RADIATION-SENSITIVE FIELD EFFECT TRANSISTOR RESPONSE TO GAMMA-RAY IRRADIATION

by

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The influence of gate bias during gamma-ray irradiation on the threshold voltage shift of radiation sensitive p-channel MOSFETs determined on the basis of transfer characteristics in saturation has been investigated. It has been shown that for the gate bias during the irradiation of 5 V and 10 V the sensitivity of these transistors can be presented as the threshold voltage shift and the absorbed irradiation dose ratio. On the bases of the subthreshold characteristics and transfer characteristics in saturation using the midgap technique we have determined the densities of radiation induced oxide traps and interface traps responsible for the threshold voltage shift. In addition, the charge pumping technique was used to determine the energy density of true interface traps. It has been shown that radiation-induced oxide traps have dominant role on threshold voltage shift, especially for gate biases during the irradiation of 5 V and 10 V.

Key words: p-channel MOS transistor, interface traps, oxide trapped charge, radiation sensitivity

INTRODUCTION

It is well known that ionizing radiation (γ, X, electrons, and ions) has significant influence on electronic component characteristics. For example, the irradiation of semiconductor over-voltage diodes causes degradation of their protection characteristics, while gas-filled over-voltage diodes exhibit a temporal improvement of their performance [1]. The operation of polycarbonate capacitors in the presence of a neutron and gamma radiation field causes a decrease of capacitance, while the loss tangent remains unchanged [2]. Changes induced by ion irradiation affect the current-voltage characteristics and state retention ability of the memristor [3]. The investigation of gamma radiation to MOS integrated circuits, *i. e.*, to transistors has been going on for several decades [4] due to their significant degradation of electrical parameters during the irradiation [5-7]. Such degradation is a consequence of the formation of defects responsible for the increase of positive charge density in oxide and interface traps on the oxide/semiconductor interface. The knowledge of these defects is very important in order to produce the component resistant to radiation. The idea of some investigators was to use the negative influence of gamma radiation to MOS components, mainly PMOS transistors, in order to produce sensors and dosimeters for ionization radiation. These components are known as radiation-sensitive field effect transistors (RADFET) or radiation sensitive p-channel MOSFET (MOS dosimeter). They are developed for applications such as space, nuclear industry, and radio therapy [8-11]. The RADFET advantages, in comparison with other dosimetric systems (thermo-luminescent dosimeters, semiconductor diodes, and optically stimulated luminescence dosimeters [12]), include an immediate, non-destructive readout of dosimetric information, very low store of the absorbed radiation dose, extremely small size of the sensor element, a wide dose range, very low power consumption, compatibility with microprocessor, and a very competitive price (especially if the cost of the read out system is taken into account). The RADFET disadvantages are a need for calibration in a different radiation field, relatively low resolution (starting from 10^{-2} Gy), and non-reusability.

The RADFET has a special thermally or CVD grown oxide [13, 14] sensitive to gamma and X-ray irradiation. The application of RADFET is based on converting the threshold voltage shift, ΔV_T, induced by radiation, into the absorbed radiation dose D. This

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dependence can be expressed as $\Delta V_T = A\ D^n$ [15, 16], where, $\Delta V_T = V_T - V_{T0}$, V_T is the threshold voltage after the irradiation and V_{T0} before the irradiation, A – the constant, and n – the degree of linearity which depends on the electrical field, oxide thickness, and absorbed radiation dose. If $n = 1$ then A represents the sensitivity, S ($S = \Delta V_T/D$). ΔV_T is the sum of threshold voltage shift caused by radiation induced oxide traps, ΔV_{ot}, and interface traps, ΔV_{it} ($\Delta V_T = \Delta V_{ot} + \Delta V_{it}$) [16]. Many investigations have shown that the radiation sensitivity of RADFET can be increased with the increase of oxide thickness [13, 14, 17] as well as with the stacking of more transistors [18, 19].

In this paper, a study of RADFET sensitivity on gamma-ray irradiation for different values of gate biases has been presented. For this reason, we have performed I-V and charge pumping (CP) measurements. This has enabled us to analyze the basic mechanisms underlying the irradiation of RADFET in particular, and discuss the role of oxide traps and interface traps for studied devices.

