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Effect of gamma ray absorbed dose on the FET transistor parameters

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ABSTRACT

This article tries to explain a modified method on dosimetry, based on electronic solid state including MOSFET (metal oxide semiconductor field effect) transistors. For this purpose, behavior of two models of MOSFETs has been studied as a function of the absorbed dose. The MOSFETs were irradiated at room temperature by ^{137}Cs gamma ray source in the dose range of 1–5 Gy. Threshold voltage variation of investigated samples has been studied based on their transfer characteristic curves (TF) and also using the readout circuit (RC). For evaluation of laboratory samples sensitivity at different operating conditions, different biases were applied on the gate. In practical applications of radiation dosimetry, a significant change occurs in the threshold voltage of irradiated MOSFETs. And sensitivity of these MOSFETs is increased with increasing the bias values. Therefore, these transistors can be excellent candidates as low-cost sensors for systems that are capable of measuring gamma radiation dose.

Introduction

Radiation dosimeters consist of a variety of devices; such as ionization chambers, thermoluminescence crystals (TLDs) and the metal oxide field effect (MOSFET) semiconductor transistors [1,2]. As a dosimeter, the semiconductor transistors can be used either in active or in passive mode [3]. In the active mode the MOSFET needs to be biased but in the passive mode it does not need any bias voltage. In the first case, the relevant dosimetry parameter is dose rate which is correlated with produced electric current [4]. But in the second case the dosimetric quantity corresponds to the absorbed dose which is correlated with the variation of a given physical parameter such as threshold voltage for the MOSFET [5–8].

Radiation dosimetry using MOSFETs, was first proposed in 1974 by Holmes-Siedle [9]. Since then, the MOSFETs mainly have been used in space-charge radiation dosimetry for detecting radiation effects on the earth orbiting satellites [10]. In recent decades, the MOSFET transistors have become increasingly popular dosimeters in the radiation therapy including LINAC IMRT, brachytherapy and micro beam radiation therapy (MRT) [11–14].

The MOSFET dosimeters are in widespread use due to their various advantages such as: immediate and non-destructive readout of dosimetry information, low power consumption, easy calibration, reasonable sensitivity and reproducibility, miniature dimensions of the sensor element, a relatively wide dose range, compatibility with microprocessors and competitive price [4,15–17]. Because of these benefits, the MOSFET dosimeters have found application in many fields over a dose range, varying from 10^{-3} rad up to 10^{7} rad [18].

Ionizing radiation leads to degradation of the *I–V* characteristic ($I_{DS} - V_{GS}$) of the MOSFETs [3,19,20]. This reduction has been done by creating electron and hole pairs in the oxide layer of the transistor [21]. Several electrical parameters of the transistor will be affected by this reduction. The holes that have lower mobility than the electrons are gradually deflected toward the Si-SiO$_2$ interface where they get trapped. The positive charge built up (Q_T) leads to significant changes in the MOSFET's channel current and hence to shifts in threshold voltage [9]. The channel current is very sensitive to the Q_T charges, because they are physically localized very close to the channel. Therefore, the threshold voltage shift will be a direct measure of the absorbed dose in the oxide layer.

The main function of the MOSFET dosimeters is to convert the threshold voltage shift to the absorbed dose. These two quantities are related by:

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

where *A* is a constant, *D* is the absorbed dose and *n* is the degree of linearity. The *n* depends on factors like the voltage applied to the gate during the irradiation, the thickness of the oxide layer and on the absorbed radiation dose [22,23]. A linear dependence ($n = 1$) is more preferable and in this case the parameter A directly refers to the MOSFET sensitivity.

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In the last decades, with rapid developments in the relevant technology, several dosimetry systems (known as RADFET) are made using MOSFETs as radiation detectors [24,25]. They are designed especially with thicker gate oxide to operate without any external connection during irradiation and high positive gate bias to ensure the good separation of electron–hole pairs and to increase the radiation sensitivity [26]. These systems are reliable and accurate, but in comparison with commercial MOSFETs they are expensive. However, the use of the MOSFET dosimeters in the unbiased mode is more beneficial due to their easy and inexpensive implementation [23,27]. There are many papers about the advantages of using MOSFET dosimeters with different types of transistors and radiation fields, dose ranges, readout circuits, and irradiation configurations [22,25,28–34]. For example, Martínez-Garcíaa et al. investigated the application of the (P-type) MOSFET dosimetry for 6 MeV electron beam and used a portable readout system [35,36]. Asensio et al. studied the MOSFET performance as dosimeter, without any bias voltage on the transistor terminals, and in the 5–58 Gy dose range [37]. Carvajal et al. discussed the challenges and strategies to reduce temperature effect on the MOSFET response to radiation [38]. Their results are based on both Monte Carlo simulation and measurement in the clinical and laboratory environments and include sensitivity of the MOSFETs to radiation dose from 5 Gy to several tens of Gy.

