A STOCHASTIC MODEL OF GAMMA-RAY INDUCED OXIDE CHARGE DISTRIBUTION AND THRESHOLD VOLTAGE SHIFT OF MOS TRANSISTORS

by

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A stochastic model of gamma-ray radiation effects on the density of the induced charge in silicon dioxide films of MOS transistors is presented in this paper. It is assumed that both radiation induced charge generation and trapped charge recombination are stochastic processes. For estimating gamma-ray induced charges spatially distributed in silicon dioxide films, a procedure similar to the Monte Carlo method was used. The proposed model implemented in the programming language MATHEMATICA enables us, for the first time, to show the gamma-ray induced charge distribution as a function of gamma-ray doses. Using the developed model, we have also calculated the corresponding threshold voltage shifts of MOS transistors. These results were compared with the experimentally determined threshold voltage shift of MOS transistors with different voltages applied during irradiation vs. gamma radiation doses. Satisfactory agreements were obtained.

Key words: gamma-ray, silicon dioxide, MOS transistor

INTRODUCTION

As shown earlier [1], gamma radiation exposure of a MOS (metal-oxide-semiconductor) transistor results both in the creation of positive trapped charges in the gate oxide and in the increase of the interface – trap density at the Si-SiO_2 interface. These charges can cause a threshold voltage shift, transconductance reduction, leakage current increase and breakdown voltage reduction [1-3]. In order to improve the resistance of the MOS transistor to these effects, it is necessary to have a reliable method of determining radiation generated charges in the oxide and at the oxide-semiconductor interface. Also, research on radiation induced charges is very important for gamma radiation dosimetry, which could be based on specially designed, p-channel MOS transistors [1].

In this paper, we are developing a new model for estimating gamma-ray induced spatial distribution of charges in oxide. This model, based on the Monte Carlo method [4, 5], takes into account the stochastic nature of gamma ray absorption, as well as the generation and recombination of induced charges. Also, the effect of the electric field established in the SiO_2 layer upon charge generation and recombination, as well as upon its spatial distribution, is taken into account. On the basis of the proposed model and the model of interface states [5, 6], we calculated the threshold voltage shift *vs*. absorbed dose dependencies and compared them with previously reported [7, 8] experimental results.

MODEL OF OXIDE CHARGE CREATION

The interaction of gamma-ray radiation with silicon dioxide films can be described by means of two significant mechanisms, *i. e.* absorption (exponential decrease of the dose with distance) and ionization (with negligible energy losses of gamma rays). A simplified model of ion formation and electron transport across the oxide can also be used [3]. In this manner, as the silicon dioxide films are exposed to gamma irradiation, the gate oxide becomes ionized by the dose it absorbs and electron-hole pairs are generated. Under the influence of the electric field which appears in the silicon dioxide films, free electrons drift. Most of these electrons would be fairly benign if they drifted out of the oxide and disappeared, but a small fraction of them will recombine by the holes in the oxide. A fraction of the holes remaining from this recombination with electrons is then subjected to the transport mechanism

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through localized states in the oxide. The holes propagate (in the direction of the electric field) towards the SiO_2 interface and capture in long-term traps. After a sufficient radiation dose, a large positive charge, spatially distributed towards the one of the SiO_2 interfaces, builds up in the oxide. The density of the oxide charge can, then, be expressed as [1, 2]

$$qn_{\rm ox}(x) \quad q\alpha_{\rm ox} f_{\rm y}(E_{\rm ef}) f_{\rm tr}(E_{\rm ef}) D \tag{1}$$

where q is the elementary charge, $n_{\rm ox}(x)$ – the concentration of the generated and trapped holes, $\alpha_{\rm ox}$ – the coefficient of the generation (number of holes generated per unit of volume and unit of absorbed dose), $f_{\rm y}$ – the part of the holes transported across localized states in the oxide [2], $f_{\rm tr}$ – the part of holes trapped at long-lived trap centers of the oxide [2], and D – the absorbed dose of gamma-ray, *i. e.* the mean energy absorbed per unit mass of irradiated oxide. The effective electric field in the oxide is given by

$$E_{\rm ef} \quad E \quad E_\gamma \quad E_{\rm ox} \tag{2}$$

where E is the electric field caused by the external bias, E_γ – the electric field caused by the work function difference between the gate electrode and the silicon [6], and

