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Experimental method for determining the supply current of a PMOS power transistor for use as a RADFET dosimeter

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ABSTRACT

Radiation Sensitive MOSFETs (RADFETs) have been commonly used as ionizing radiation dosimeters. The threshold voltage variation is the main transistor parameter used for radiation dosimetry, as this voltage variation is directly related to total dose and it can be easily determined by using simple measurement and biasing circuits. In this work it is presented a novel experimental method to determine the optimal drain-source current value to be supplied to a p-type MOSFET used in a traditional RADFET configuration (diode connected transistor) for monitoring of the accumulated X- and gamma-radiation dose. Experimental results from irradiations with ^{60}Co gamma-rays and comparison measurements with semiconductor analyzer indicate that lower supply current values result in more precise dose measurement results.

Keywords: **RADFET, PMOS, dosimeter, gamma-radiation, threshold voltage.**

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1. INTRODUCTION

Ionizing radiation can induce significant charge buildup in oxides and insulators of MOSFETs (Metal Oxide Semiconductor Field Effect Transistors) leading to changes in their electrical response. The two primary types of radiation-induced charge are oxide-trapped charge and interface-trapped charge. These charges cause threshold voltage shifts and increases in leakage currents growing proportionally to accumulated dose [1, 2]. Therefore, transistors with thicker oxide layer tend to be more sensitive to radiation. For this reason, p-type power MOSFETs are a good fit for this purpose and are the ones more commonly used in this case [3, 4]. Moreover, the threshold voltage variation (ΔV_{Th}), since it depends on total dose and can be easily determined using simple measurement and biasing circuits, is the main parameter of a RADFET dosimeter used for radiation dosimetry [5].

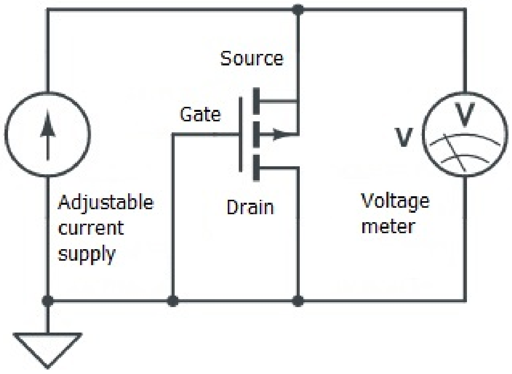
The usual procedure for measuring a RADFET threshold voltage variation (ΔV_{Th}) consists of biasing the transistor with a constant current source between its source and drain (I_{DS}), keeping the gate and drain terminals short-circuited and measuring the voltage between the drain and source (V_{DS}), during exposure or between irradiation steps. On the first case, the accumulated dose is measured in real time, noting that, in this case, the dosimeter is irradiated under its operation bias. Using that process, Commercial off-the-shelf (COTS) transistors can be an alternative to low-cost dosimetry in laboratory test procedures of irradiation with X-rays and gamma-rays [6, 7].

In a previous work [8], the expected response of a p-type MOSFET up to the saturation dose was modeled, based on the free charges (electron-hole pairs) generated by ionizing radiation. Part of these charges is trapped in the gate isolation oxide, causing a negative threshold voltage variation. This work presents a novel experimental method in order to determine the optimal source-drain bias current value of a commercial off-the-shelf (COTS) power p-type MOSFET to be used as a RADFET dosimeter for real time monitoring of the accumulated dose of penetrating X- and gamma-radiation.

2. MATERIALS AND METHODS

Figure 1 presents the circuit topology used for the traditional use of a transistor as a RADFET dosimeter. Using this configuration, only a current source and a voltage meter are enough in order to determine threshold voltage variation and, thus, total dose.

Figure 1: *Basic circuit for measuring the RADFET voltage under operation.*



The transistor is biased by the current supply and its drain-source voltage is measured by the voltage meter. In this configuration, the transistor is operating on saturation mode and the drain-source current I_{DS} is given by equation (1).

$$I_{DS} = \beta_P (V_{GS} - V_{Th})^2/2 \tag{1}$$

where β_P is the PMOSFET current gain factor. Keeping fixed the supply current of the circuit, the value of the drain-source voltage (V_{DS}) is given by equation (2).

$$V_{DS} = V_{GS} = \sqrt{2I_{DS}/\beta_P} + V_{Th} \tag{2}$$

According to equation (2), since the first term on the right-hand side is a constant, any variation on V_{Th} would cause the same change on the measured value of V_{DS}, leading to equation (3).

$$\Delta V_{Th} = \Delta V_{DS} \tag{3}$$

In theory, this relation would be independent of chosen I_{DS}. The purpose of this work is, then, to evaluate how the choice of this current impacts on the theory.

