THE EFFECTS INDUCED BY THE GAMMA-RAY RESPONSIBLE FOR THE THRESHOLD VOLTAGE SHIFT OF COMMERCIAL *P*-CHANNEL POWER VDMOSFET

by

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The variations in the threshold voltage shift in *p*-channel power VDMOSFET during the gamma ray irradiation was investigated in the dose range from 10 to 100 Gy. The investigations were performed without the gate bias and with 5 V gate bias. The devices with 5 V gate bias exhibit a linear dependence between the threshold voltage shift and the radiation dose. The densities of radiation-induced fixed and switching traps were determined from the sub-threshold I-V characteristics using the midgap technique. It was shown that the creation of fixed traps is dominant during the irradiation. The possible mechanisms responsible for the fixed and switching traps creation are also analyzed in this paper.

Key words: VDMOSFET, gamma ray irradiation, threshold voltage shift, radiation dose

INTRODUCTION

The attention of today's research on the impact of ionizing radiation on MOSFET is directed in two ways. The first one is the production of MOSFET with the highest possible resistance to the ionizing radiation (the radiation hardness), while the other is toward the ionizing radiation sensors and dosimeters production. The radiation sensitive MOSFET can be used to estimate the ionizing radiation absorbed dose by measuring in the threshold voltage (V_T) [1, 2]. The *p*-channel MOSFET, also known as the Radiation Sensitive Field Effect Transistors (RADFET) or pMOS dosimeters, were used in many application areas, such as the space radiation measurements, high energy physics experiments, radiotherapy and personal dosimeter for military applications [3-6]. Using the RADFET for radiation dose measurements has certain positive aspects, such as the immediate and non-destructive readout, the low power consumption, an easy calibration and a reasonable sensitivity and reproductability [7].

In recent years, many investigations were driven toward the application of low-cost commercial *p*-channel MOSFET as a dosimeter in radiotherapy [8, 9]. The authors of these papers concluded that the *p*-channel power MOSFET 3N163 and DMOS BS250F, ZVP3306 and ZVP4525 would be an excellent candidate for low-cost systems capable of measuring the gamma and the electron beam dose.

A comparative study of the RADFET manufactured by Tyndal National Institute, Cork, Ireland, with the 100 nm gate oxide layer thickness and the commercial *p*-channel VDMOSFET IRF9520 sensitivity to the gamma-ray irradiation in the dose range from 100 to 500 Gy is given in the paper [10]. The results demonstrate a linear dependence between the threshold voltage shift ΔV_T and the radiation dose D for components with 10 V gate bias during the irradiation. The experimental results of $\Delta V_T = f(D)$ dependence for components irradiated without the gate bias can be very well described by the exponential function. It was also shown that the VDMOSFET sensitivity is greater than the RADFET sensitivity for this dose interval.

The numerous investigations have shown that the ionizing radiation leads to the creation of electron-hole pairs. A field-dependant fraction of them escapes the initial recombination, leading to a further rapid electron movement toward the gate electrode, while the holes move slowly toward the SiO_2/Si interface. A part of these holes is trapped in the oxide, leading to the accumulation of positive trapped charge, whose trapping rate depends on the gate bias (the ap-

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plied field), the number of empty traps and their capture cross-section [11-13]. The interface trap generation is commonly accepted to be associated with the intermediate processes involving the holes capture, the release and the migration of hydrogen ions in the oxide [14, 15]. With the respect to the influence of these defects on the charge carriers in the MOS transistor channel, they can be divided into fixed traps (FT) and switching traps (ST) [16] or border traps. The FT represents the traps created in the oxide that do not capture the carriers from the channel. The ST represents the traps created near and at the Si/SiO_2 interface and they do capture (communicate with) the carriers from the channel within the electrical measurement time frame. The ST created in the oxide near the Si/SiO_2 interface is called the slow switching traps (SST), but the ST created at the interface is called the fast switching traps or the true interface traps [17].