It appears from the aforementioned studies that numerous investigations have been carried out on the dosimetric potential of the MOSFET transistors. However, no attempt was made to find an optimum read out method. This paper, on the other hand, compares two dose readout methods for p-type MOSFETs in the lower level of absorbed dose. For this purpose, two types of MOSFETs have been irradiated whit ^{137}Cs radiation source. The dose response characteristics of these MOSFETs were studied as a function of the absorbed dose. The linear behavior, sensitivity and the threshold voltage shift were examined for the selected transistors. Two readout methods were used based on the transfer characteristics (TF method), and the read out circuit (RC method). Then the results of both methods were compared together. In order to investigate the gate polarization effects, sensitivity of the experimental samples was studied for different gate biases and operating conditions. The results suggest that the dose rate measured by the studied transistors can be effectively readout using the RC method. To our knowledge, for these transistors, there is no report on using the RC method for reading the absorbed dose in the 1–5 Gy range.

Materials and methods

MOSFET selection

To find a cheaper alternative to the RADFET it is necessary to investigate the effect of radiation on the commercial MOSFETs. There is a huge variety of the MOSFETs at markets with different structures and configurations. For studying commercial MOSFET's response to gamma radiation the first step is to select the most sensitive MOSFET.

Both trapped holes and interface state charges are involved in threshold voltage shifts. These are in the same direction in the p-type of MOSFETs (PMOSs) and in the opposite direction in the n-type MOSFETs (NMOSs). In NMOSs the positive oxide trapped charges decrease the threshold voltage shift but the interface trappings increase the threshold voltage shift of the transistor that compensate the effect of each other. Both trapped positive oxide charges and interface states increase the absolute value of threshold voltage variations in PMOSs. Namely the PMOS threshold voltage variations are happening in the same direction that the absolute value of the dose occurs.

In addition, in PMOSs there is a one-to-one correspondence in the threshold voltage and the absorbed dose. But in the NMOSs a same threshold voltage may correspond to two different doses. Using those considerations, the PMOSs are preferred more than NMOSs for dosimetry purpose. For dosimetry purposes, germanium chips are not so interesting because of their large effective atomic number compared with biological tissue [39].

As far as we know, the best commercially available transistors for radiation dosimetry have the following properties: (1) maximum oxide layer thickness, (2) manufactured with standard low power enhancement mode, (3) free from parasitic structure, and (4) lateral pMOS technology. Most of the vertical transistors have a high voltage protection diode that acts as a parasitic device which diminishes the radiation sensitivity. Nevertheless, few recent studies have considered vertical transistors designed for small signal, having no metal encapsulation and the maximum gate-source voltage [35,37]. The thickness of the oxide layer is rarely given in the data sheets by the manufacturers. Since the absolute value of maximum gate-substrate voltage (V_{GB}) is directly related to the thickness of the oxide layer, we considered the maximum gate-substrate voltage before breakdown. Taking all criteria together we selected 3N163 (manufactured by Vishay-Siliconix) and ZVP3306 (manufactured by Diodes Incorporated) transistors. Before irradiation, the experimental samples were grouped according to their similar electronical specifications.

Irradiation

The MOSFET polarization during irradiation is an important factor which seriously affects the sensitivity of the radiation dosimeter. A MOSFET can be irradiated either in a biased (polarized) or in an unbiased (non-polarized) mode. In the biased mode, a positive voltage is applied between the gate and body that increases the electric field in the oxide and reduces the recombination probability of the electron–hole pairs created by radiation. In the unbiased mode, during irradiation, all terminals are short circuited together [40,41]. Using a MOSFET dosimeter without any bias during exposure is an excellent choice for many applications, including set up adjustments related to radiation therapy for in vivo applications. However, in this case, the sensitivity and the linearity of sensor are both much less than that of the biased mode.