The method used in order to do this evaluation basically consists of irradiating a p-type power MOSFET (we used IRF4905PBF) in several steps. At each step, the device is exposed to gamma radiation at a constant rate of 6 krad/h from a source of ^{60}Co and then measured with a semiconductor analyzer (Keithley SCS4200). After all steps, the total dose is 987 krad. To perform the irradiations, it was used the radiotherapy equipment model Eldorado 78 (ACEL, Canada) with a ^{60}Co source of 2,4 kCi activity located at the *Laboratório de Radiação Ionizante* (LRI), a facility within the Institute for Advanced Studies (IEAv). During radiation, the device was placed in the center of the beam and a 5mm acrylic plate was put between the source and the device for electronic equilibrium. The room temperature was kept at 23±1ºC during the whole experiment. The test was conducted considering the European Space Agency standard nº 22900 for total ionizing dose tests in electronic devices [9].

Between each irradiation step, two different characteristic curves of the transistor are extracted with a semiconductor analyzer (Keithley SCS4200) and the value of the threshold voltage (V_{Th}) is extracted from each curve. The characteristic curves are current versus voltage traces based on measurements under specific bias conditions, made with high precision voltage and current sources. According to Keithley reference manual [10], the uncertainties of these measurements are less than 0.1%, and the threshold voltage, calculated through the derivative of these curves is less than 0.15 to 1%, depending on the number of measurement points chosen.

These two independent values of the threshold voltage for each cumulative dose step are compared with each other and their variation with the accumulated dose is fitted to the model developed in a previous work [8]. This last model considers the physical phenomena of trapping and detrapping of charges and is shown in equation (4).

$$\Delta V_{Th} = S_1(1 - e^{-L_1 D}) + S_2(1 - e^{L_2 D}) \quad (4)$$

where S_1, L_1, S_2 and L_2 are model parameters. Note that two types of traps were considered (oxide and interface Si/SiO$_2$ traps [11]) and that S_1 and S_2 represent saturation values, i.e., the condition when both trap types are fully occupied by trapped ionization charges.

The first curve is the I_{DS} versus V_{GS} curve ($I_{DS} \times V_{GS}$, with $V_{DS} = -100$ mV), which is the measured drain-source current (I_{DS}) as a function of the gate-source voltage (V_{GS}), with the drain-source voltage (V_{DS}) fixed at a low voltage level, in this case $V_{DS} = -100$ mV. For this measurement, all the terminals are independent from each other, as shown in Figure 2. From this curve, using the first derivative method [12], the threshold voltage (V_{Th}) is extracted at each dose step and, hence, it is possible to determine the variation of V_{Th} (ΔV_{Th}) as a function of the accumulated dose. Figure 3 shows the first derivative method for the extraction of V_{Th} in Keithley SCS4200 analyzer, where the I_{DS} versus V_{GS}

curve (I_{DS} × V_{GS}) is shown in blue; its first derivative (dI_{DS}/dV_{GS} × V_{GS}), in red, and the tangent line in dashed black.

Figure 2: *Circuit configuration for tracing I_{DS} x V_{GS} curve with Keithley SCS4200 analyzer.*