EXPERIMENTAL DETAILS

The experimental samples were Al-gate RADFET, manufactured by Tyndall National Institute, Cork, Ireland [20]. The samples have 100 nm thick oxides, grown at 1000 °C in dry oxygen and annealed for 15 minutes at 1000 °C in nitrogen. The post-metallization anneal was performed at 440 °C in forming gas for 60 minutes. The channel width and length of these samples are 300 μm and 50 μm, respectively.

Experimental samples were irradiated at room temperature using the $^{60}_{27}Co$ source to 500 Gy at the dose rate of 0.2 Gy/s. All doses are given in Gy(H_2O); to convert to Gy(SiO_2) Gy(Si), one has to multiply the dose with 0.898. The gate bias during the irradiation (V_{irr}) was 0, 5 V or 10 V. For every value of V_{irr} we used two samples.

Transfer and charge pumping characteristics were monitored for every sample before the irradiation in order to determine threshold voltage before the irradiation V_{T0} as well as charge pumping current before irradiation I_{CP0}. The same characteristics were measured after five irradiation doses of 100 Gy up to 500 Gy in order to obtain the threshold voltage shift and the change in the charge pumping current. Transfer characteristics, $I_D = f(V_G)$, were monitored for every sample up to 4 mA using a two channel source measuring unit (Keithley model 2636). The samples drain was biased with –10 V. The threshold voltages before and after irradiation were determined by the transistor transfer characteristics in saturation, *i. e*., as the intersection between the V_G-axis and the extrapolation linear region $I_D^{1/2} = f(V_G)$ curves. The change in areal densities of gamma-ray irradiation induced oxide traps, ΔN_{ot}, and interface traps, ΔN_{it}(MG), were determined using the midgap technique (MG) of McWharter and Winocur [21].

Keithley model 2636 was used for the measurement of charge pumping current and HP8116 function generator was used for applying the saw tooth signal at the samples gate. The frequency of the saw tooth signal was 1 MHz with the 50% duty cycle, the amplitude was 3 V and the signal offset was varied from 2 V to –3 V. CP technique was used for the determination of the energetic densities of interface traps (ΔD_{it}), $\Delta N_{it} = \Delta D_{it}\ \Delta E$, where ΔE is the energy range within Si band gap scanned by the measurement. The aerial density of the interface traps, N_{it}(CP), was determined using the Elliot-type CP curves [22].

EXPERIMENTAL RESULTS

The RADFET transfer characteristics in saturation before irradiation (curve 0) and after the absorbed radiation dose D of 100, 200, 300, 400, and 500 Gy (curves 1, 2, 3, 4, and 5, respectively) for $V_{irr} = 5$ V are shown in fig. 1. The fitting of the upper part of the $I_D^{1/2} = f(V_G)$ characteristics, which are linear, gives the values of threshold voltage V_{T0}, V_{T1}, V_{T2}, V_{T3}, V_{T4}, and V_{T5} and these values increase with the increase of D. The similar behavior of characteristics (which is not represented) is observed for V_{irr} of 0 and 10 V.

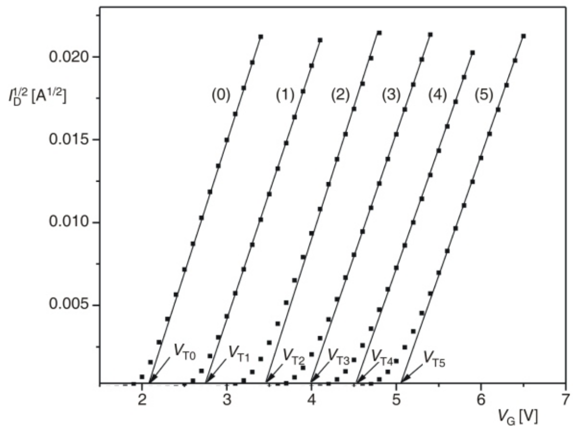

Figure 1. Transfer characteristics in saturation: (0) – before irradiation, and after irradiation for the absorbed radiation dose, (1) – 100 Gy, (2) – 200 Gy, (3) – 300 Gy, (4) – 400 Gy, and (5) – 500 Gy; the gate bias during irradiation V_{irr} = 5 V

