A Stochastic Model of Gamma-Ray Irradiation Effects on Threshold Voltage of MOS Transistors

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***Abstract* – In this paper a stochastic model of gamma-ray irradiation effects on density of charge in oxide of MOS transistors is explained. In this model the Monte Carlo method were used to develop an approach for estimating gamma-ray induced traps spatially distributed in oxide. The developed model enables the gamma-ray induced threshold voltage shift determination as a function on gamma-ray doses.**

***Keywords* – MOS transistors, threshold voltage, gamma-ray irradiation, Monte Carlo method.**

I. INTRODUCTION

The gamma radiation can degrade the electrical characteristics of MOS transistors and integrated circuits: threshold voltage, transconductance, leakage current and breakdown voltage [1] - [3]. However, the threshold voltage is considered to be the most radiation sensitive parameter. Also, the investigation of the radiation induced charge is very important for the gamma radiation dosimetry, which can be based on p-channel MOS (pMOS) dosimetric transistors [1]. The threshold voltage shift of gamma irradiated MOS transistors is caused by the change and incorporation of charges in oxide, i.e. introduction charges in SiO_2 (oxide charge) and by increasing the density of Si/SiO_2 traps (interface traps).

Experimentally determined dependences of the threshold voltage shift vs. absorbed dose are reported in many papers [1], [3] - [6]. But, regardless that, a model which is enable to describe the effects of irradiation on gate oxide and threshold voltage don't exist. The existing models very roughly take into account the physical mechanisms of gamma ray interaction with silicon dioxide, regardless that gamma ray absorption and ion formation in the oxide are a stochastic processes. Also, in the threshold voltage estimation, these models neglect the spatial distribution of positive charge in the oxide.

In this paper, we are evaluated an approach for estimating gamma-ray induced charge spatially distributed in oxide, based on Monte Carlo method. On the basis of this model and model of interface states, we are calculated the threshold voltage shift vs. absorbed dose dependencies, which are compared with our previously reported [4] - [6] experimental results.

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II. THRESHOLD VOLTAGE OF IRRADIATED DEVICES

The change in threshold voltage of MOS transistor due to the irradiation was determined simply as:

$$\Delta V_T = V_T - V_{T0} \tag{1}$$

where V_{T0} denotes threshold voltage before devices where irradiated, and V_T is the threshold voltage after irradiation. The irradiation directly affects densities of oxide charge $q \cdot N_{ot}$ and interface states N_{it}, the change of threshold voltage caused by the effect of device irradiation can be expressed as:

$$\Delta V_T = \Delta V_{ot} + \Delta V_{it} = \pm \frac{q}{C_{ox}} \cdot \Delta N_{ot} + \frac{q}{C_{ox}} \cdot \Delta N_{it} \tag{2}$$

where C_{ox} is the gate oxide capacitance per unit area. The plus sign applies to pMOS transistors, and minus to nMOS devices. Consequently, in the case of pMOS transistors, the threshold voltage monotonously increased with absorbed dose. But, in the case of nMOS transistors, the threshold voltage decreased with absorbed dose up to certain doses (of about $200\,Gy$ [4]), and then increased as result of rapid increase of negatively charged interface states.

In eq. (2) $q \cdot N_{ot}$ denote effective density of oxide charge on the Si/SiO_2 interface:

$$q \cdot \Delta N_{ot} = \frac{q}{d_{ox}} \cdot \int_0^{d_{ox}} n_{ox}(x) \cdot x \cdot dx \tag{3}$$

where $n_{ox}(x)$ is the concentration of long-term traps in oxide which are occupied by positive charge, i.e. $q \cdot n_{ox}(x)$ denote the concentration of spatially distributed charge towards the Si/SiO_2 interface, builds up in oxide.