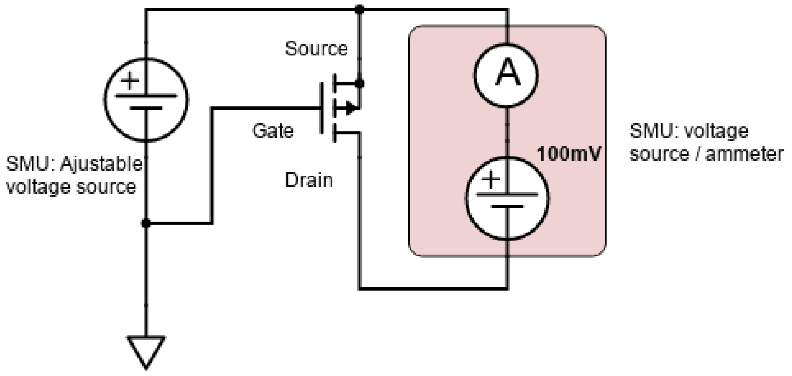
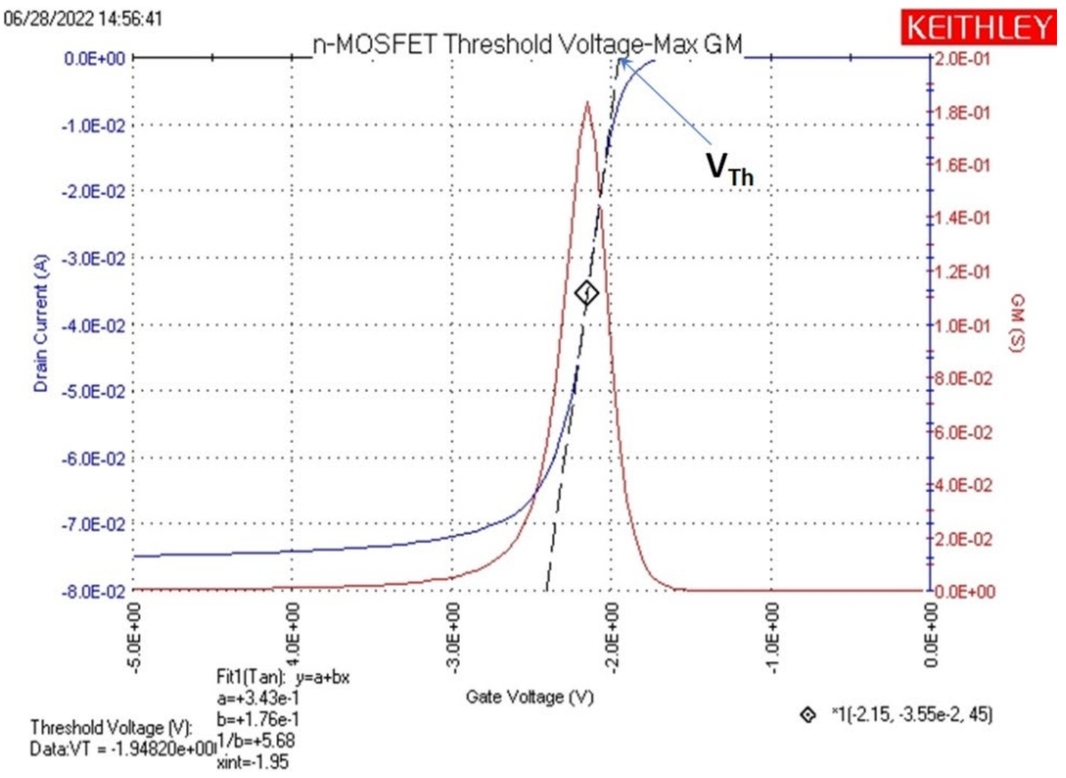
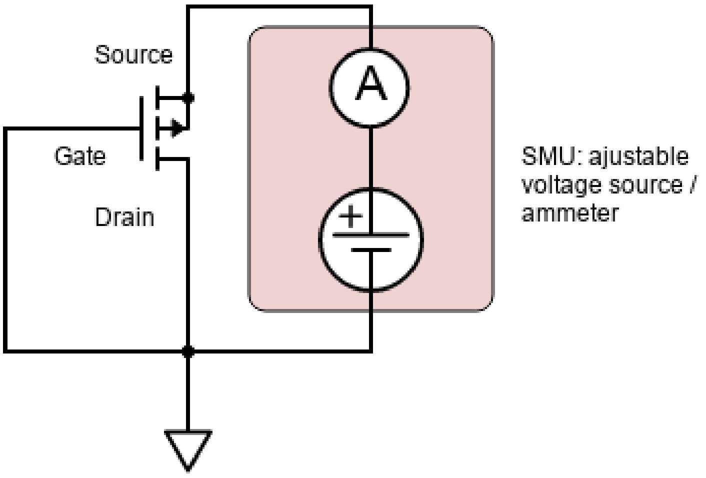