The influence of gate bias during irradiation V_{irr} on threshold voltage, V_T, is shown in fig. 2. Transfer characteristics in saturation have been obtained for D = = 300 Gy and for V_{irr} of 0, 5 and 10 V (curves 1, 2, and 3, respectively). It can be seen that the values of V_T insignificantly differ for the gate biases of 5 and 10 V and that they are for about 1.5 V bigger then for the gate bias of 0 V.

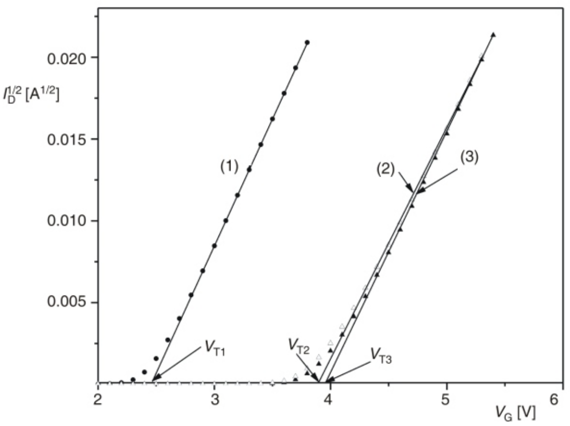

Figure 2. Transfer characteristics in saturation for the absorbed radiation dose of 300 Gy: (1) – V_{irr} = 0 V, (2) – V_{irr} = 5 V, and (3) – V_{irr} = 10 V

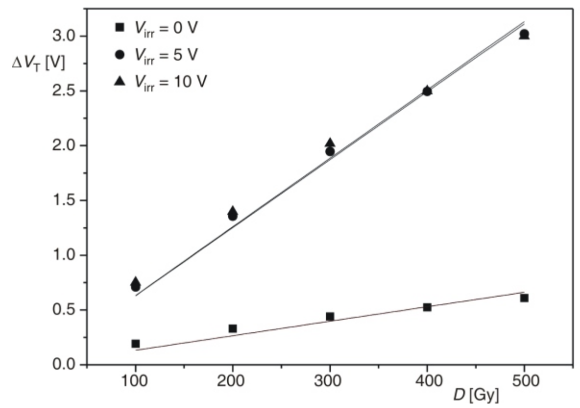

Figure 3. Threshold voltage shift, ΔV_T, as a function of the absorbed radiation dose, *D*, for three values of gate bias during irradiation

Figure 3 gives the $\Delta V_T = f(D)$ dependence for V_{irr} values of 0, 5, and 10 V. The symbols in the figure represents the $\Delta V_T = V_T - V_{T0}$ values obtained from RADFET transfer characteristics in saturation, while the solid lines were determined by fitting of the experimental results with the expression $\Delta V_T = AD^n$ for the degree of linearity $n = 1$. The value of fitting correlation factors for the gate biases of 5 and 10 V is 0.998, while for the gate bias of 0 V the correlation factor is 0.887. This shows that for the gate biases of 5 and 10 V the sensitivity can be confidently determined as $S = \Delta V_T/D$ for the range of the absorbed radiation dose from 100 Gy to 500 Gy.

In fig. 4 the subthreshold characteristics of RADFET before irradiation (curve 0) and after irradiation for the absorbed radiation doses of 100, 200, 300, 400, and 500 Gy (curves 1, 2, 3, 4, and 5, respectively) for V_{irr} = 5 V are presented. The parameters relevant for the determination ΔN_{it} using midgap technique are marked in the figure (the similar characteristics were obtained for V_{irr} of 0 and 10 V). The increase of ΔN_{ot} during the irradiation is manifested through the subthreshold characteristics shift along the axis, while the increase of ΔN_{it} is manifested through the decrease of the subthreshold curve slope.