The contribution of FT (ΔV_{FT}) and ST (ΔV_{ST}) to the total threshold voltage shift ΔV_T is [18]

$$\Delta V_T \quad \Delta V_{FT} \quad \Delta V_{ST} \qquad (1)$$

Both FT and ST contribute to the increase in ΔV_T for pMOS transistors. On the other hand, the areal density of FT, ΔN_{FT} and the areal density of ST, ΔN_{ST}, of irradiated transistors could be determined as [18]

$$\Delta N_{FT} \quad \frac{C_{ox}}{q}\Delta V_{FT}, \quad \Delta N_{ST} \quad \frac{C_{ox}}{q}\Delta V_{ST} \qquad (2)$$

where C_{ox} is the capacitance per unit area and q the absolute value of electron charge.

The aim of this work was to investigate the sensitivity of commercial *p*-channel power VDMOSFET to gamma-rays originating from ^{60}Co for radiation dose in the 10 to 100 Gy interval. The influence of induced fixed and switching traps to the threshold voltage shift without and with the gate bias during the irradiation is also analyzed.

EXPERIMENTAL DETAILS

The experimental samples were the commercial *p*-channel power VDMOSFET, IRF9520, manufactured by the International Rectifier encapsulated in the standard TO-220 casing. According to the catalog specifications, the drain to the source breakdown voltage V_{DSS} is 100 V, the maximum conduction resistance is 0.6 and the maximum drain current at room temperature is 6.8 A. The additional testing have proven that the breakdown voltage and the conduction resistance match the catalog data, and that the corresponding chip size of 1.5 mm^2 further matches the specified current. In addition, the IRF9520 consists of 1650 cells and the total effective area over epi p^- layer is 11.61 10^{-3} cm^2 and the nominal oxide thickness is 100 nm [19]. The initial threshold voltage value of the virgin devices was V_{T0} –3.6 V. The two half-cells cross-section is presented in fig. 1. Note that the bulk region is internally connected to the source region over the common contact.

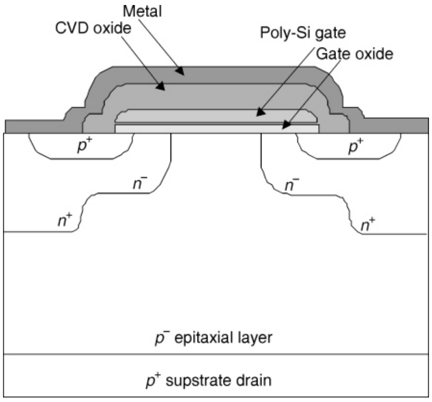

Figure 1. Cross-section of power VDMOSFET

The power VDMOSFET samples were irradiated using the ^{60}Co beam in the absorbed radiation dose range from 10 Gy to 100 Gy at the absorbed dose rate 0.02 Gy(SiO_2)s^{-1}. The irradiation was performed in the Secondary Standard Dosimetry Laboratory of Vinca Institute of Nuclear Sciences, Belgrade, Serbia. All measurements were conducted in a climate controlled environment with an ambient temperature of 20 0.2 °C . The irradiation was conducted for samples without the gate bias (V_{irr} = 0 V), *i. e.*, all terminals were shortened together and with the gate bias of V_{irr} = 5 V. In order to monitor the progress of gamma beam degradation, the radiation was interrupted at some point to measure the devices sub-threshold and the transfer characteristics in saturation using the Keithley model 4200 semiconductor characterization system. The system is equipped with the three medium power source measuring units. The units have four voltage ranges: 200 mV, 2 V, 20 V, and 200 V, while the current ranges are 100 nA, 1 A, 100 A, 1 mA, 10 mA, and 100 mA. One of the source measuring units is equipped with pre-amplifier which provides the measurements of very low currents (order of 1 pA).