As already mentioned, the electron–hole pairs created in the SiO_2 layer are separated by the electric field within the layer. The threshold voltage is again proportional to density of the surface charge generated by radiation. The charge density is proportional to the energy localized within the oxide. Therefore an increment in the threshold voltage would be directly proportional to the dose absorbed in the oxide layer. MOSFETs were irradiated by ^{137}Cs gamma ray source perpendicular to the gate at room temperature in the dose range of 1–5 Gy. To ensure electronic equilibrium conditions, one centimeter of solid water was placed above the transistors. For irradiation purpose, twenty selected MOSFETs were divided into four test groups. During gamma ray exposure, the first group of transistors was short circuited and other groups were biased with a +5, +8, +10 V on the gate, respectively.

Selection of a dosimetry parameter and dose read out

In MOSFET transistors, depending on the dose range and dosimetry application, various parameters can be used to quantify the radiation dose. After irradiation, a dosimetry parameter can be measured by different methods [42,43]. The theoretical basis of the measurements has been reported in previous work [44]. The most commonly used technique is based on measuring the threshold voltage shift according to Eq. (1). The threshold voltage shift is influenced by both types of the generated charges, fixed oxide charges and interface traps [23]. In this paper, we present two different readout methods that can be used to measure the threshold voltage shift in MOSFETs. One is based on extrapolation of the linear region of transfer characteristic curve. In the other method a read-out circuit is used to obtain the threshold voltage.

The transfer characteristic curve (TF method)

For each transistor the transfer characteristic curve (I_{DS}–V_{GS}) was obtained using a semiconductor parameter analyzer WQ4832 model before and after irradiation. To establish proper transistor polarization, these curves were extracted in the saturation regime, with the gate and drain shorted together [45]. The V_T could be determined as the intersection between V_G-axis and the extrapolated linear regions of the $(I_{DS})^{1/2}$–V_{GS} curve that are modeled by [45].

$$I_{DS} = \frac{\beta}{2}(V_{GS} - V_T)^2 \tag{2}$$

This measurement technique, is more complex than the measurements at constant drain current which is used in commercial dosimeters. The TF method is effective, however the required parameter analyzer equipment is relatively expensive, and an alternative approach would be more beneficial.

Readout circuit (RC method)

As an alternative to the TF method, it is also possible to use a readout circuit (RC) for measuring the shift in the threshold voltage. A schematic diagram of the readout circuit has been shown in Fig. 1. This configuration provides fast readout of the threshold voltage without any complicated electronic or logic circuits around the MOSFET. In the readout circuit, the gate and drain are connected together and body is connected to source. In this case the MOSFET is operated as a two-terminal device. A constant current is applied to the source and bulk connection while the gate and drain are grounded.

Using the reader circuit, an increase in the drain-source voltage can be measured at constant drain current [42]. Under these circumstances, a shift in the drain-source voltage would be roughly equal to the threshold voltage. In order to reduce the temperature effect, the drain current must be set to the zero temperature coefficient current (I_{ZTC}). In this case the temperature dependence of drain-source voltage cancels out. The use of reader circuit configuration provides a quick measurement of threshold voltage and it minimizes the temperature sensitivity of the readout. In order to minimize thermal drift and to avoid fading effect, we used thermal drift reduction method by applying I_{ZTC} for 3N163 transistors. As reported in the literature [38] the I_{ZTC} value for this transistor is 225 μA. Therefore, we measured the V_{GS} voltage at I_{ZTC} = 225 μA. Due to the presence of the parasitic diode in the ZVP3306 transistor, there is no crossing point in the *I*–*V* curves of this type of the transistor [35]. When the I_{ZTC} value is not available, it is a common practice for researchers to adopt a drain current of 10 μA [26]. But careful attention still must be paid to the thermal drift in the measurement with these transistors. For example, one should reduce the time interval between irradiation and V_T measurements and also eliminate any possible thermal shock.

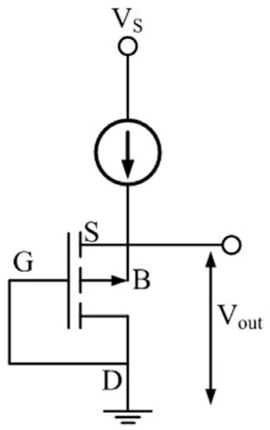

Fig. 1. Electronic scheme of reader circuit (RC).