It is known that no matter the distribution within the band gap of the substrate, oxide traps are neutral when the surface potential φ_s is equal to the Fermi potential φ_F. In that case, the shift between two subthreshold characteristics along the V_G axis is a consequence of the change of the oxide trap density, and the gate voltage corresponding to this value of surface potential which is marked as V_{MG} (midgap voltage) is obtained from the point (V_{MG} , I_{MG}), fig. 4. The position of this point is determined on the basis of its ordinate, *i. e.*, current I_{MG} (midgap current) which can be

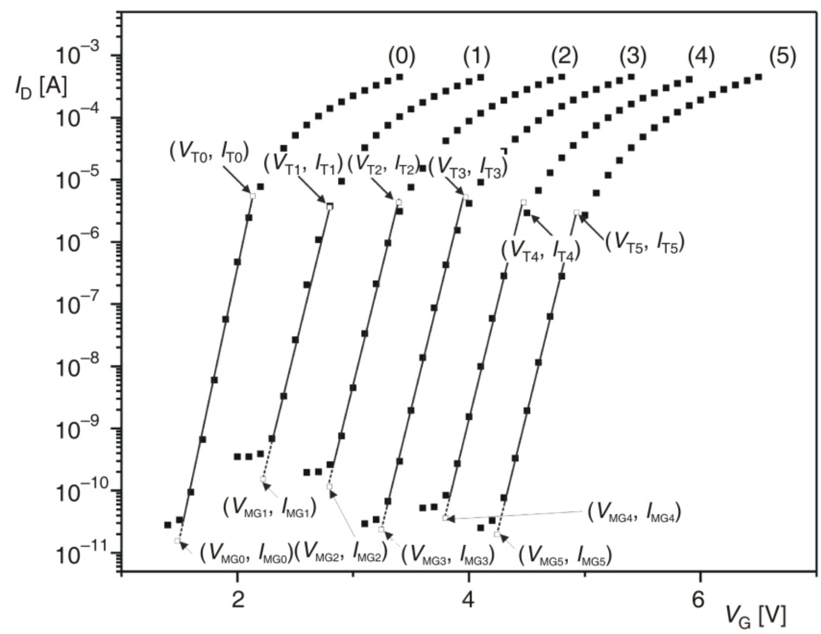

Figure 4. Subthreshold characteristics: (0) – before irradiation, and after irradiation for the absorbed radiation dose (1) – 100 Gy, (2) – 200 Gy, (3) – 300 Gy, (4) – 400 Gy, and (5) – 500 Gy; the gate bias during irradiation V_{irr} = 5 V

determined by the introduction of the appropriate values of surface potential $\varphi_S = \varphi_F$ and experimentally determined mobility in the equation given in [23]. I_{MG} is in order of pA and its value is on the extension of the linear part of the subthreshold characteristics marked by the dotted line in fig. 4. The change in the aerial density of the oxide trap caused by irradiation can be expressed as [21]

$$\Delta N_{ot} = \frac{C_{ox}}{q}(V_{MG0} - V_{MG}) \tag{1}$$

where C_{ox} is the oxide capacitance per unit area, q – the absolute value of electron charge, V_{MG0} – the midgap voltage before irradiation, and V_{MG} – the midgap voltage after irradiation.

The other significant point (V_T, I_T) in fig. 4 is determined using the threshold voltage V_T (see fig. 2). Namely, as it has already been said, interface traps change the slope of subthreshold characteristics, *i. e.*, the difference of the voltages V_T and V_{GM}. The change in the areal density of the interface trap caused by irradiation can be determined as [22]

$$\Delta N_{it}(\text{MG}) = \frac{C_{ox}}{q}[V_{S0} - V_{S0}(0)] \tag{2}$$

where $V_{S0}(0)$ is the value of stretchout voltage before irradiation and V_{S0} is the value of stretchout voltage after irradiation.

