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Radiation dose response of N channel MOSFET submitted to filtered X-ray photon beam

Luiz C. Gonçalves Filho, David S. Monte, Fabio R. Barros, and Luiz A. P. Santos

***Abstract*—MOSFET can operate as a radiation detector mainly in high-energy photon beams, which are normally used in cancer treatments. In general, such an electronic device can work as a dosimeter from threshold voltage shift measurements. The purpose of this article is to show a new way for measuring the dose-response of MOSFETs when they are under X-ray beams generated from 100kV potential range, which is normally used in diagnostic radiology. Basically, the method consists of measuring the MOSFET drain current as a function of the radiation dose. For this the type of device, it has to be biased with a high value resistor aiming to see a substantial change in the drain current after it has been irradiated with an amount of radiation dose. Two types of N channel device were used in the experiment: a signal transistor and a power transistor. The delivered dose to the device was varied and the electrical curves were plotted. Also, a sensitivity analysis of the power MOSFET response was made, by varying the tube potential of about 20%. The results show that both types of devices have responses very similar, the shift in the electrical curve is proportional to the radiation dose. Unlike the power MOSFET, the signal transistor does not provide a linear function between the dose rate and its drain current. We also have observed that the variation in the tube potential of the X-ray equipment produces a very similar dose-response.**

***Index Terms*—MOSFET, Radiation, Dosimeter.**

I. Introduction

MOSFET has been used for many years as a radiation detector mainly in high-energy photon beams, which are normally used in cancer treatments. More recently, the MOSFETs are also being used to measure the dose in X-ray beams of the diagnostic radiology energy range. In general, such an electronic device can operate as a dosimeter from the threshold voltage shift measurements. This means that the dose is obtained from the increase in gate voltage value, which causes the transistor to turn on. The purpose of this article is to show a new way for measuring the dose-response of typical MOSFETs when they are under X-ray beam generated from 100kV potential, that is, an energy range which is normally used in diagnostic radiology. The method is based on the analysis of the transistor drain current rather than the threshold voltage. Here, we present how someone can bias the MOSFET so that, by plotting its electrical curve or analyzing the variation of the drain current, it is possible to measure the radiation dose.

Actually, the MOSFET has to be biased with a voltage (V_{DD}) and a high resistance resistor, R_D, connected to the drain (Fig. 1). The device becomes too slow, but it does not matter because it will not operate as switch. To measure the drain current, I_D, an ammeter is in series with V_{DD} source.

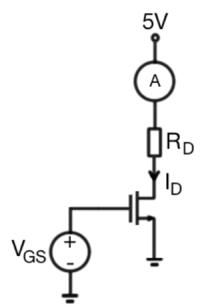

Fig. 1. MOSFET biased with 5V and a resistor R_D connected to the drain. To plot an $I_D \times V_{GS}$ electrical curve, V_{GS} can be varied from 0 up to 3V, for while.

By systematically varying the gate-source voltage, V_{GS}, one can obtain an $I_D \times V_{GS}$ electrical curve as showed in Fig. 2. Notice that the drain current depends on the resistor value, i.e., the saturation point can be changed. For example, if a 100 kΩ resistor is used in the circuit we have I_D=50 μA at V_{GS}=2.1 V. On the other hand, if we choose another resistor with the thousand times lower value, the saturation point naturally goes to I_D=50 mA at V_{GS}=2.9 V. As it will be seen later, there are some considerations that must be taken into account both in the choice of MOSFET bias, type of transistor, and the spectrum of radiation to be measured.

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L. C. Gonçalves Filho is with Comissão Nacional de Energia Nuclear (CNEN/CRCN-NE) and with Universidade Federal de Pernambuco (UFPE), Av. Prof. Luiz Freire, 200, Recife, 50740-545 (e-mail: lcar.br@hotmail.com).
D. S. Monte is with Universidade Federal de Pernambuco (UFPE), Av. Prof. Luiz Freire, 1000, Recife, 50740-545, and with SCIENTS, Estrada do Monjope, 5100, Igarassu, 53645-337 (e-mail: dsmonte@scients.com.br).
F. R. Barros and L. A. P. Santos are with Comissão Nacional de Energia Nuclear (CNEN/CRCN-NE), Av. Prof. Luiz Freire, 200, Recife, 50740-545, and with SCIENTS, Estrada do Monjope, 5100, Igarassu, 53645-337 Brazil (e-mail: frbarros12@gmail.com; lasantos@scients.com.br).