Used one modification of a relation from [1] and [7], the density of interface traps charged due to the irradiation of dose D can be expressed as:

$$\Delta N_{it} = \left(\Delta N_{it}\right)_{sat} \cdot \left\{1 - \exp\left[-\alpha_1 \cdot D + \alpha_2 \cdot \Delta N_{it}\right]\right\} \tag{4}$$

where $\left(\Delta N_{it}\right)_{zas} = 3 \cdot 10^{12}\ cm^{-2}$ is the maximal possible density of traps on the interface SiO_2/Si [9], [3]. Coefficients α_1 and α_2 are function on oxide characteristics. We are use the values $\alpha_1 = 1.43 \cdot 10^{-6}\ Gy^{-1}$ and $\alpha_2 = 2 \cdot 10^{-13}\ cm^{-2}$.

III. MODEL OF OXIDE CHARGE CREATION

We assumed that only two mechanisms of gamma ray interaction with oxide are significant, i.e. absorption (dose decrease exponentially with distance) and ionization (with neglecting energy losses of gamma ray). Also, we are used simplified model of ion formation and electron transport across oxide [7], [8]. On this way, as the MOS devices are exposed to the gamma irradiation, the gate oxide becomes ionized by the dose it absorbs and electron-hole pairs are generated. The free electrons drift under the influence of the electric field that appears due to the work function difference between gate electrode and silicon. These electrons would be fairly benign if they drift out of the oxide and disappear, but a small fraction of them were to recombine by hole in the oxide. The fraction of holes remaining from recombination with electrons is subject to a transport mechanism through localized states in the oxide. The holes propagate towards the Si/SiO_2 interface and capture in long-term traps. After sufficient radiation dose, a large positive charge, spatially distributed towards the Si/SiO_2 interface, builds up in oxide. The density of oxide charge can be expressed as:

$$q \cdot n_{ox}(x) = q \cdot \alpha_{ox} \cdot f_y(E_{ef}) \cdot f_{tr}(E_{ef}) \cdot D \tag{5}$$

where α_{ox} is generation coefficient, f_y is the fraction of holes that are transported through localized states, f_{tr} is the fraction of holes that are captured in oxide, and E_{ef} is the effective electrical field in the oxide. The effective electrical field in the oxide is:

$$E_{ef} = E_\chi - E_{ox} \tag{6}$$

where E_χ is the field caused by work function difference and:

$$E_{ox} = (q/\varepsilon_{ox}) \cdot \Delta N_{ot} \tag{7}$$

is caused by spatially distributed holes.

Because the processes of gamma ray absorption and electron-hole pair's creation and recombination are stochastic processes, we are assumed that they are randomly occurred with certain probability. Therefore, we are assumed that the oxide is partitioned into number of layers and dose is dispensed on number of portions ΔD absorbed in oxide during time Δt, similar as in [8]. We are suppose that number of produced electron-hole pairs in each layer during the time Δt is Gaussian random variable. During the time Δt, holes migrate toward the Si/SiO_2 interface, and on the end of Δt they are captured in oxide. We are suppose that the electric field, hole mobility and time interval Δt are so small such that hole can move only in the neighbor layer for the time Δt. Also, we are using that number of migrated holes linearly dependent of the resultant electric field in the oxide. Due to this effect, trapped holes will be concentrated in few last layers, close to the Si/SiO_2 interface. Also, created electrons are moving in opposite direction of electric field and can recombine with previously generated and captured holes. We supposed that time required for finish of recombination process in each iteration is much smaller of time step Δt. So, all created electrons are being recombined or they leave material in time much smaller than Δt. Also, we are assumed that the probability of electrons recombination depends directly on the concentration of previously captured holes.