Figure 5 shows Elliot curves before gamma-ray irradiation (curve 0) and after irradiation for the absorbed radiation dose of 100, 200, 300, 400, and 500 Gy (curves 1, 2, 3, 4, and 5, respectively) for $V_{irr} = 5$ V (similarly behaved curves are also obtained for $V_{irr} = 0$ V and $V_{irr} = 10$ V). It can be seen that the increase of the absorbed radiation dose leads to the increase of the maximum charge pumping current, and it can be expressed as [24]

$$I_{CP\,max} = \nu q A_G N_{it}(\text{CP}) \tag{3}$$

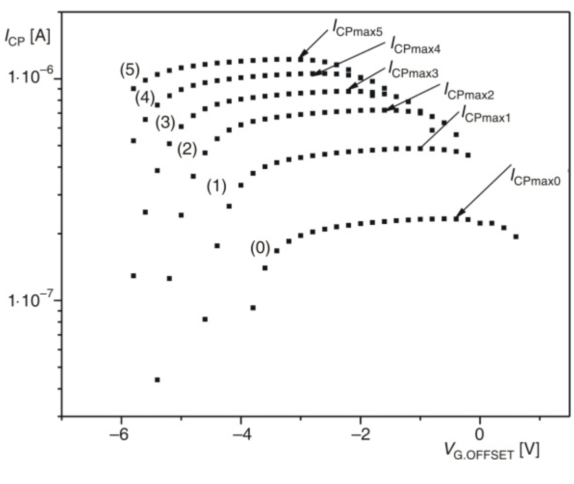

Figure 5. Elliot-type CP curves: (0) – before irradiation, and after irradiation for the absorbed radiation dose, (1) – 100 Gy, (2) – 200 Gy, (3) – 300 Gy, (4) – 400 Gy, and (5) – 500 Gy; the gate bias during irradiation $V_{irr} = 5$ V

where ν is the frequency, A_G – the area under the gate active in charge pumping, and N_{it}(CP) – the absolute value of the areal density of the interface trap after gamma-ray irradiation. The change in the areal density of the interface traps is $\Delta N_{it}(\text{CP}) = N_{it}(\text{CP}) - N_{it0}(\text{CP})$, where N_{it0}(CP) is the absolute value of the areal density of the interface trap before gamma-ray irradiation.

DISCUSSION

The behavior of oxide trap density, ΔN_{ot}, and interface trap density, ΔN_{it}, during the gamma-ray irradiation of RADFET for three different values of gate bias, V_{irr}, are presented in figs. 6 and 7, respectively. The oxide trap density was determined using the expression (1), while the interface trap densities were determined using the expressions (2) and (3). It can be seen that the increase of the absorbed dose rate, D,

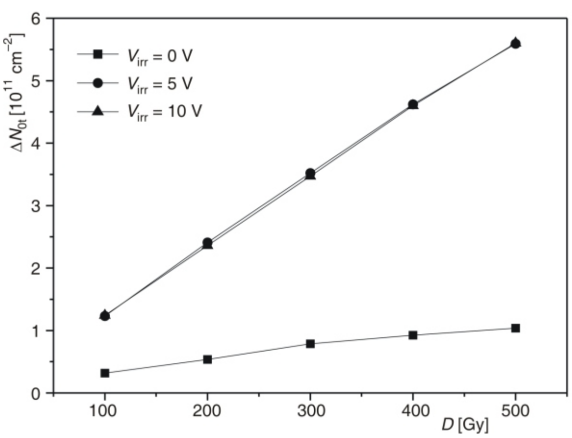

Figure 6. The change in the areal density of oxide traps ΔN_{ot}, as a function of the absorbed radiation dose D, obtained by MG technique for three values of gate bias during irradiation V_{irr}