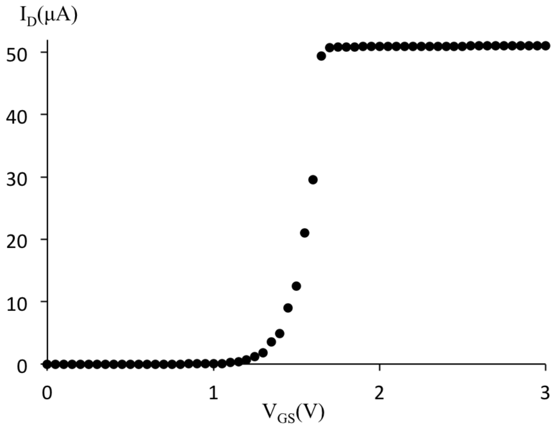

Fig. 2. $I_D \times V_{GS}$ curve for a MOSFET biased: V_{DD}=5 V and R_D=100 kΩ. In this case the saturation point is reached at the V_{GS}=1.7 V with I_D=50 µA.

II. Materials And Methods

A. MOSFETs

Three types of N channel MOSFETs and a total of 24 devices were used in the experiments: 6 BSS138 – signal transistor with SOT-23 encapsulation; and 12 FQP12N60C, and 6 BUZ91A – power device with TO-220 package (Fig. 3.) The type of transistor package influences significantly when it is used as a radiation detector. In fact, the epoxy material thickness of the encapsulation depends on the device, and it is a crucial factor for increasing the number of interactions, and consequently the amount of charges generated on the oxide of the MOSFET, as well as the damage in the semiconductor crystal itself. The increase in the photon interactions due to the thickness of the material is known as the build up cap effect.

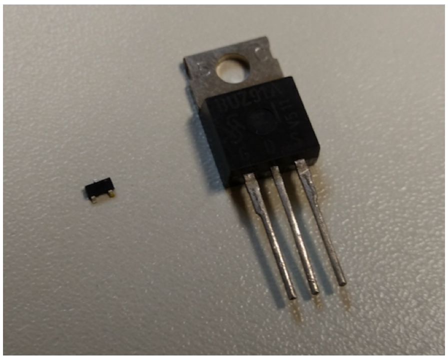

Fig. 3. MOSFETs with their respective packages in parenthesis: BSS138 (SOT-23); and BUZ91A (TO-220).

B. Instruments and Bias

An EFF1506 SCIENTS system was used to take I_D measurements and simultaneously bias the device with both signals: V_{DD} and V_{GS}. The drain was biased with a R_D=91 kΩ resistor at V_{DD}=4.5 V. The bias circuit is exactly as showed in Fig. 1. The V_{GS} bias was systematically varied from 0 V up to 3 V each 50 mV step to trace the $I_D \times V_{GS}$ curves. A W23342 PTW ion chamber connected to the 6517A Keithley system was used to take the dose rate measurements.

C. X-ray unit, radiation beam and experimental set up

An HF-320 Pantak X-ray unit was used to generate the photon beam, which was filtered with an 1 mm aluminum plate. Aiming to test the devices for measuring the radiation dose in the energy range normally used in diagnostic radiology, the tube potential of the X-ray equipment was set to be 100 kV. The photon beam spectrum is fully specified setting the potential on the control panel of the X-ray unit, and selecting a material with a certain thickness to filter the radiation. The experimental set up is illustrated in Fig. 4.

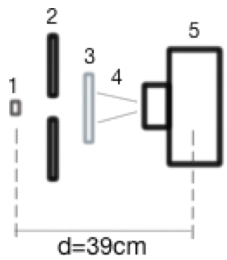

Fig. 4. Experimental set up used to irradiate the MOSFETs with a filtered X-ray photon beam: 80kV, 100kV and 120kV tube potentials. 1) Device under irradiation; 2) Collimator; 3) 1 mm Al plate as a radiation filter; 4) Photon beam without filtration; 5) X-ray generator unit.

D. Experimental procedures

First of all, the technique consisted in evaluating the MOSFET response after the irradiation procedure, which was done delivering 20 Gy radiation dose each time. The $I_D \times V_{GS}$ curve was plotted immediately after the irradiation procedure by varying the gate voltage, V_{GS}, in steps of 50 mV up to 3 V.

A second experimental method was based on the $I_D \times V_{GS}$ response curves by choosing a V_{GS} value, for each type of MOSFET, and evaluate the drain current as a function of the dose rates, or more specifically as a function of the photon fluence. The dose rates were obtained based on the X-ray tube current, which can be selected in the control panel of the equipment from 5 mA up to 25 mA, for each 5 mA step. The dose rate data are showed in the Table I.