Suppose that total depth of material is d_{ox}. We will divide whole material in n layers, each of the depth d_{ox}/n. Denote with G intensity of radiation at $x = 0$ and with γ absorption coefficient. Then the intensity of radiation at depth x is:

$$g(x) = G\exp(-\gamma x) \tag{8}$$

Denote with α_k number of produced ions in k-th layer during the time Δt. For small ion concentrations, this number is independent of the concentration and for every time interval (of length Δt) is the same. We will suppose that α_k is Gaussian random variable, i.e. that holds:

$$\alpha_k : N(\overline{\alpha_k}, \sigma_\alpha) \tag{9}$$

where mean value:

$$\overline{\alpha_k} = \alpha \cdot g(x_k) \tag{10}$$

is directly proportional to the radiation intensity $g(x_k)$ in k-th layer. Denote with $\rho(x)$ charge density due to ionization.

In the small period of time, after creation, created ions act as holes and due to electrical field migrate in the direction of field. After this small period they become stationary and are not moving till the end of process. In our model we chose that period of time equal to Δt. So, new created ions are moving only in one iteration of our model. Due to this effect, produced ions will be concentrated in few last layers, close to the bound of material ($x = d_{ox}$). That concentration will produce electrical field in opposite direction. We will suppose that the field (and time interval Δt) is so small such that ions can move only in the neighbor layer ($k+1$-th) for the time Δt. We will use that number of migrated ions $\Delta\alpha_k$ linearly dependent of the resultant field, i.e. that holds:

$$\Delta\alpha_k = \alpha_k \cdot s_1 \cdot \left[E - s_2 \cdot (\rho_{k+1} - \rho_k)\right] \tag{11}$$

where we denoted $\rho_k = \rho(x_k)$ and s_1 and s_1 are constants. If the ratio:

$$\frac{\Delta\alpha_k}{\alpha_k} > 1 \tag{12}$$

we will set:

$$\Delta\alpha_k = \alpha_k \tag{13}$$

This means that the field is sufficiently large, so all created ions will migrate to the neighbor layer.

We also included the recombination mechanism in our model. For each created ion we have also one electron created. Electrons are moving in opposite direction of field and can recombine previously generated ions. We supposed that time required for finish of recombination process in each iteration is much smaller of time step Δt (so all created electrons are being recombined or they leave material in time much smaller than Δt). The probability that electron will be recombined, depends directly on the concentration of positive ions ρ. For the smaller values of ρ, we can approximate this dependence to linear. When ρ becomes large, this probability reaches the saturation. Denote with $\beta(\rho)$ this dependence. In our model we will use the following approximation:

$$\beta(\rho) = \begin{cases} \beta_0 \cdot \dfrac{\rho}{\rho_{crit}}, & \rho < \rho_{crit} \\ \beta_0, & \rho \geq \rho_{crit} \end{cases} \tag{14}$$

Where with ρ_{crit} we denoted the critical concentration of positive ions when saturation appears and β_0 is saturated probability.

In our model, electrons from the k-th layer can recombine ions from the layers $1,2,\ldots,k$ (because, the field direction does not change during the process). Denote with β_{ki} the number of electrons from k-th layer which enter the i-th layer and with $\Delta\beta_{ki}$ number of recombined electrons in the i-th layer. From previous consideration, we have that $\Delta\beta_{ki}$ is random variable with normal distribution:

$$\Delta\beta_{ki} : N(\overline{\Delta\beta_{ki}}, \sigma_\beta) \tag{15}$$

where mean value is:

$$\overline{\Delta\beta_{ki}} = \beta_{ki} \cdot \beta(\rho_i) \tag{16}$$

For the next entering number we have:

$$\beta_{k,i-1} = \beta_{ki} - \Delta\beta_{ki} \tag{17}$$

If we obtain $\beta_{k,i-1} < 0$, we set $\Delta\beta_{ki} = \beta_{ki}$ and recombination process from k-th layer is over.

IV. Results of oxide charge distribution

This model has been developed through computer simulations using the Monte Carlo method. A clear advantage of such Monte Carlo computer simulations is that it is perhaps to quickly calculate new oxide charge distribution after each dose portion absorbed in oxide. To create Monte Carlo code for our computer simulations, we are employed programming language MATHEMATICA.