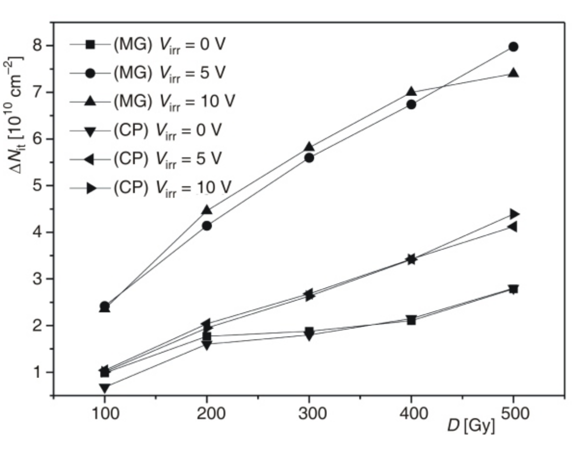

Figure 7. The change in the areal density of interface traps ΔN_{it}, as a function of the absorbed radiation dose D, obtained by MG and CP techniques for three values of gate bias during irradiation, V_{irr}

leads to the increase of both ΔN_{ot} and ΔN_{it}, and that those increases are smaller for $V_{irr} = 0$ V than for $V_{irr} = 5$ V and $V_{irr} = 10$ V. Also, for the same values of D and V_{irr} the increase of oxide trap density is considerably bigger then the increase of interface trap density. The interface trap density ΔN_{it}(MG) calculated using the expression (2) is bigger than the interface trap density ΔN_{it}(CP) calculated using the expression (3) for V_{irr} of 5 V and 10 V.

In order to explain the curve behavior in figs. 6 and 7 it is necessary to consider important mechanisms responsible for the formation of oxide traps and interface traps caused by RADFET irradiation. Namely, gamma-ray irradiation interacts with the gate oxide and breaks Si_0–O covalent bonds between Si and O atoms, as well as weakly Si_0–H and Si_0–OH bonds to produce electron-hole pairs [25, 26]. The creation of electron-hole pairs is followed by the creation of the trivalent silicon atoms Si_0 (E_γ centre [27]) as well as amphoteric non-bridging oxygen (NBO). Some fractions of electron-hole pairs undergo an initial recombination process. Electrons, being much more mobile then holes in SiO_2, are swept out from the oxide under the positive electric field in a time of 1 ps [4]. During the motion in the oxide these electrons can break the covalent bonds in the oxide [28], what leads to the further increase of the density of NBO and E_γ centers as well as the formation of positive charge Si_0–O^+ and Si_0 centers (E centers [29] known as a E_s centers [30]). The survived holes, under the positive field in the oxide, drift to SiO_2/Si interface, react with the hydrogen defect precursors (Si_0–H and Si_0–OH) and create E_γ, E_s, and NBO centers [31, 32]. The creation of these centers is followed by the release of H atoms or OH groups which can easily drift through the oxide after which those centers became stable [31]. A part of holes, which reaches near the SiO_2/Si interface, is being captured on the defects giving the rise of the oxide trap charge. It should be pointed out that oxide trapped charge can be positive (oxide trapped holes) and negative (oxide trapped electrons) and the former is more important, since the hole trapping centers are more numerous, including three types (E_s, E_γ, and NBO centers) [28]. The number of created oxide and interface traps rises with the number of surviving holes. For $V_{irr} = 0$ V an electrical field in the oxide appears only due to the work function difference between the gate and substrate, so the probability of electron-hole pair recombination is higher than for the case when V_{irr} 0 V. For higher values of V_{irr}, a large number of holes will escape the initial recombination process leading to the creation of more oxide trapped charge and more interface traps. Such conclusion is in agreement with the results shown in figs. 6 and 7 for $V_{irr} = 0$ V and 5 V (the values of ΔN_{ot} for $V_{irr} = 5$ V and $V_{irr} = 10$ V insignificantly differ).

The fixed traps (FT) in the oxide do not have the ability to exchange the charge with the channel. They attract or repulse the channel carriers by the Coulomb force, depending on the charge sign of both their charges and channel carrier charges. The influence of FT on the channel carriers by their electric field leads to the parallel shift of the subthreshold characteristics (see fig. 4) and ΔN_{ot} is equal to ΔN_{FT}.

The defects at the SiO_2/Si interface, known as true interface traps, represent an amphoteric defect Si_0 that represents a silicon atom at SiO_2/Si interface back bonded to three silicon atoms from the substrate denoted as Si_s (P_b center [33, 34]). They can be directly created by incident gamma photons, but this amount can be neglected. The biggest density of Si_0 is created by trapping holes (h^+ model) [35-37] and by hydrogen released in the oxide (hydrogen-released species model – H model) [38-40].