The threshold voltage shift was estimated at the intersection between the V_G axis and the extrapolated linear region of the $(I_D)^{1/2} – V_G$ curve (I_D is the drain current and V_G is the gate voltage). The threshold voltage shift ΔV_T can be expressed as $\Delta V_T = V_T – V_{T0}$, where V_{T0} is the threshold voltage before the irradiation, and V_T after the irradiation. The densities of radiation-induced FT, ΔN_{FT} and ST, ΔN_{ST} were determined using the midgap technique of McWhorter and Winokur [20]. This technique is based on the fact that the FT influences the carriers in the channel by the electric field, and does not have the ability to capture them. The ST captures the carriers from the channel in the framework of subthreshold/transfer characteristics measurements, and the ST influence on the channel carriers by the electronic field is neglected. In this way, the influences of FT and ST on the transfer subthreshold characteristics in saturation are in their parallel shift and their slope changes, respectively.

The absolute value of FST density (the absolute value of the true interface trap density) can be determined using the charge pumping technique [21, 22]. The results performed for RADFET have shown that the FST density obtained by this method is considerably smaller than the one obtained by the midgap technique [23]. This is due to a fact that the midgap method, besides the FST, can also register a part of SST located very closely to the Si/SiO$_2$ interface. It was also shown that the ST density is much smaller than the FT density obtained by the midgap technique. On the basis of such RAFET behavior it was concluded that the dominant impact to ΔV_T during the irradiation is played by the increase in the oxide trapped charge density (FT density).

RESULTS AND DISCUSSION

The VDMOSFET IRF9520 transfer characteristics in saturation before the irradiation (curve 0) and after the radiation dose D of 50 and 100 Gy (curves 1 and 2) for gate bias during the irradiation $V_{irr} = 5$ V are shown in fig. 2. The fitting of the upper part of $(I_D)^{1/2} - V_G$ characteristics, which are linear, gives the values of threshold voltage V_{T0}, V_{T1}, and V_{T2} and these values increase with the increase of D. The similar behavior of characteristics is observed for $V_{irr} = 0$ V.

Figures 3(a) and 3(b) display the dependence between the threshold voltage shift (ΔV_T) and the radiation dose (D) for gate bias during the irradiation $V_{irr} = 0$ V and $V_{irr} = 5$ V, respectively. The contributions of fixed traps to the threshold voltage shift (ΔV_{FT}) and the contribution of switching traps (ΔV_{ST}) to the total threshold voltage shift are presented in the same figures. It can be seen that the FT influence on the threshold voltage is predominant ($\Delta V_{FT}/\Delta V_{ST} > 95$ %). It can be concluded that during the irradiation, the IRF9520 shows similar behavior as the RADFET [23], *i. e.*, the ST density makes an insignificant impact to ΔV_T value.

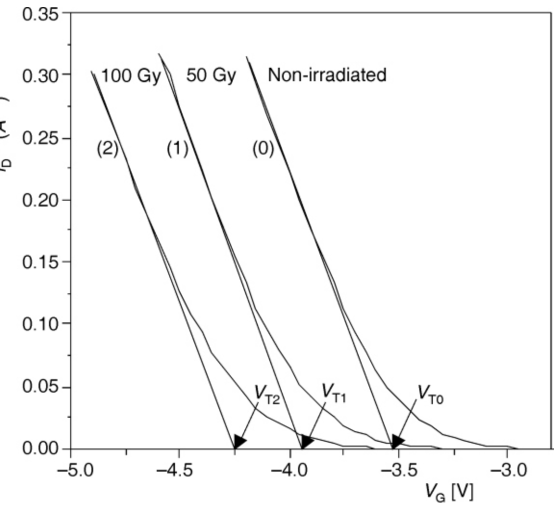

Figure 2. The transfer characteristics in saturation before and after the irradiation for 50 and 100 Gy doses. The V_{T0}, V_{T1}, and V_{T2} represent the threshold voltage values before and after the irradiation with 50 and 100 Gy, respectively; the gate bias during the irradiation $V_{irr} = 5$ V