In presented calculation, we are accepted that oxide is divide in $n = 30$ layers as oxide thickness is $d_{ox} = 110\ nm$. In the cases of other oxide thickness, we accept the same ratio d_{ox}/n. Also, we are accepted that the portions of doses ΔD absorbed in oxide during time Δt, are $\Delta D = 1\,Gy$. On this way, the total absorbed dose is $D = N \cdot \Delta D$, or total time of irradiation is $T = N \cdot \Delta t$.

All of calculation are repeated hundred times with new generated random variable α_k and $\Delta\beta_{ki}$. Presented results are average values of all corresponding calculations.

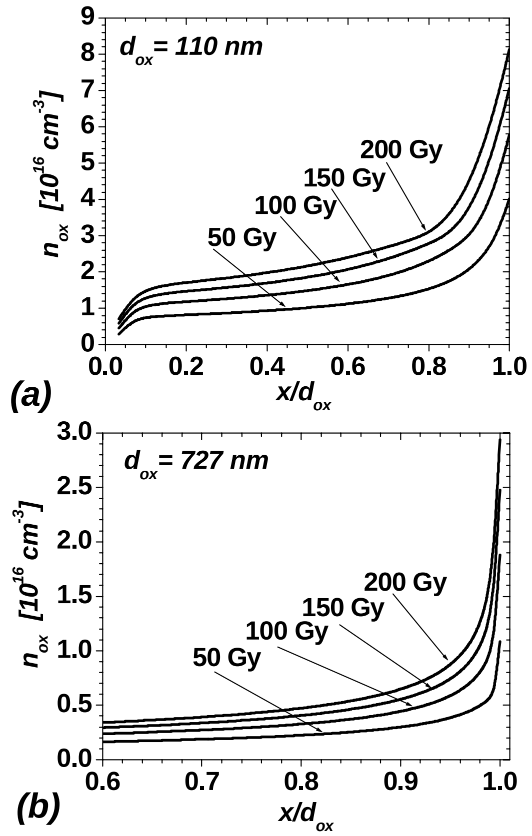

Fig 1. Spatial distribution of the oxide trapped holes induced by gamma ray for different doses of radiation and oxide thickness of 110 nm (a) and 727 nm (b).

On Fig. 1 it is shown spatial oxide charge distribution evaluated by predicted model. It was see that the oxide charges (i.e. trapped holes) are distributed near to the SiO_2/Si interface, but the spatial distribution of them is not negligible. For same doses, the density of trapped holes n_{ox} is lower as the oxide thickness is larger. The density of trapped holes is mainly uniform and has the values which are not negligible. Near the SiO_2/Si interface, the density of trapped hole rapidly increases. In all case, the slope of the holes distribution near the SiO_2/Si interface increases as both of irradiation doses and oxide thickness increases. Also, it was see that the most of trapped holes are distributed in narrow layer near to the SiO_2/Si interface. The thickness of this layer is about 20 nm, for all of irradiation doses and oxide thickness. The influence of irradiation dose on the trapped holes (i.e. oxide charge) density is approximately linear in the range of considered doses (up to 2000 Gy), in the area of uniformly distributed charge, as well as, in the area of rapid density increases.

V. Results of threshold voltage shifts

Fig 2. shows the calculated threshold voltage change ΔV_{th} as a function of radiation dose (lines) and experimentally determined values (dots) for MOS transistors as reported in [4], [5]. In the case of nMOS transistors (fig. 2.a), ΔV_{th} vs. dose dependence show a turnaround (or 'rebound'). This can be explained by fact that at low absorbed doses (up to