The traps created near and at SiO_2/Si interface that captures a carrier from the channel (exchange the charge with the channel) represent switching traps (ST). The ST created in the oxide, near the SiO_2/Si interface, represent slow switching traps (SST) and ST created at SiO_2/Si interface represent fast switching traps (FST). FST are true interface traps (P_b centers).

The density ΔN_{it}(CP) found by the CP technique (expression 3) is, in fact, the density of FST, *i. e.*, $\Delta N_{it}(CP)$ ΔN_{FST}. Namely, as a much faster technique, the CP technique can sense only the FST and eventually just the fastest amount of SST. The simultaneous use of both (MG and CP) techniques is a great advantage. For instance, if ΔN_{ST}(MG) has been changed but ΔN_{ST}(CP) has not, it means that ΔN_{SST}, *i. e.*, the density of SST has been changed, since $\Delta N_{ST}(MG)$ ΔN_{SST} ΔN_{FST} and $\Delta N_{ST}(CP)$ ΔN_{FST} [16, 41]. Such conclusion is in agreement with the curve behavior in fig. 7. Namely, ΔN_{ST}(CP) are smaller then ΔN_{it}(MG) especially for V_{irr} values of 5 V and 10 V. For the case when $V_{itt} = 0$ V, the creation of ST during irradiation is relatively small so the data for ΔN_{FST} are not reliable.

CONCLUSION

The radiation response of RADFET for the absorbed irradiation dose of gamma-ray irradiation from 100 to 500 Gy has been investigated. The radiation response of these components has been observed on the bases of the threshold voltage shift determined from transfer characteristics in saturation. The obtained results show that for the values of gate bias during the irradiation of 5 V and 10 V there is a linear dependence between the threshold voltage shift and adsorbed irradiation dose, which makes these components useful for commercial applications. In order to optimize the RADFET radiation response it is necessary to resolve microscopic processes that occur during irradiation. This study has demonstrated the use of sub threshold mid-gap technique and charge pumping technique. These electrical techniques have limitations, such as that they cannot provide information on the microscopic structure of the defects in the oxide and at the SiO_2/Si interface, so the contribution of electrons and holes to the charge trapped in oxide can not be clearly distinguished. However, the used techniques can still provide valuable information about the effects of slow switching oxide traps and fast switching traps (true interface traps) which are indistinguishable when a single technique (*e. g.* midgap technique) is used. The knowledge about the behavioral patterns of fast switching traps and slow switching traps, together with the fixed traps, is crucial in the optimization of RADFET response. Our results (figs. 6 and 7) have shown that fixed traps play a crucial role in threshold voltage shift, especially for the gate bias during the irradiation of 5 V and 10 V.

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ОДЗИВ РАДИЈАЦИОНО ОСЕТЉИВОГ ТРАНЗИСТОРА СА ЕФЕКТОМ ПОЉА НА ГАМА ЗРАЧЕЊЕ

Истраживан је утицај поларизације гејта током гама зрачења на промену напона прага који је одређиван из преносних карактеристика радијационо осетљивих p-каналних МОСФЕТ. Показано је да се за напоне поларизације на гејту од 5 V и 10 V осетљивост ових транзистора може представити као однос промене напона прага и апсорбоване дозе гама зрачења. На основу потпраговских карактеристика и преносних карактеристика у сатурацији коришћењем MD (*midgap*) технике одређене су густине, формиране радијацијом, центара захвата у оксиду и површинских стања, одговорне за промену напона прага. Додатно је коришћена CD (*charge pumping*) техника за одређивање енергетске густине правих површинских стања. Показано је да гама зрачењем створени центри захвата у оксиду имају доминантну улогу на промену напона прага, нарочито за напоне поларизације на гејту од 5 V и 10 V.

Кључне речи: p-канални МОС транзистор, површинска стања, захваћена наелектрисања у оксиду, радијациона осетљивост