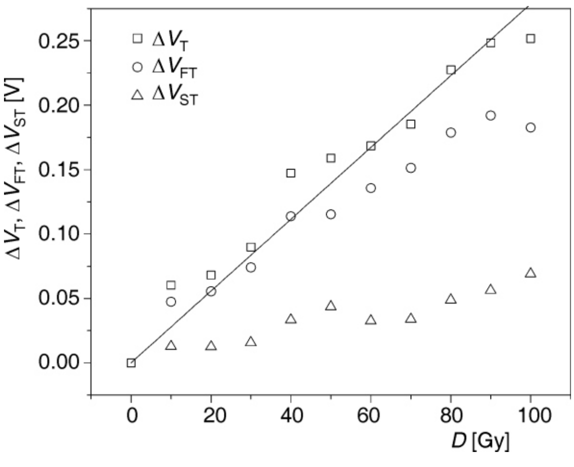

Figure 3(a). The contribution of FT (ΔV_{FT}) and ST (ΔV_{ST}) to the total threshold voltage shift (ΔV_T) for radiation dose from 10 to 100 Gy, for gate bias during the irradiation $V_{irr} = 0$ V

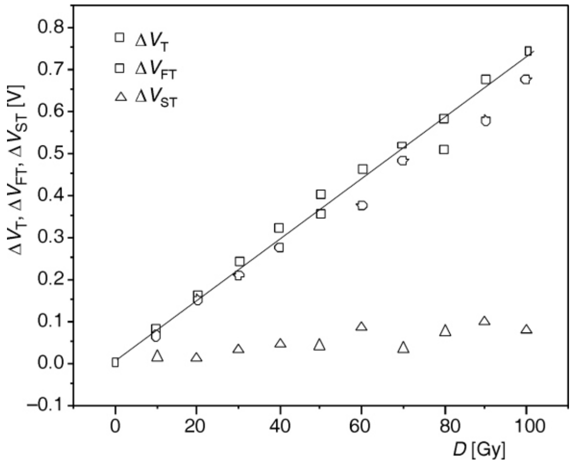

Figure 3(b). The contribution of FT (ΔV_{FT}) and ST (ΔV_{ST}) to the total threshold voltage shift (ΔV_T) for radiation dose from 10 to 100 Gy, for gate bias during the irradiation $V_{irr} = 5$ V

In order to establish the possible application of p-channel power VDMOSFET IRF9520 as the sensors of ionizing radiation, the experimental results, $\Delta V_T = f(D)$ are fitted with three different models. The first one is a linear function, $\Delta V_T = AD$, where A is a constant. The second model represented is so called the power law function, $\Delta V_T = AD^n$ where A and n are the constants. The third model is a standard exponential function, $\Delta V_T = Ae^{-D/b} + c$, where A, b, and c are constants. The values of correlation coefficients for all three models for samples without the gate bias and the 5 V gate bias during the irradiation are presented in tab. 1.

From the data presented in tab. 1 it can be assumed that the power law function model is the best

Table 1. Values of adjuster R-squared for V_{irr} = 0 V and V_{irr} = 5 V

Model	Adjusted R-squared V_{irr} = 0 V	Adjusted R-squared V_{irr} = 5 V
Linear function	0.945	0.996
Power law function	0.979	0.998
Exponential function	0.975	0.997

Table 2. AIC test results for V_{irr} = 0 V and V_{irr} = 5 V

Model	AIC V_{irr} = 0 V	AIC V_{irr} = 5 V
Linear function	–82.297	–89.395
Power law function	–90.316	–92.927
Exponential function	–84.055	–83.807

one for describing the experimental data. It can be also concluded that all three models very well describe the experimental data for samples irradiated with gate bias V_{irr} = 5 V. In order to verify the mentioned assumption, the Akaike information criterion test was performed on all of the three proposed models. The Akaike information criterion (AIC) is a measure of the relative quality of the statistical models for a given set of data. Given a collection of models for the data, AIC estimates the quality of each model, relative to each of the other models. Hence, the AIC provides means for model selection. The results of AIC test on all three models are presented in tab. 2 both for samples irradiated with 0 V and 5 V gate bias.