$$E_{\rm ox} \quad \frac{q}{\varepsilon_{\rm ox}} \Delta N_{\rm ot} \tag{3}$$

is the electric field caused by spatially distributed holes. In the last relation, the effective charge density of the Si/SiO_2 interface is given by

$$q\Delta N_{\rm ot} \quad \frac{q}{d_{\rm ox}} {}_{0}^{d_{ox}} n_{\rm ox}(x) x \mathrm{d}x \tag{4}$$

where $\Delta N_{\rm ot}$ is the increase in the oxide charge per unit area due to gamma radiation, $d_{\rm ox}$ being the oxide layer thickness, while $\varepsilon_{\rm ox}$ is the permittivity of the silicon dioxide.

Let us denote the intensity of gamma radiation (energy per time interval) by G, at $x = 0$ and by γ, the attenuation coefficient. In that case, the intensity of radiation at depth x is $g(x) = G \exp(-\gamma x$. But, considering the values of γ ($>10\ \mu\mathrm{m}^{-1}$ [1, 3]) for layers with thicknesses much smaller then 3 μm, it can be considered that gamma-ray intensity is almost constant. In such a case, as G does not depend on time, *i. e.* G is a constant over the whole period of irradiation, the absorbed dose for time T is approximatelly $D \quad GT$.

We should bear in mind that gamma-ray absorption, electron-hole pair creation, the trapping hole and electron recombination, are processes which randomly occur with certain probabilities. To take into account the stochastic nature of these processes, we will divide the whole material of thickness $d_{\rm ox}$ into n layers. The thickness of each layer being $\Delta d = d_{\rm ox}/n$. Also, the total absorbed dose of gamma ray D will be partitioned into ΔD portions absorbed by the oxide over time Δt, [5].

Denote with $\alpha_{\rm k}$ the number of produced electron-hole pairs in the k-th layer of the oxide for the time Δt. We assume that this number depends only on the ΔD dose absorbed in this layer during the Δt time. Let us suppose that α_k is a Gaussian random variable, *i. e.* that the following holds

$$\alpha_{\rm k} : N(\overline{\alpha_k}, \sigma_\alpha) \tag{5}$$

where $\overline{\alpha_{\rm k}}$ is the mean value of the number of pairs created in the k-th oxide layer, and that it is directly proportional to radiation intensity $g(x_k)$ in the k-th layer

$$\overline{\alpha_{\rm k}} \quad \alpha g(x_k) \quad \alpha\frac{D}{T} \quad \alpha\frac{\Delta D}{\Delta t} \tag{6}$$

where α is the total number of holes generated in the oxide by the incident gamma ray, and σ represents the standard deviation.

We suppose that the electric field (and time interval Δt in which the holes are mobile) is small enough so that the holes can only move from the k-th layer in which they were created to the neighboring layer (k + + 1-th layer) over time Δt. We will adopt that the number of migrated holes $\Delta\alpha_k$ linearly depends on the resultant field, *i. e.* that the effect is described by the equation

$$\Delta\alpha_k \quad \alpha_k s_1 [E \quad s_2(\rho_{k \ 1} \quad \rho_k)] \tag{7}$$

where $\rho_k = \rho(x_k)$ denotes the charge density due to trapped holes and s_1 and s_2 are constants.

If $\Delta\alpha_k > \alpha_k$, we will set $\Delta\alpha_k = \alpha_k$. This means that the field is sufficiently large, so that all created holes will migrate to the neighboring layer.

The probability of radiation induced electrons recombination with previously captured holes can be represented by the following simple relation

$$\beta(\rho) = \begin{matrix} \beta_0 \dfrac{\rho}{\rho_{\rm crit}}, & \rho \quad \rho_{\rm crit} \\ \beta_0, & \rho \quad \rho_{\rm crit} \end{matrix} \tag{8}$$

where, $\rho_{\rm crit}$ represents the critical charge density of trapped holes when saturation appears and β is the saturated probability.