Results

Threshold voltage shift

During gamma irradiation, different biases were applied on the gate of the MOSFET namely: +5, +8, +10 V (active mode) and 0 V (passive mode). The threshold voltage shifts measured by the two readout methods during gamma irradiation with various gate biases are depicted in Figs. 2 and 3. The absolute value of the threshold voltage shift increases linearly with radiation dose up to 5 Gy. The experimental error bars have been omitted for clarity but an average value of 1.1 mV. On the basis of these figures the voltage shifts obtained from TF and RC measuring methods agree very well, which confirm the functionality of the readout circuit. Due to the simplicity of readout circuit, the RC configuration is particularly suitable for practical applications and calibration measurements. The discrepancies between two methods were less than 1–2% in all cases.

The results presented on Figs. 2 and 3 clearly show good linearity between threshold voltage shift and absorbed dose. A similar behavior was observed by the TN-502DI MOSFET (Thomson-Nielson Electronic Ltd, Ottawa, Canada) [45].

Linear behavior of threshold voltage shift is required to confirm the linearity performance of the dosimeter. Achieving higher linearity is very hard even using the MOSFETs designed especially for commercial radiation dosimeter. As it can be seen, the changes of the threshold voltage are more pronounced in the case of active mode than in the case of passive mode. Moreover, the shifts of PMOS threshold voltages increase with increasing gate bias voltage. As expected, applying a positive voltage to the gate increases the density of positive oxide trapped charges, which in turn increases the threshold voltage shift of MOSFETs. The reason is a higher electric field in the oxide lowers the probability of the electron–hole recombination as a consequence of the bond breaking in the oxide. In the active mode, electrons leave the oxide more easily and they can be absorbed by the gate.

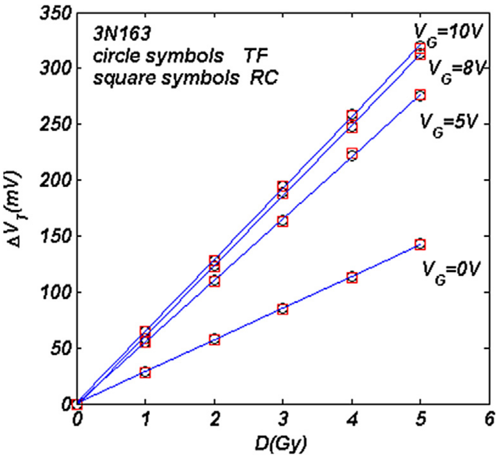

Fig. 2. Threshold voltage shift of 3N163 as a function of dose measured by TF and RC methods.

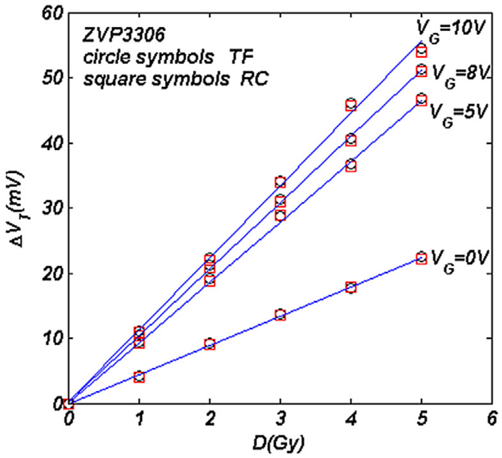

Fig. 3. Threshold voltage shift of ZVP3306 as a function of dose measured by TF and RC methods.

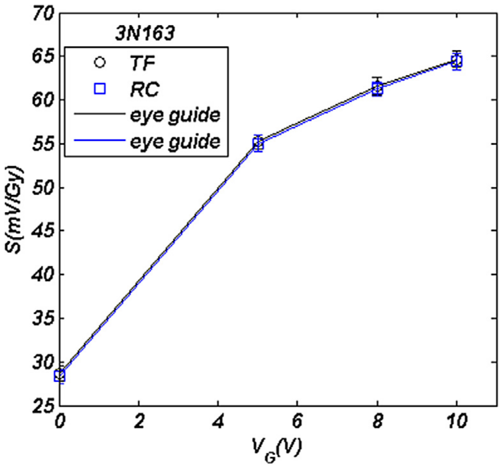

Fig. 4. Sensitivity of 3N163 measured by TF and RC methods. Symbols represent experimental data and error bars. The line shown for eye guided.