Figure 3: *First derivative method on the I_{DS} vs V_{GS} curve with Keithley SCS4200 analyzer*



The second curve is obtained by using the configuration shown in Figure 4, where the transistor operates as a RADFET dosimeter (we have proposed the name "RADFET Curve"). This curve is obtained by keeping the gate and drain in short circuit ($V_{GS} = V_{DS}$), varying V_{DS} from zero to a value below the maximum V_{DS} specified in the transistor datasheet (which is -40V) and measuring the source-drain current value (I_{DS}). It is, then, the I_{DS} versus V_{DS} curve ($I_{DS} \times V_{DS}$, with $V_{GS} = V_{DS}$). Under these conditions, the transistor is always operating in saturation mode and, thus, it can be modeled by equation 1 and the threshold voltage can be assessed by equation 3.

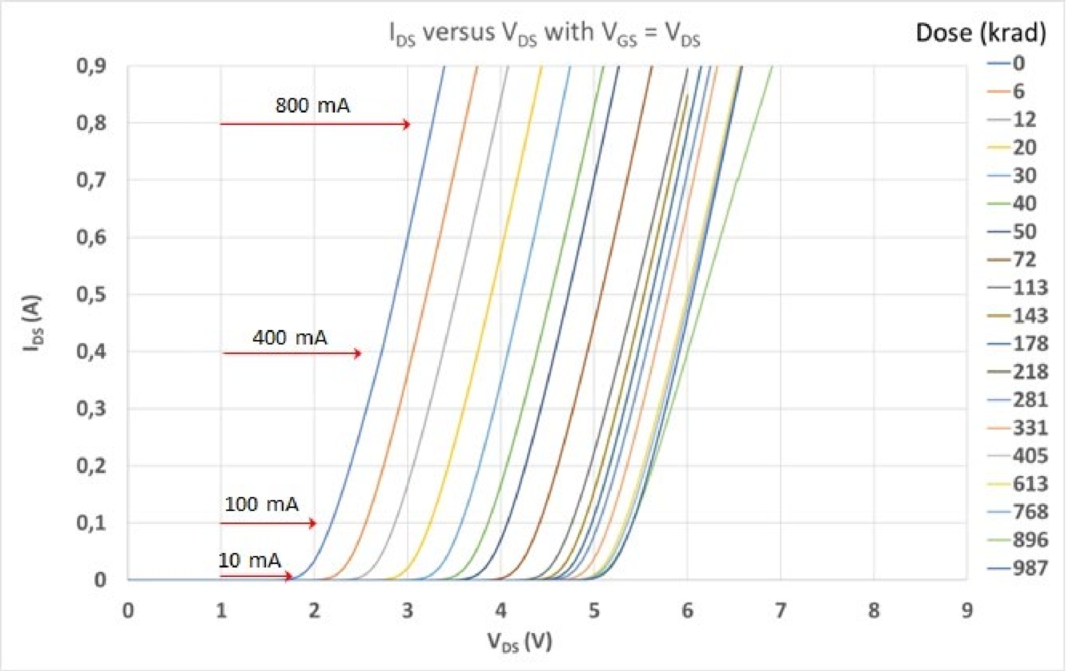
Figure 4: *Circuit configuration for tracing I_{DS} x V_{DS} curve with Keithley SCS4200 analyzer.*



3. RESULTS AND DISCUSSION

In Figure 5, it is shown the measured RADFET curves of the tested transistor for 18 radiation steps, from 0 to 987 krad. From these curves, the variation of V_{Th} (ΔV_{Th}) was extracted based on equation (3) using V_{DS} values for I_{DS} equals to 10, 100, 400 and 800 mA, at each accumulated dose value (D): $\Delta V_{Th}(D) = V_{Th}(D) - V_{Th}(0\ \text{krad}) = V_{DS}(D) - V_{DS}(0\ \text{krad})$. After each dose step, V_{Th} was extracted from the I_{DS} versus V_{GS} curves as well, using the first derivative method, and ΔV_{Th} was also calculated.

