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# Investigation of sensitivity and threshold voltage shift of commercial MOSFETs in gamma irradiation

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**Abstract** This article is about the absorbed-dose-dependent threshold voltage shift of the MOSFET transistors. Performance of the MOSFETs has been tested in different gate voltages. Sensitivity of the transistors for 662 keV gamma ray is studied in 1–5 Gy dose range. It was found that for transistors irradiated in biased mode, significant changes in the threshold voltage occurred, and the sensitivity to gamma rays increased with the bias voltage.

**Keywords** Dosimetry · Gamma radiation · $^{137}$Cs · Active and passive mode · P-channel MOSFET · Threshold voltage

## 1 Introduction

Nuclear radiation dosimetry can be carried out with different devices such as thermoluminescence dosimeters (TLDs), gas chambers and semiconductor components [1–4]. A detailed survey of radiation dosimetry approaches and instrumentations is expressed in Ref. [1]. The TLDs, small and standard, are the most frequently used. Nevertheless, readout of the TLDs is time-consuming and destructive, and they are not appropriate for distant dosimetry. The semiconductor diodes are small but suffer from two main drawbacks. One is their small dosimetric response and the other is the need of high voltage. In the past decade, OSL (optically stimulated luminescence) dosimetry reappeared with promising advances [5–7], but it requires integration of optical and electronic components in the readout system, and dosimetry information disappears after readout.

However, efforts have been made in application of the metal-oxide semiconductor field-effect transistors (MOSFETs) in areas of dosimetry in space crafts, nuclear industry, skin dosimetry, personal dosimetry, clinical control, radiology and radiation therapy [2, 8–14]. MOSFETs are advantageous in their fast readout, accuracy, small volume, low power consumption, the ability to work without bias, suitable sensitivity and reproducibility, low cost and low radiation attenuation [15, 16].

MOSFETs are used as a switch or an amplifier. As a switch, when the gate voltage is lower than the threshold voltage the transistor turns off, otherwise it turns on. A low conduction channel can be established between the source and drain. The effective resistance of the channel is regulated by the bias voltage on the gate. To create this channel, a positive and a negative gate–source voltage ($V_{GS}$) need to be applied for the NMOS and the PMOS transistors, respectively. The absolute value of $V_{GS}$ should be greater than the threshold voltage. The channel carriers are electrons for NMOS and holes for PMOS. The $V_T$ for the NMOS and PMOS transistors are positive and negative, respectively.

When a MOSFET is exposed to gamma rays, a shift in the $V_T$ takes place. The principle behind the $V_T$ shift is the creation of electron–hole pairs by radiation in the oxide layer. This effect leads to a rise in the number of the holes trapped in the bulk and the interface of the $SiO_2$ layer. The $V_T$ shift, being proportional to the surface charge density, is

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proportional to the energy deposition in the oxide. Therefore, $\Delta V_T$ is a key factor in measuring the absorbed dose ($D$) by the MOSFET.

Asensio et al. [17] studied performance of the 3N163 PMOS irradiated in unbiased mode to accumulated doses of 5–58 Gy. In this paper, dosimetry application of commercially available 3N163 and ZVP3306A PMOS transistors is studied in dose range of 1–5 Gy by 662 keV gamma ray of $^{137}$Cs, at 20 mGy/s of dose rate and room temperature, in both biased and unbiased modes. The $\Delta V_T$ value is considered as a measure of the accumulated radiation dose. The extent of linearity in the threshold voltage shift of the transistors is studied. The results show that the appropriate sensitivity and very good linearity make this type of PMOS an excellent candidate for reliable dosimetry. The sensitivity analysis, as an important dosimetry factor, is performed at different PMOS biases.