Since electrons created in the k-th layer move towards the gate, they may be recombined by holes trapped in the $k, k-1, ...2, 1$ layers. Let us denote with β_{ki} the number of electrons created in the k-th layer which enter the i-th layer and with

$$\overline{\Delta\beta_{k,i}} \quad \beta(\rho_i)\beta_{k,i} \tag{9}$$

an average number of electrons created in the k-th layer and those recombined in the i-th layer. Taking into consideration all of the above said, we assume that the number of electrons created in the k-th layer and recombined in the i-th layer $\Delta\beta_{ki}$ is a random variable with a normal distribution of

$$\Delta\beta_{k,i} : N(\overline{\Delta\beta_{k,i}}, \sigma_\beta) \tag{10}$$

where σ_β is a standard deviation. The number of electrons entering in the next, $(i-1)$-th layer is $\beta_{k,i-1} \quad \beta_{k,i} - \quad \beta_{k,i}$. If we obtain $\beta_{k,i-1} < 0$, we set $\beta_{k,i-1} = 0$ and $\Delta\beta_{ki} = \beta_{ki}$ and the recombination process from the k-th layer as being over. All electrons in that layer are recombined.

Therefore, as for time Δt, the dose ΔD of the gamma ray is absorbed and the charge created in the k-th layer can, thus, be expressed as

$$\Delta\rho_k \quad q \quad \alpha_k \quad \Delta\alpha_{k\ \ 1} \quad \Delta\alpha_k \quad \mathop{}\limits_{\iota\ \kappa}^{n} \Delta\beta_{ik} \tag{11}$$

This charge is caused by the change in the numbers of holes in the k-th layer, *i. e*. the number of holes increases with each hole generation and hole transport from the preceding layer, but it decreases with holes transported to the successive layer. Also, the number of holes in the k-th layer decreases by recombination with electrons which have reached that layer from the layers between the Si-SiO_2 interface (n-th layer) and the k-th layer. The described processes are shematically shown in fig. 1.

ALGORITHM FOR OXIDE CHARGE DENSITY CALCULATION

The stohastic model of charge creation in the oxide of a MOS transistor, described in the previous section, relations (1) – (11), is implemented in the programming language MATHEMATICA and composed of five blocks:

(1) the input block in which the input variables and primary charge density are defined,
(2) the block of randomly generated electron-hole pairs in all layers, caused by the elementary dose ΔD,
(3) the block of transportation and trapping holes in the next layer,
(4) the block of transportation electrons and their random recombination with trapped holes which is repeated separately for each layer, and
(5) the block in which the new charge density (trapped hole distribution) is calculated.

It should be mentioned that this model presupposes a random generation of a certain number of electron-hole pairs in each layer under the influence of gamma radiation with dose ΔD. The holes are localized in the layer where they were created and in the neighbouring layer, and electrons are transported towards the gate and are randomly recombined with the holes trapping in the layers they moved through.

In this manner, algorithm execution corresponds to the change of charge distribution caused by the absorption of the elementary dose ΔD of the gamma ray. The charge distribution caused by the absorption of gamma ray dose D can be obtained by repeating this algorithm (without the first block) $N = D/\Delta D$ times. A big advantage of this algorithm is that after the determination of the charge distribution caused by a dose of gamma radiation, the one caused by a higher dose can be obtained by simple reiteration of the algorithm. Therefore, the time of calculation is significantly reduced when determining charge distribution caused by different doses of gamma irradiation is needed.

In block 2, the number of randomly generated electron-hole pairs is determined, and in block 4, the number of randomly recombined electrons. In both cases, the programming language MATHEMATICA generator of random numbers was used, *i. e*. the function:

RandomReal [Normal Distribution [sredvr, stdev]]

This function gives random generated numbers with normal distribution (average value sredvr and standard deviation stdev).

The charge distribution determined in this way is one of the possible results and depends on randomly generated numbers α_k and $\Delta\beta_{k,i}$. The real and definitive charge distribution can be obtained as an average of several possible distributions. To this purpose, the whole algorithm must be executed quite a number of times, always with new values of randomly generated numbers α_k and $\Delta\beta_{k,i}$. Thus, the procedure of charge

