oxide capacitance (C^{ox}) for both oxide body traps and the silicon oxide interface traps. Thus, the threshold voltage will vary with the accumulated dose according to:

$$\Delta Vth(D) = \frac{Q(D)}{C^{ox}} = \frac{Q_0^{ox}}{C^{ox}}\left(1 - e^{-\mu^{ox} D}\right) + \frac{Q_0^{it}}{C^{ox}}\left(1 - e^{-\mu^{it} D}\right) \tag{7}$$

Thus, in this modeling, the variation of the threshold voltage of a RADFET dosimeter at the accumulated dose D will be described by equation 7.

This equation shows that the response of a RADFET dosimeter is always sublinear and reaches a saturation value when $D \gg 1/\mu$. However, for low accumulated doses and small values of μ, we can use the first term of the series expansion of the exponential terms of equation 7: $exp(-\mu.D) \approx 1 - \mu.D$. In this way, the variation in Vth will be approximately linear:

$$\Delta Vth(D) = \left(\frac{Q_0^{ox}\mu^{ox}}{C^{ox}} + \frac{Q_0^{it}\mu^{it}}{C^{ox}} \right).D \tag{8}$$

This modeling was verified in an irradiation experiment with gamma radiation from a ^{60}Co source of the PMOS transistor IRF4905PBF, where the variation of the threshold voltage was measured as a function of the accumulated dose up to 310 krad(Si). The results are presented in the next section.

3. Results and Discussion

The PMOS transistor IRF4905PBF was irradiated in several steps of accumulated dose in the range of 0 to 310 krad(Si) accumulated dose with a constant dose rate of 0.973 krad(Si)/h in the gamma radiation field of the ^{60}Co source of the LRI/IEAv. There were, in total, 17 steps of irradiation, and between each step, the variation of the threshold voltage was measured with the Keithley semiconductor parameter analyzer model 4200. The experimental values and the fit of the model developed in this work to the experimental data are shown in figure 1. The adjusted parameters and respective experimental errors are shown in table 1.

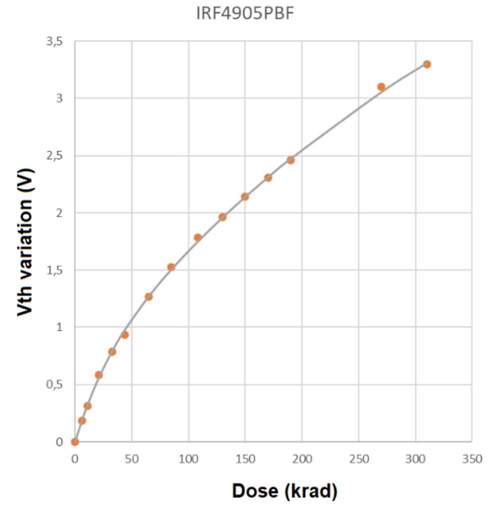

Figure 1: Vth variation of the P-type MOS transistor IRF4905PBF as a function of the accumulated dose (experimental points) and adjustment to our charge trapping model (line)

Table I: Fitting of the parameters of our charge trapping model to experimental data

Parameter	$\frac{Q_0^{ox}}{C^{ox}}$	μ^{ox}	$\frac{Q_0^{it}}{C^{it}}$	μ^{it}	Correlation coefficient R^2
Values	0,5998	0,0354	5,4402	0,002222	0,999546

4. Conclusions

As the IRF4905PBF is a commercial power MOSFET transistor, neither the thickness of the oxide nor the oxide traps concentration is available in the manufacturer datasheet, so that the model parameters could not be compared with the physical data of the transistor.

So, in general, for COTS transistors, the rate of trapping of charges in the oxide traps is a parameter that could only be determined experimentally. Also, there are few estimates in the literature of the cross sections of charge capture in traps in the oxide body and in the oxide-silicon interface.

The parameters related to the probability of capture per trap per unit of time are dependent on the dose rate to which the transistor was exposed during irradiation, according Equation 2, since the flux of charges moved by the electric field applied to the transistor gate is proportional to the dose rate. Experiments with different dose rates can verify the linearity of this parameter with the dose rate, demonstrating the physical reality of the model developed in this work.

This model predicts that the response of a RADFET dosimeter is always sublinear and reaches a saturation for high accumulated doses ($D >> 1/\mu$) and its behavior is somewhat linear for low accumulated doses ($D << 1/\mu$). So, the parameter $\lambda = \mu.D'$ that relates the charges capture rate by unoccupied traps must be considered in searching the RADFET suitable for the dose range to be measured and according to the intended application. Thereby, this parameter needs a more detailed treatment in a future expansion of the microscopic description of the fluence of free charges in the gate oxide of the model developed in the present work.

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