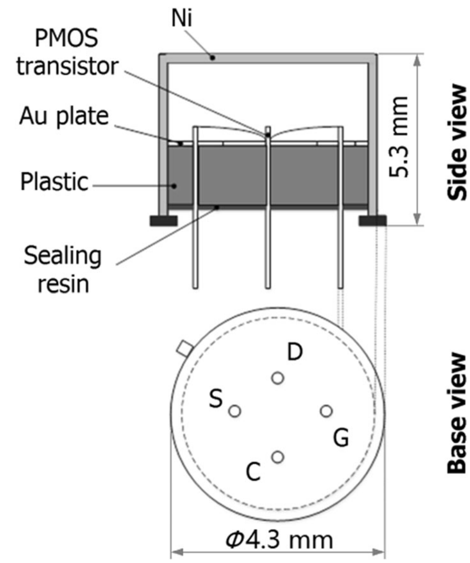


**Fig. 1** Schematic structure of the 3N163 transistor

## 2 Experimental section

### 2.1 MOSFET selection

A MOSFET dosimeter can be made in small sizes because no additional circuit is needed to read its accumulated dose. Also, it keeps the accumulated dose even when it is out of power, and the memorized dose can be readout after irradiation. Due to its small size and weight, MOSFET finds its dosimetry uses in nuclear industry, space crafts, robot systems and camera.

For p-type MOSFETs, there is a one-to-one relation between $V_T$ and $D$, while for n-type transistors one threshold voltage value can correspond to two different doses. For this reason, PMOSs are the preferred transistors for dosimetry purposes. Another advantage of PMOSs is that their threshold voltage always changes in one direction.

To investigate the possibility of using MOSFETs available commercially as gamma-ray dosimeter, the first step is choosing appropriate commercial MOSFETs. Most commercial MOSFETs include internal body diodes as parasitic devices. Since the protective diode in reverse bias reduces MOSFETs sensitivity to radiation, these MOSFETs are not suitable for low-dose measurement [18]. Another factor affecting the sensitivity of MOSFETs to radiation is thickness of the oxide layer, which is rarely given in the data sheets of the transistor by the manufacturers. Since the absolute maximum gate–substrate voltage ($V_{GB}$) depends on the $SiO_2$ layer thickness, we look into account the maximum gate–substrate voltage.

Based on the $V_{GB}$ information, ZVP3306A and 3N163 transistors are selected, which are shown schematically as an example in Fig. 1. For this transistor, maximum $V_{GB}$ is −125 V. The MOSFET is fixed on a dice of 0.3 mm by 0.3 mm surface, covered by a Ni cylinder of 0.4 mm wall thickness.

### 2.2 Irradiation arrangement

The threshold voltage shift, $\Delta V_T$, is frequently used as dosimetry parameter [19], and it is given by:

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

where $A$ is a coefficient, $D$ is the absorbed dose and $n$ is degree of linearity. The linearity depends on the voltage applied to the gate during exposure, absorbed radiation dose and thickness of the oxide layer. A linear dependence ($n = 1$) would be perfect, so the parameter $A$ would define the MOSFET sensitivity [20, 21].

The MOSFET sensitivity denotes changes in the threshold voltage per unit dose:

$$S_V = \Delta V_T / D. \tag{2}$$

The sensitivity of a PMOS dosimeter basically is affected by electric field in the oxide layer, radiation energy, the γ-ray beam incidence, packing of the transistor, thickness of the oxide layer, the absorbed dose and process of gate oxide growing.

To increase the radiation sensitivity, the MOSFETs are especially manufactured to have a thick oxide layer and hence greater detection volume [22]. This type of MOSFETs, known as RADFETs, is relatively high in price due to limited production. Evidently, the use of commercial MOSFETs will reduce the cost of a final dosimetry system [23, 24].

The sensitivity of a PMOS transistor is varied by altering either $V_{GS}$ or the gate oxide layer thickness. The sensitivity can be also improved by stacking multiple MOSFETs [25]. In general, the PMOS sensitivity for medical or personal dosimetry applications should be more than that of the nuclear and space industries. In the other words, the absorbed dose in the oxide layer of the PMOS dosimeter is affected by the composition, shape and thickness of the chip package [26–28].

The MOSFET transistors are irradiated in unbiased mode (passive) or biased mode (active). In the passive mode, no voltage is applied on the gate of a transistor and all terminals of the transistor are short-circuited together [29]. In the biased mode, a positive voltage is applied to the gate which leads to a quick charge collection. Consequently, the probability of electron–hole recombination decreases and the probability of charge trapping in the oxide layer increases, hence the increased sensitivity and linearity range for the PMOS dosimetry in the active mode. After irradiation, the variation of threshold voltage can be determined [30, 31].