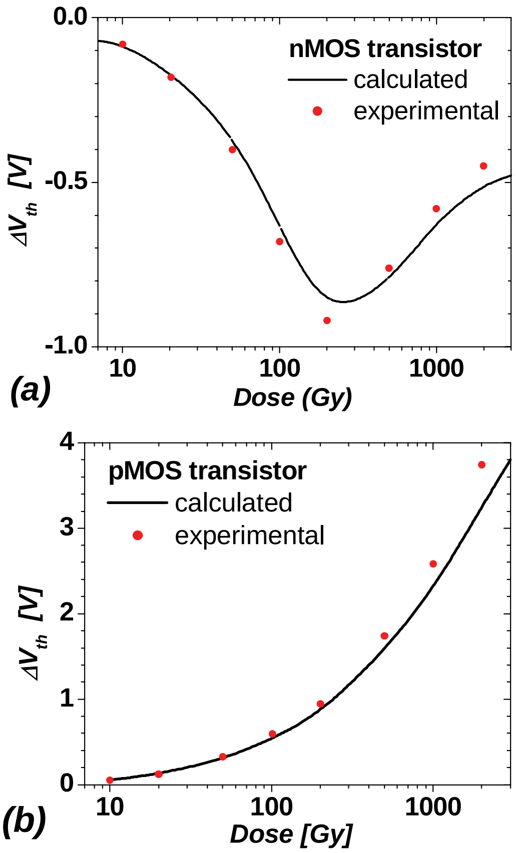

Fig 2. Calculated and experimentally determined threshold voltage shift vs. dose for nMOS (a) and pMOS (b) Al-gate transistor with 110 nm oxide thickness. Experimental results are previously reported in [4], [5].

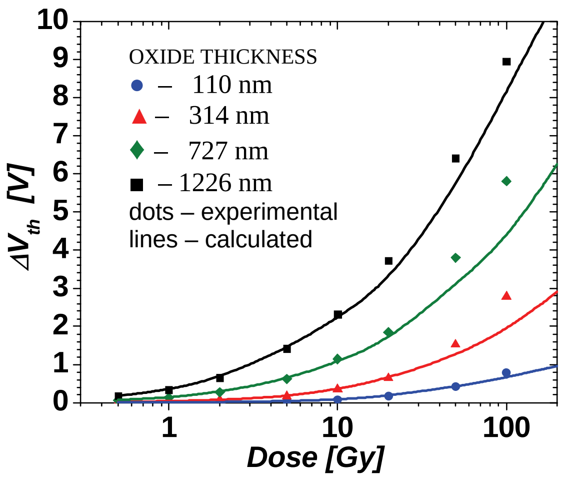

Fig 3. Threshold voltage shift vs. dose dependencies for different oxide thickness. Experimental results are previously reported in [6].

100 Gy) the contribution of trapped oxide charges dominates and results in a decrease of ΔV_{th} and above these doses the density of negatively charged acceptors at the SiO_2/Si interface is not negligible. In the case of pMOS transistors (fig. 2.b), it can be see that ΔV_{th} increase continually with dose. The agreement of these dependencies with our previously reported [4], [5] experimental results obtained on nMOS and pMOS transistors with same layout and which are made by same technology processes is good. Therefore, we can conclude that the method of N_{ot} and N_{it} calculation and relation (5) are valid. Also, dependencies on Fig 2 can be explain the fact that pMOS are most sensitive on irradiation then nMOS transistors.

On Fig 3. it is shown calculated and experimentally determined ΔV_{th} vs. dose dependencies for especially designed pMOS transistors with different oxide thickness. These transistors with very thick oxide layer are described in [6]. As it was seen, calculated and experimentally determined dependencies have satisfactory agreement.

VI. Conclusion

In this paper we are explain a stochastic model based on Monte Carlo method for simulation distribution of charge trapped in SiO_2 gate layer of MOS transistor due to irradiation. This method is based on electron-hole generation model and it is enable to calculate the threshold voltage shift ΔV_{th} vs. dose dependencies of irradiated MOS transistors. Calculated dependencies are compared with experiment and satisfactory agreements are shown. Also, we are demonstrate that calculated values of effective density of holes trapped in oxide due to irradiation N_{ot} depend on irradiation dose but not depend on oxide thickness.

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