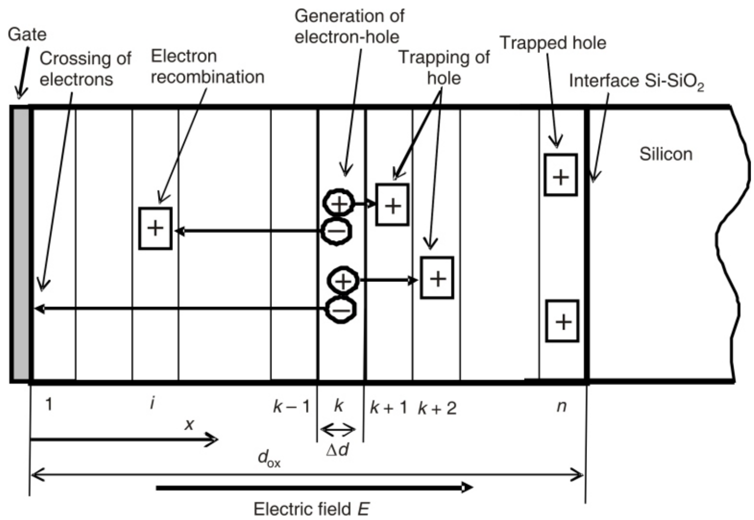

Figure 1. Schematic representation of the creation of electron-hole pairs induced by gamma radiation, trapping holes, and the recombination of electrons