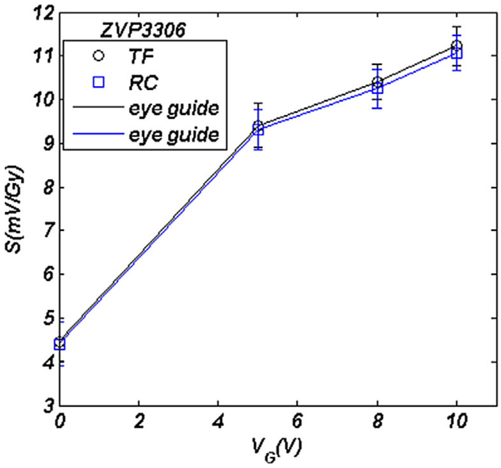

Fig. 5. Sensitivity of ZVP3306 measured by TF and RC methods. Symbols represent experimental data and error bars. The line shown for eye guided.

In case of unbiased MOSFETs, the electric field within the oxide is derived from only the work function difference between the gate and the substrate. In this case, the probability of electron–hole recombination is higher than the biased mode. During irradiation in the biased mode, a large number of holes will escape from the initial recombination, which causes more trapping of holes in the oxide and increasing oxide charge.

Sensitivity

Sensitivity is defined as the ratio of changes in the threshold voltage to absorbed dose.

$$S_V = \frac{\Delta V_T}{D} \tag{3}$$

Improving the sensitivity to radiation is one of the key issues in designing MOSFET's dosimetry sensors. This can be achieved by increasing the thickness of the gate oxide layer or by stacking more transistors [46,47]. The sensitivity depends on: the radiation energy, the electric field inside the oxide layer, transistor packaging, incident irradiation beam direction, the thickness of the oxide layer, the gate oxide grown, the electric field applied during the exposure, and the amount of energy absorbed (absorbed dose) [48,49]. In general, the thicker the oxide layer, the more sensitive is the dosimeter.

An appealing idea to produce a thick gate oxide layer is making a two-layer structure by the chemical vapor deposition (CVD) method. Most of the RADFETs are constructed in this way and they are expensive compared to the commercial MOSFETs. [25,50]. Therefore, the main idea is to find out sensitive and cheaper commercial MOSFETs, which can be used as a radiation dosimeter. Mean sensitivity values in terms of bias voltage are depicted in Figs. 4 and 5. As can be seen, from the figures sensitivity in the biased mode is greater than that in unbiased mode. We can conclude that the MOSFET's response to gamma radiation depends on the bias voltage. This means that an increment of the electric field during irradiation leads to considerable variation in threshold voltage. As a result, gate bias voltage determines the range of the absorbed dose. The improvement of sensitivity of 3N163 is almost linear function of the absorbed dose. Although, it starts to saturate close to 8 V, and the values of the sensitivity are higher than those of the ZVP3306 model. The averaged value of the ZVP3306 sensitivity is much lower than that of the 3N163. Thus, for photons dose measurements the 3N163 is better choice than ZVP3306. With the correct electronic amplification and the proper readout techniques, these MOSFETs in biased mode can be used for clinical control in radiotherapy, reducing the cost of the system and increasing control in the radiotherapy treatments.

Conclusions

In this paper we have shown that the commercially available low power lateral MOSFETs with enhancement mode, could be used as the sensors for radiation dosimetry. The production cost of the RADFET transistors is much higher than that of the MOSFETs. In view of the low production cost, designing a measurement system using the MOSFETs has obvious advantages.

Response of the evaluated chips to the gamma radiation was determined via two different readout methods based on the variation in threshold voltage and constant drain current measurement. The agreement between both readout methods is satisfactory in all cases. The comparison suggests the reader circuit is more desirable in practical applications. According to the results, MOSFETs show good linearity on their threshold voltage shift with radiation dose and are more sensitive to gamma radiation in the dose range of 1–5 Gy which would enable their efficient application for measuring low doses.

Compared to the unbiased mode, in the biased mode their sensitivity is significantly higher. In addition, well their sensitivity increases with increasing bias voltage. It can be concluded that in the mentioned doses range, the adequate response of these MOSFETs ensure effective use of them in dosimetry. Furthermore, as it was expected the threshold voltage shift to radiation shows good linear and reliable sensitivity for use of these MOSFETs as reliable dosimetry sensors. Considering the above results, our further study will focus on the MOSFETs for measuring low doses for a wide range of gamma rays.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.rinp.2016.07.003.

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