Figure 5: *RADFET curves (I_{DS} × V_{DS}, with $V_{GS} = V_{DS}$) after 18 accumulated dose steps up to 987 krad measured with Keythley SCS4200 Analyzer.*



Figures 6, 7, 8 and 9 show the ΔV_{Th} values as a function of the accumulated dose for the selected values of I_{DS} of 10, 100, 400 and 800 mA, respectively, as indicated in Figure 5 (RADFET curves). For a proper comparison, each figure also presents the ΔV_{Th} values as a function of the accumulated dose (D) calculated both from the first derivative method, as well as the theoretical proposed model, shown in equation (4) [8], and its parameters (S_1, L_1, S_2 and L_2) that were adjusted to the collected experimental values with the first derivative method. The results are presented in Table 1.

Table 1: Curve parameters of ΔV_{Th} versus cumulative dose [8] adjusted to experimental data obtained by SCS4200 Keithley Analyzer by the first derivative method.

Adjusted parameter	**Value**	**Unit**
S_1	2.168 ± 0.014	V
L_1	0.0280 ± 0.0001	$krad^{-1}$
S_2	1.0203 ± 0.0060	V
L_2	0.0055 ± 0.0001	$krad^{-1}$

The values obtained by the first derivative method were considered as the reference for this comparison since they were obtained using a well-established method for measuring MOSFET threshold voltage [10].

Considering that the uncertainty of each measurement of V_{Th} is of a statistical nature and in the order of 1% (see section 2) for both methods, the uncertainty of its variation can be calculated for all ΔV_{Th} values and results from 1% ($\Delta V_{Th} = 0$) to 3% ($\Delta V_{Th} = 3.2V$).

Figure 6: *Threshold voltage variation as a function of accumulated dose for I_{DS} = 10 mA on the RADFET curve*

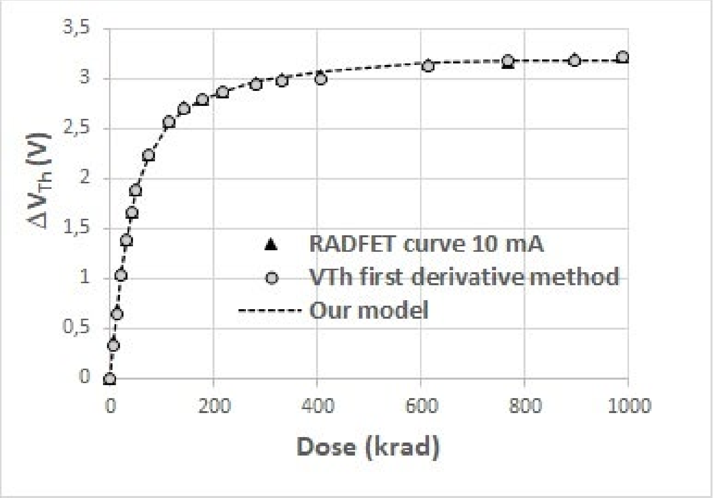


Figure 7: *Threshold voltage variation as a function of accumulated dose for I_{DS} = 100 mA on the RADFET curve*

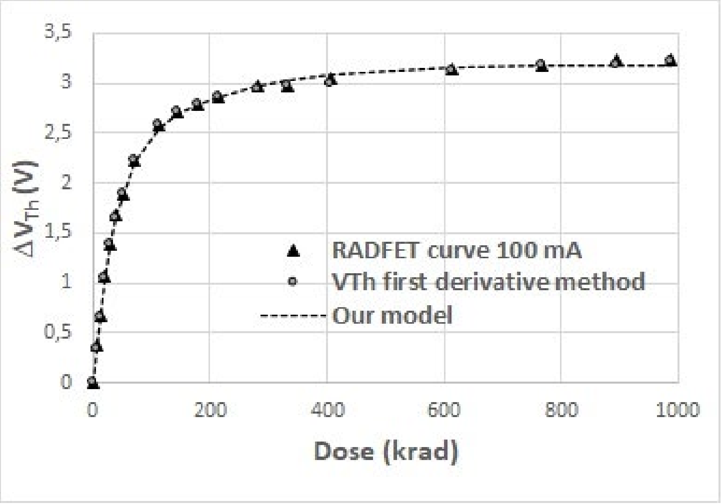


Figure 8: *Threshold voltage variation as a function of accumulated dose for I_{DS} = 400 mA on the RADFET curve*