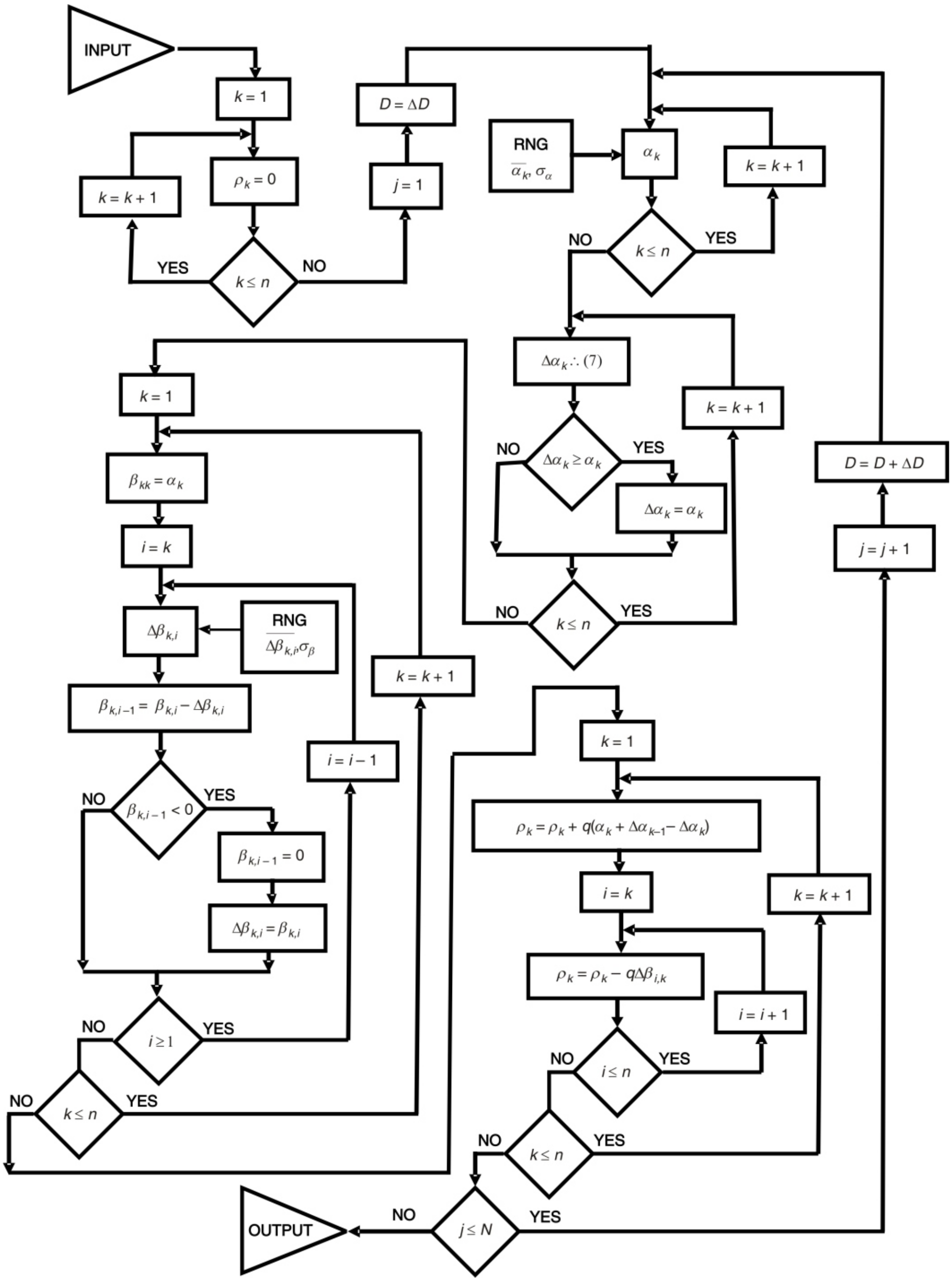

Figure 2. The block diagram for calculation of the charge distribution in the silicon dioxide caused by gamma radiation

distribution calculation is similar to the Monte Carlo method [4, 5], but different from the detailed Monte Carlo simulation of radiation effects in the gate oxide which include features of particle transport [9].

CALCULATED DEPENDENCE OF OXIDE CHARGE DISTRIBUTION

All of our results correspond to the case of an oxide of thickness d_{ox} divided into n layers, *i. e.* to the ratio $(d_{ox}/n) = 4$ nm. This means that in the case of oxide thickness d_{ox} = 120 nm, the number of layers n into which it is divided is 30, just as is shown in fig. 1. Calculations have also shown that the absorbed dose of the gamma ray in the oxide is $\Delta D = 1$ Gy, when the time equals Δt. In this manner, the total absorbed dose of gamma rays is $D = N\Delta D$ and the total time of irradiation $T = N\Delta t$.

In all calculations, the following values of parameters $\alpha = 1$ s cm^{-3}Gy *s* $^{-5}$ cm V, *s* ε_{SiO} $^{-13}$ F/cm, ρ_{crit} $^{-4}$ C/cm^3, and $\beta_0 =$

= 0.8 [1,10] were used. All calculations were repeated a hundred times, with new values of randomly generated numbers α_k and $\Delta\beta_{k,i}$. In fig. 3, the average values of results obtained in this way are shown.

In fig. 3(a), the spatial distribution of trapped holes in the oxide, without externally applied bias, evaluated by the predicted model, is presented. As can be seen, trapped holes are distributed near the SiO_2/Si interface, but their spatial distribution is not negligible at all. Near the SiO_2/Si interface, the density of the trapped hole rapidly increases. In all cases, the slope of the holes' distribution near the SiO_2/Si interface increases as irradiation doses increase, which is pretty much a new result. It can, also, be seen that most of the trapped holes are distributed in the narrow layer near to the SiO_2/Si interface. The thickness of this layer is about 20 nm, for all doses of radiation. The density of trapped holes rapidly increases close to the SiO_2/Si interface.

The influence of the externally applied bias on the spatial distribution of the oxide charge during radiation is shown in fig. 3(b). As can be seen, the externally applied bias which increases the total charge in the oxide and the density of the trapped holes near the SiO_2/Si interface shows relatively higher amounts. The layer in which most of the charge is distributed is thinner and charge density in it is higher as the intensity of the electric field grows. This can be explained by the fact that, in the presence of an effective electric field, the gains in charge density with externally applied bias in the oxide are followed by a great number of pairs that do not recombine and that a significant number of generated holes start to drift through the oxide, to be captured near the SiO_2/Si interface.