Twenty MOSFETs of each type were divided into four groups of 5. They were irradiated to 1–5 Gy at 20 mGy/s and room temperature by 662 keV γ-ray of $^{137}$Cs. The γ-ray beam incidence was perpendicular to the oxide layer. Group 1 were irradiated in passive mode, while Groups 2–4 were irradiated in active mode, at 2, 5 and 8 V gate voltage for 3N163 and 5, 8 and 10 V for ZVP3306A. To reduce the dosimetry errors due to temperature variation, the threshold voltage was measured immediately after each irradiation. Then, for each group of MOSFETs, the mean threshold voltage changes were determined and the sensitivity of transistors in each group was calculated.

### 2.3 Extraction of dosimetry parameter

To obtain satisfactory dosimetry results, particular attention was paid to the absorbed dose reader and its corresponding readout electronics. In saturation region, the characteristic transfer curve of the MOSFET transistor is given by:

$$I_{DS} = \beta(V_{GS} - V_T)^{1/2}/2 \tag{3}$$

where $I_{DS}$ is the drain current and $\beta$ is a factor which depends on some material constants and the device size and geometry. The $I_{DS}$ and $V_{GS}$ were measured before and after irradiation using an analyzer of semiconductor parameters (WQ-4832, Wu Qiang Electronics, LTD, Hangzhou, China). The block diagram of a hardware module is shown in Fig. 2.

As illustrated in Fig. 3, the threshold voltages ($V_T$ and $V_{T0}$) were obtained on the $V_{GS}$ axis by extrapolating the linear region of the $I_{DS}^{1/2} - V_{GS}$ curves. To minimize drift effects, the $V_T$ was measured immediately after each irradiation.

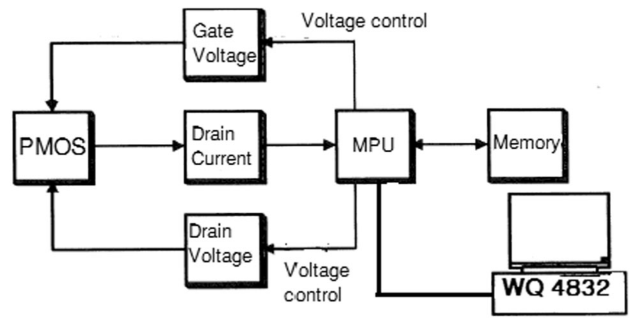


**Fig. 2** Block diagram for reading threshold voltage

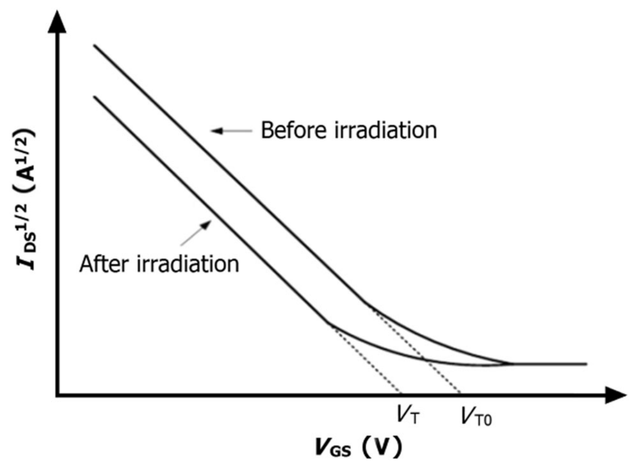


**Fig. 3** Typical current–voltage plots before and after irradiation showing schematically the irradiation effect

## 3 Results and discussion

Figure 4 shows that the absolute value of the threshold voltage shifts after irradiation. The threshold voltages were measured before and after each irradiation, and the characteristic curves were obtained from the measurements.