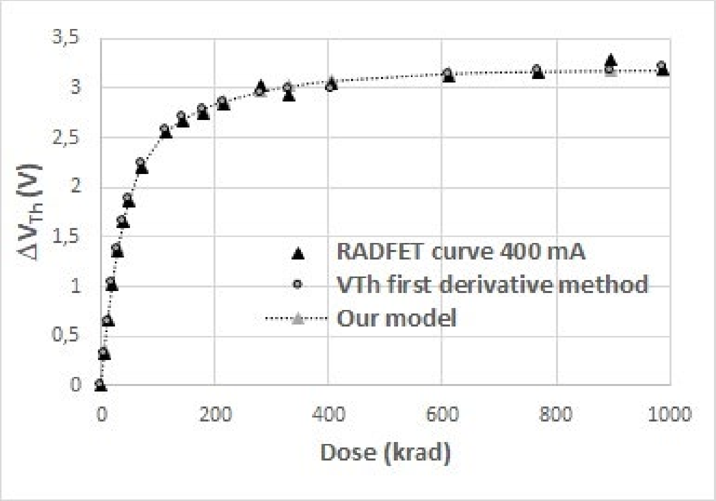
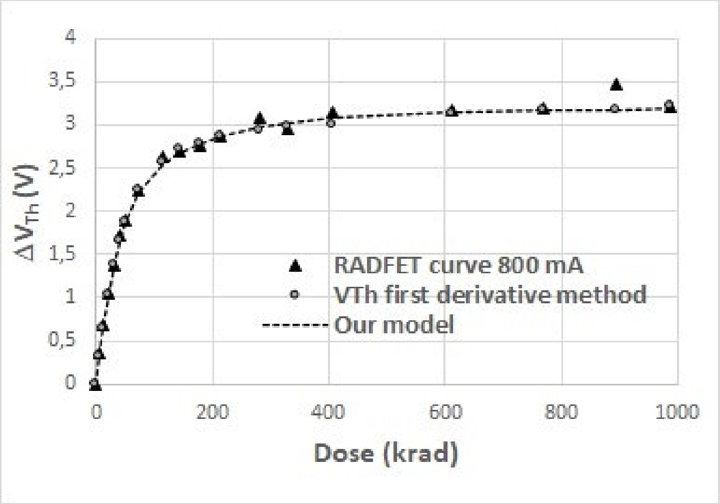


Figure 9: *Threshold voltage variation as a function of accumulated dose for I_{DS} = 800 mA on the RADFET curve*



Figures 6, 7, 8 and 9 show that the values for ΔV_{Th} obtained from the RADFET curves, for a wide range of supply current, are consistent with those obtained by the method of the first derivative using a semiconductor analyzer equipment (adopted as the reference in this experiment). Moreover, by a simple visual inspection of RADFET curves, one can notice that lower values of bias currents imply in smaller fluctuations from the model predicted behavior and, therefore, a smoother dosimetric response curve would be achieved. In addition to it, choosing lower current implies lower power consumption in the measurement system.

This result demonstrates that using the simple relation in equation (3) is a reliable way to measure the threshold voltage variation and, therefore, accumulated dose. Hence, the RADFET configuration with a constant supply current (Figure 1), where simpler equipment than a semiconductor analyzer system is used (current source and voltage meter), produces reliable results even though it uses a simpler setup. Furthermore, since this measurement can be made online, with and embedded circuit without the necessity of an external semiconductor analyzer, this simpler system can provide faster (online) results.

4. CONCLUSION

This experiment has demonstrated that the measurement of the output voltage of a RADFET powered by a constant current source produces results that allow to reliably obtain the threshold voltage variation as a function of the dose, using of a commercial p-type power MOSFET. Moreover, it shows that better results are achieved when lower bias current values are applied. This operating mode was confronted with recognized reliable measurements using a semiconductor analyzer equipment to extract the threshold voltage value.

The transistor IRF4905PBF (a power p-type MOSFET) was tested up to dose values in which the amount of charges trapped in the oxide traps reached a saturation, which could be observed by the saturation of the threshold voltage. In terms of dosimetry, its response is sublinear at high doses up to about 1 Mrad. Future tests should be conducted in order to establish the region of dosimetric interest, as well as to determine any dependence with the dose rate and with the energy of ionizing radiation (gamma rays and X-rays).

Lastly, this experiment also demonstrated that the tested transistor obeys the behavior predicted in our model [8] until its trapped charge saturation.

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