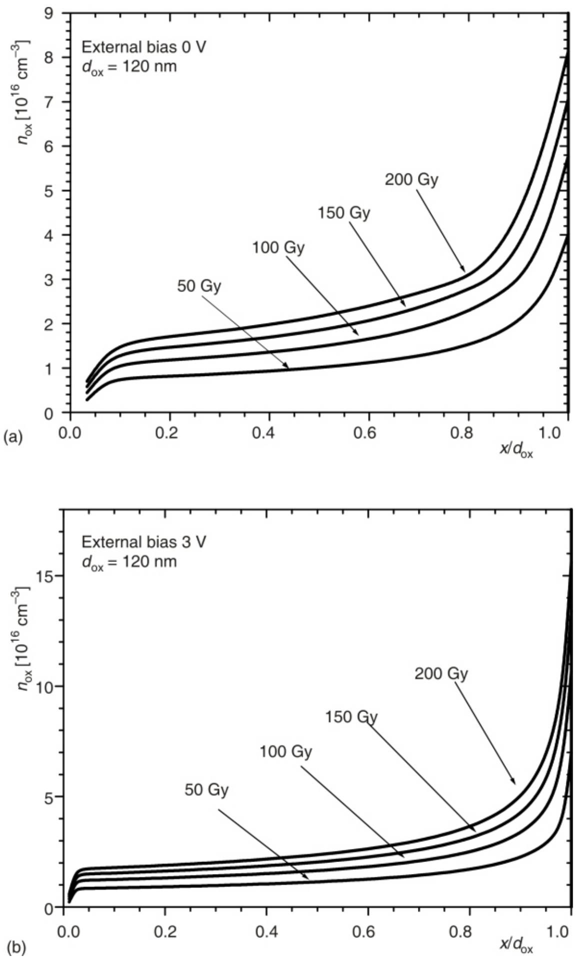

Figure 3. The spatial distribution of oxide trapped holes induced by gamma rays for different doses of radiation: without external bias (a), and with external bias of 3 V (b)

In previously described cases it has been assumed that the externally applied electric field is directed towards the SiO_2/Si interface (with "+" on the gate electrode). In cases of reverse polarization, the effective electric field is towards the gate electrode and the generated holes are transported and captured towards the gate/SiO_2 interface. The shape of oxide charge distribution is the same as in fig. 3(a), but the peak of distribution is near the gate/SiO_2 interface.

THRESHOLD VOLTAGE SHIFT

The radiation induced shift in the threshold voltage of MOS transistors can be expressed in the form of

$$\Delta V_{th} = V_{th} - V_{th0} \tag{12}$$

where V_{th0} denotes the threshold voltage before the devices were irradiated and V_{th} is the threshold voltage after irradiation. Since radiation directly affects the densities of the oxide charge qN_{ot} and the interface states N_{it}, the mentioned change of threshold voltage can be expressed as

$$\Delta V_{th} \quad \Delta V_{ot} \quad \Delta V_{it} \quad \frac{q}{C_{ox}}\Delta N_{ot} \quad \frac{q}{C_{ox}}\Delta N_{it} \tag{13}$$

where C_{ox} is the gate oxide capacitance per unit area. The plus sign applies to pMOS transistors, the minus sign to nMOS devices. In eq. (13), qN_{ot} denotes the effective density of the oxide charge at the Si/SiO_2 interface defined by eq. (4), where $qn_{ox}(x)$ denotes the concentration of the spatially distributed charge towards the Si/SiO_2 interface which is formed in the oxide. The density of interface traps charged due to irradiation N_{it} can be calculated as described in [5, 6].

The calculated threshold voltage shift ΔV_{th} as a function of the irradiation dose (lines) and experimentally determined values (dots) and the influence of external bias applied on the SiO_2 film during irradiation of nMOS and pMOS transistors are shown in figs. 4 to 5. Previously reported [7, 8] experimental results, shown in figs. 4 and 5, were obtained on nMOS and pMOS transistors with the same layout and manufactured in the same technology. Consequently, it is possible to directly compare the ΔV_{th} *vs.* dose dependence for nMOS and pMOS transistors, according to relation (13). As has been seen, both dependencies represented

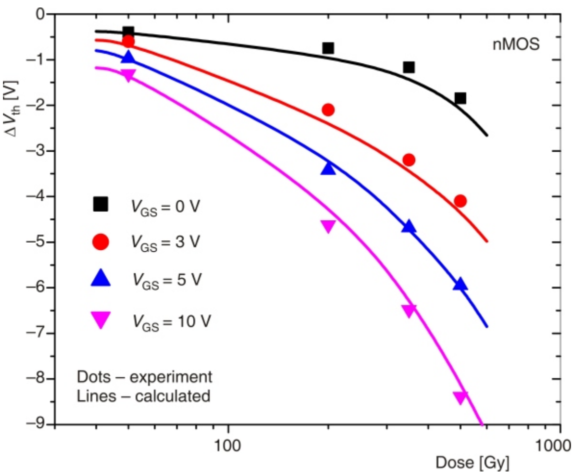

Figure 4. Threshold voltage shift of a nMOS transistor *vs.* dose dependencies for different gate polarization during irradiation. Experimental results were previously reported in [7]