From the data presented in tab. 2 it can be concluded that the previous assumptions were correct, and that the Power law model best describes the experimental data in both cases of gate bias. On the basis of data from tab. 1, it can be concluded that the IRF9520 can be implemented as the gamma irradiation sensors. Because the linear dependence is established between the ΔV_T and D, for samples with gate bias during the irradiation, fig. 3(b), their sensitivity, $S = \Delta V_T/D$ is the same in radiation dose range from 10 to 100 Gy. This makes them suitable for dosimetry applications. For samples irradiated without the gate bias, the linear dependence cannot be established, what makes their application in dosimetry inappropriate due to the variation in sensitivity for different radiation doses range.

The comparison between the ΔV_T results for VDMOSFET IRF9520 and RADFET with 100 nm gate oxide thickness [24] for 10 to 50 Gy dose interval show that the VDMOSFET sensitivity is some higher than the RADFET. This could be a consequence of different technologies used for VDMOSFET and RADFET production. This proves that the commercial VDMOSFET, with relatively low price, can be used as a replacement for RADFET, with the same oxide thickness in dosimetry in the dose range from 10 to 100 Gy.

Figures 4 and 5 present the change in the areal density of FT, ΔN_{FT} and ST, ΔN_{ST}, respectively, for V_{irr} = 0 V and V_{irr} = 5 V. As expected, the increase in radiation dose leads to the increase in both ΔN_{FT} and ΔN_{ST}. Such increase is more intense for V_{irr} = 5 V than for V_{irr} = 0 V. It can also be seen that ΔN_{ST} is for about order of magnitude smaller than the ΔN_{FT}, which proves that the ΔN_{FT} predominantly contributes to the ΔV_T increase during the irradiation. Considering this, we will focus only on the defects that lead to the creation of positive trapped charge during irradiation. The model that explains the formation of these defects is proposed by Lelis and coworkers (HDL model) [25-27]. A crucial role in this model belongs to the E'_γ center, which is a weak Si-Si bond in the oxide caused by an oxygen atom vacancy between the two Si atoms, each back-bonded to three oxygen atoms. The E'_γ center acts as a hole trap and it is predominantly responsible for the increase in positive trapped charge during the irradiation. The E'_γ centers are formed in the oxide and near the Si/SiO$_2$ interface. They represent the FT centers in the oxide, while the centers near the Si/SiO$_2$ interface represent the SST. For V_{irr} = 0 V electric field in the oxide is only due to the work function difference between the gate and the substrate (the

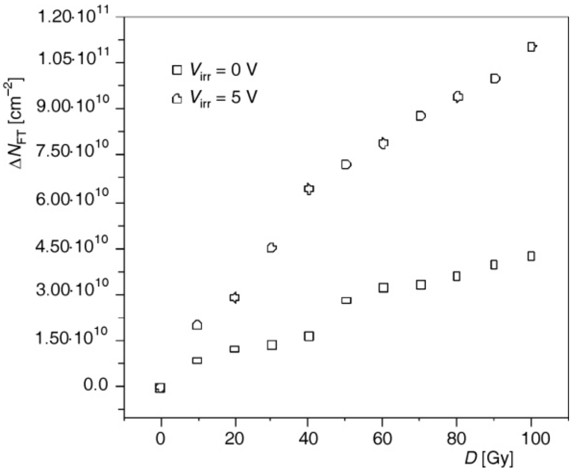

Figure 4. The change in the areal density of fixed traps, (ΔN_{FT}) as a function of radiation dose, (D), without (V_{irr} = 0 V) and with the gate bias during the irradiation (V_{irr} = 5 V)