As can be seen from Fig. 4, the absolute value of the $V_T$ in every gate bias voltage increases with accumulated dose. At 0–5 Gy, the threshold voltage shift is directly related to the gate bias voltage. A linear relationship between the threshold voltage shift and the absorbed dose is preserved over the studied dose range. The linear relationship proves that the threshold voltage is an adaptable parameter for radiation dosimetry.

The linear relation between $\Delta V_T$ and $D$ can be clarified by the reality that the density of interface states increases the density of interface states and reduces the holes mobility through Coulomb interactions in the conduction

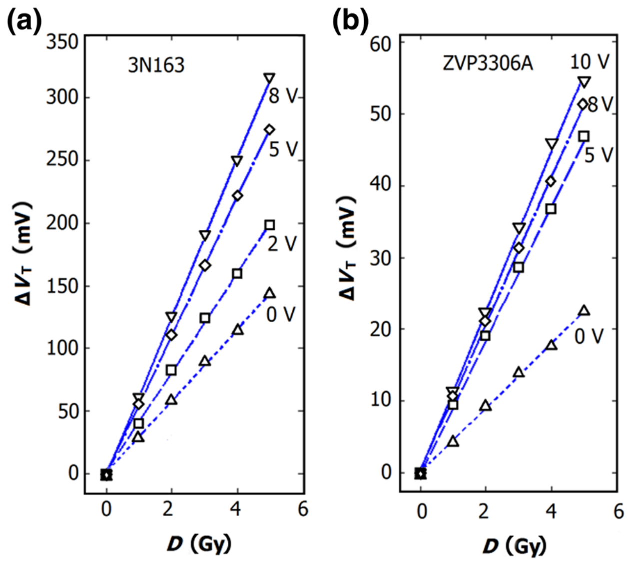


**Fig. 4** Measured threshold voltage shift as a function of the absorbed dose. The experimental data are fitted linearly

channel. The $V_T$ shift can be increased by the high-dose irradiation. The essential reason behind the $V_T$ shift should be the shifted flat-band voltage that comes from the interface trapped charges [32]. In Fig. 4, the slope of each line represents dosimetry sensitivity of the PMOS, which increases with the gate bias voltage and remains constant with accumulated dose. A similar response of RADFETs was reported in gamma irradiation from several tenths to several hundreds of Gy [20, 21, 33–36].

The bias-dependent sensitivity of the MOSFET can be explained in terms of electron–hole pairs: a higher bias voltage means a stronger electric field in the oxide layer; hence, the reduced recombination probability of electron–hole pairs formed by the radiation. And in a stronger oxide electric field, electrons can easily leave the oxide and be absorbed by the gate layer which gives rise to the interface trapping. This effect, in turn, causes an increase in the threshold voltage shift. Using linear behavior between threshold voltage shift and radiation dose for this type of commercial MOSFETs, low price and good dosimeters can be constructed.

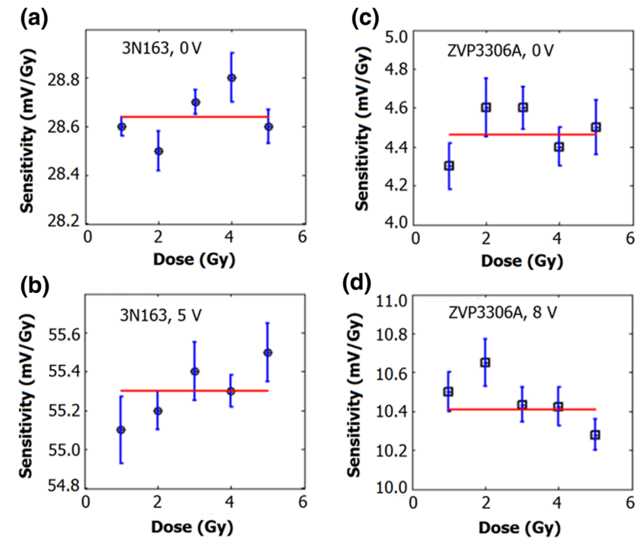


**Fig. 6** Sensitivity per session (*symbols*) versus accumulated dose. The *solid line* represents the mean sensitivity of experimental data