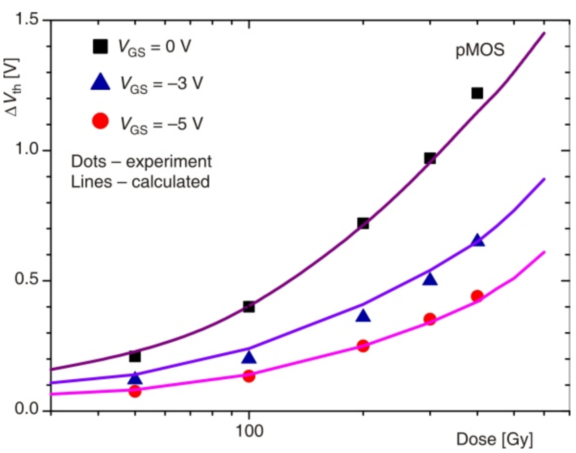

Figure 5. Threshold voltage shift of a pMOS transistor *vs.* dose dependencies for different gate polarization during irradiation. Experimental results were previously reported in [8]

in figs. 4 and 5 exhibit a satisfactory agreement with the experimentally determined results. We can, therefore, conclude that the method of N_{ot} and N_{it} calculation and relation (13) are valid.

As can be seen (fig. 4), external bias applied to the gate of the nMOS transistor during irradiation increases the absolute value of the threshold voltage shift $|\Delta V_{th}|$. This is caused by the increase in oxide charge density near the SiO_2-Si interface and the effective density of the oxide charge qN_{ot}. The increases of qN_{ot} with applied bias and its influence on the threshold voltage shift are significantly higher than the influence of interface traps, N_{it} even more so in cases of very high irradiation doses.

In the case of a pMOS transistor, as the negative bias is applied on the gate during irradiation, the threshold voltage shift decreases (fig 5). In such a case, the generated holes (oxide charge) are distributed near the gate/SiO_2 interface and the effective density of the oxide charge qN_{ot} is neglected. The threshold voltage shift is caused only by the charges at interface traps N_{it}.

Also, the dependencies presented in figs. 4 and 5 can serve as an explanation for the fact that pMOS are much more sensitive to irradiation than nMOS transistors, as the transistors are irradiated without external bias. But, as external bias is applied, the threshold voltage shift of nMOS transistors rapidly decreases with the increase of the dose, making them more sensitive than pMOS transistors.

CONCLUSIONS

Applying the Monte Carlo method, we have proposed a novel model of creating the charge in the oxide of a MOS transistor due to gamma radiation. This statistical method is based on the electron-hole generation model and takes into account the stochastic nature both of the process of generating electron-hole pairs and that of the recombination of electrons-holes previously trapped in the oxide.

We have researched the influence of different doses of gamma radiation on the concentration of trapped holes in a layer of SiO_2, with and without an externally applied electric field. The obtained results are in agreement with some real experiments and the computational experiments performed through other methods.

The model presented here is specific to gamma rays and can be easily applied to SiO_2 with different characteristics, allowing for the study of spatial charge distribution and threshold voltage *vs*. the absorbed dose of radiation dependencies in oxide layers of MOS transistors. We also believe that our model could be applicable to other types of radiation.

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СТОХАСТИЧКИ МОДЕЛ РАСПОДЕЛЕ НАЕЛЕКТРИСАЊА У ОКСИДУ И ПРОМЕНЕ НАПОНА ПРАГА МОС ТРАНЗИСТОРА ИЗАЗВАНОГ ГАМА ЗРАЧЕЊЕМ

У раду је описан стохастички модел утицаја гама зрачења на наелектрисање које се ствара у слоју оксида MOS транзистора. Претпостављено је да су и процес стварања наелектрисања под утицајем гама зрачења и процес рекомбинације тог наелектрисања стохастички процеси. За одређивање просторне расподеле наелектрисања у оксиду коришћен је поступак сличан Монте Карло методи. Предложен модел, имплементиран у програмском језику MATHEMATICA, омогућио је да се одреди просторна расподела наелектрисања у зависности од дозе гама зрачења и одговарајућа промена напона прага MOS транзистора. Израчунате зависности су упоређене са експерименталним резултатима о утицају гама зрачења на промену напона прага MOS транзистора и добијено је задовољавајуће слагање.

Кључне речи: гама зрачење, силицијум диоксид, MOS транзистор