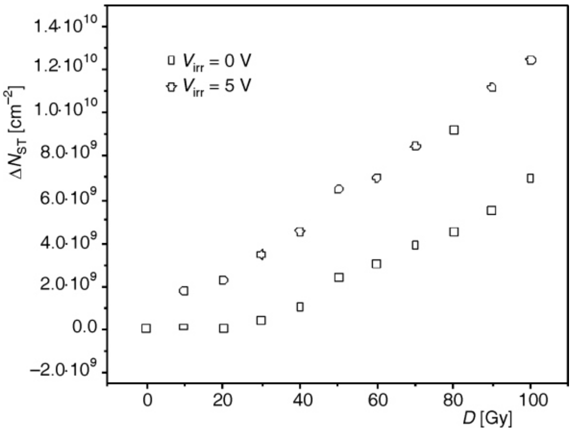

Figure 5. The change in areal density of switching traps, (ΔN_{ST}) as a function of radiation dose, (D), without (V_{irr} = 0 V) and with the gate bias during the irradiation (V_{irr} = 5 V)

zero-bias conditions is equal to the gate bias of 0.3 V), so the probability for the electron-hole recombination is higher than in the case when $V_{\mathrm{irr}} = 5$ V. Namely, for $V_{\mathrm{irr}} = 5$ V the large number of holes will escape the initial recombination, what further increases the probability for their capture at the E'_{γ} centers. This further leads to the increase in the positive charge in the oxide and the interface states. Such conclusion is in agreement with the results shown in fig. 4.

CONCLUSIONS

In order to verify the possible application of commercial power VDMOSFET IRF9520 as gamma radiation sensors, the threshold voltage shift was monitored in the radiation dose interval from 10 to 100 Gy. In order to confirm the possible application of VDMOSFET in the dosimetry, three different models were used to establish the dependence between the threshold voltage shift ΔV_{T} and the radiation dose D – the linear function, the power law function and the exponential function. Based on the adjusted R-squared values and the Akaike criteria, it was concluded that the power law function is the best for describing the experimental data, *i. e.*, exponential function and linear function are the least likely to be used in experimental data verification. However, for practical application, the linear function is the most important. The linear dependence between the threshold voltage shift and the radiation dose D when the gate bias during the irradiation was shows that the sensitivity is the same for the whole considered dose interval and hence, the biased VDMOSFET can be used in dosimetric applications. Such behavior is the crucial criteria for transistor application in the dosimetric applications. It was verified that the sensitivity of these components is higher than the specially designed radiation sensitive field effect transistors (RADFET) sensitivity, with the 100 nm gate oxide thickness, manufactured by the Tyndall National Institute, Cork, Ireland [24]. During the irradiation, similar as for the RADFET, the dominant role in the threshold voltage shift is played by the positive trapped charge, which density is in order of magnitude higher than the interface traps density. Such behavior proves that the VDMOSFET IRF9520 can be used as sensors of the gamma radiation for dose interval from 10 to 100 Gy.

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AUTHORS' CONTRIBUTIONS

The theoretical and experimental analysis carried out by M. D. Obrenović and M. Pejović. The calculations were carried out by M. D. Obrenović. All authors analysed and discussed the results. The manuscript was written by M. D. Obrenović, and the figures were prepared by M. I. Pejović.

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ЕФЕКТИ ИЗАЗВАНИ ГАМА ЗРАЧЕЊЕМ ОДГОВОРНИ ЗА ПОМЕРАЈ НАПОНА ПРАГА КОМЕРЦИЈАЛНИХ *P*-КАНАЛНИХ СНАЖНИХ VDMOSFET ТРАНЗИСТОРА

Истраживан је померај напона прага комерцијалних *p*-каналних снажних VDMOSFET-а током озрачивања гама зрачењем у опсегу доза од 10 до 100 Gy. Озрачивање је урађено без присуства напона на гејту као и са напоном на гејту од 5 V. Показано је да постоји линеарна зависност између помераја напона прага и абсорбоване дозе зрачења за компоненте код којих је напон на гејту током озрачивања износио 5 V. Густине фиксних и променљивих центара захвата су одређиване из потпраговских I-V карактеристика коришћењем мидгап технике. Показано је да се током озрачивања формира знатно већа густина фиксних центара захвата. Такође су анализирани могући механизми одговорни за формирање фиксних и променљивих центара захвата током озрачивања.

Кључне речи: VDMOSFET, гама зрачење, промена напона прага, апсорбовна доза