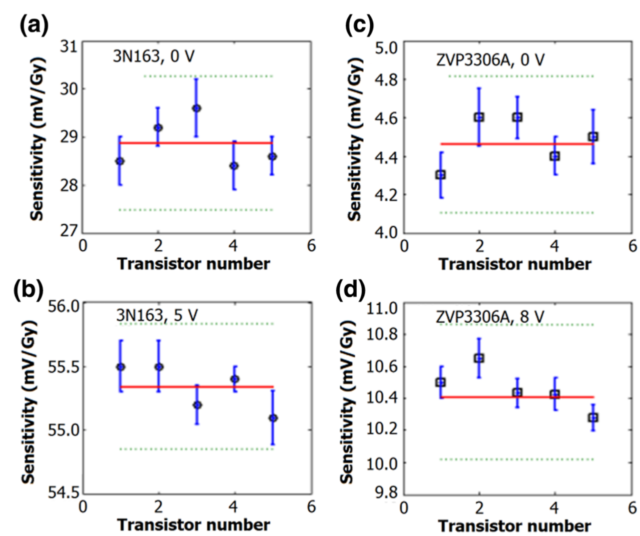


**Fig. 7** Transistor sensitivity versus transistor number. The *solid line* represents the mean sensitivity of experimental data

In the unbiased mode, the difference between work functions of the gate and substrate is the main reason of the electric field in the oxide layer. Therefore, in the unbiased

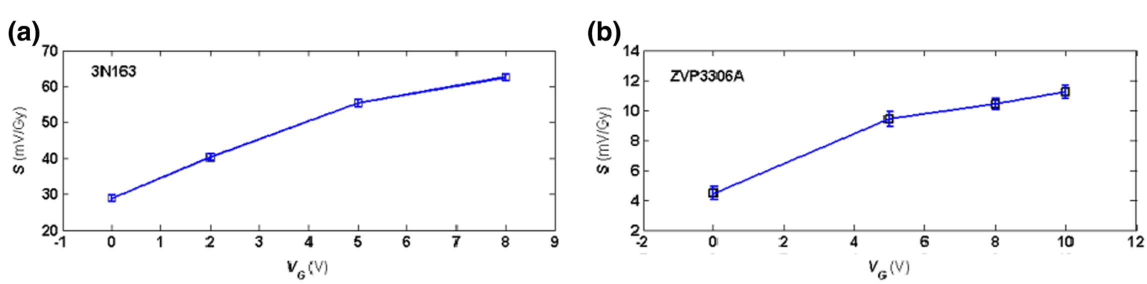


**Fig. 5** Mean values of the sensitivity for gamma radiation. *Symbols* represent experimental data and line shown for eye guided

mode, probability of electron–hole recombination is higher than that of the biased mode. During irradiation in the biased mode, a large number of the holes escape from the primary recombination, which cause the oxide layer trapping.

Figure 5 shows mean sensitivity values for the transistors in four groups of bias voltage. As the sensitivity increases with the $V_{GS}$, due to increased interface trapped charges, the sensitivity is greater in biased mode than unbiased mode.

Figure 6 shows typical values of the sensitivity verses the dose, from one of the MOSFETs in biased mode ($V_{GS} = 5$ V for 3N163 and $V_{GS} = 8$ V for ZVP3306A) and in unbiased mode. The remaining transistors show similar behavior. As shown in Fig. 7, the obtained sensitivities are of good linearity and low uncertainty.

## 4 Conclusion

In this paper, commercial MOSFETs were irradiated in biased mode (active) and unbiased mode (passive). Linear response of the evaluated MOSFETs to gamma radiation in the dose range of 1–5 Gy was obtained for both biased and unbiased modes. It was observed that the absolute value of the threshold voltage increases with increasing accumulated dose and the sensitivity of the PMOS increases with increasing gate bias.

Results have shown that the analyzed MOSFETs may be used as a dosimeter but requires further investigation for a particular use. Due to low cost and complexity, compared to the RADFET dosimeters developing of PMOS dosimeters would be more beneficial. These results suggest that using appropriate methods of irradiation and suitable electronics for readout, these transistors can be used for dosimetry in various areas, which significantly reduces the cost of the final system.

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