TABLE I
DOSE RATE VALUES USED IN THE EXPERIMENTS

k	X-ray tube current (mA)	Dose rate (mGy/s) at the MOSFET position
1	5.00 ± 0.01	8.07 ± 0.06
2	10.00 ± 0.01	15.90 ± 0.09
3	15.00 ± 0.01	24.20 ± 0.21
4	20.00 ± 0.02	32.00 ± 0.23
5	25.00 ± 0.02	40.40 ± 0.41

The third stage of the experiments was made varying the X-ray tube potential ±20% (80 kV and 120 kV). With this procedure, one can evaluate how the changes in the spectrum can bring about variations in the MOSFET dose-response. All experiments were done with samples of transistors in triplicate aiming to verify reproducibility. The same transistor is not used in another experiment, since if irradiated it is discarded.

III. Results and Discussions

The $I_D \times V_{GS}$ curves for the three types of MOSFETs are showed in Fig. 5. The curves without irradiation (0 Gy) show that the saturation point is not the same. Actually, the structure of the device and its own geometry (e.g. channel dimension, components internally connected) can determine the saturation point. After any irradiation, from 20 Gy onwards, regardless of the encapsulation of each device type, we can observe that the behavior of the $I_D \times V_{GS}$ curves is very similar: as the dose increases, systematically the curves take a shift to the left. Notice that the BUZ91A has a signature as a soft peak, which systematically appears with the same shift to the left. At this point, we may think that the dose-response is practically the same for any type of MOSFET. However, our purpose is to verify how the drain current value varies with the dose rate in order to correlate the present value of I_D with the dose that was received by a transistor. Then, some results for I_D as a function of the dose rate, $\dot{D}$, are in the graphs of Fig. 6.

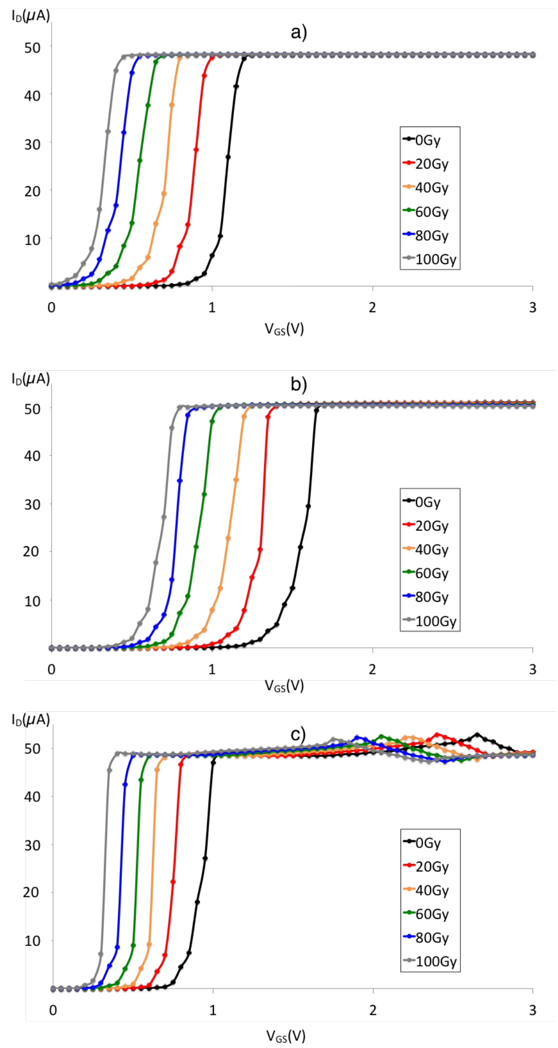

Fig. 5. $I_D \times V_{GS}$ curves after 100 Gy dose in steps of 20 Gy for each Mosfet: a) BSS138; b) FQP12N60C; c) BUZ91A.

To evaluate $I_D \times \dot{D}$, the latest results (Fig. 5) have helped us to choose a V_{GS} value to set the bias for each transistor: 450 mV for BSS138; 950 mV for FQP12N60C; and 500 mV for BUZ91A. In this test, the real-time measurements mode was used. The results show that for the signal transistor the drain current is very low and practically increases continuously with the dose, whereas for the power MOSFETs each step of photon fluence can be seen as practically constant I_D during the irradiation. The I_D variation more pronounced for the BSS138 MOSFET probably means that it could not be used as a dosimeter, since I_D does not hold over time.

The proportionality between I_D and $\dot{D}$ can be seen in Fig. 7, where the results of three samples of FQP12N60 MOSFET are displayed together with the average between them. Notice that T2 transistor has practically the same response of the average.

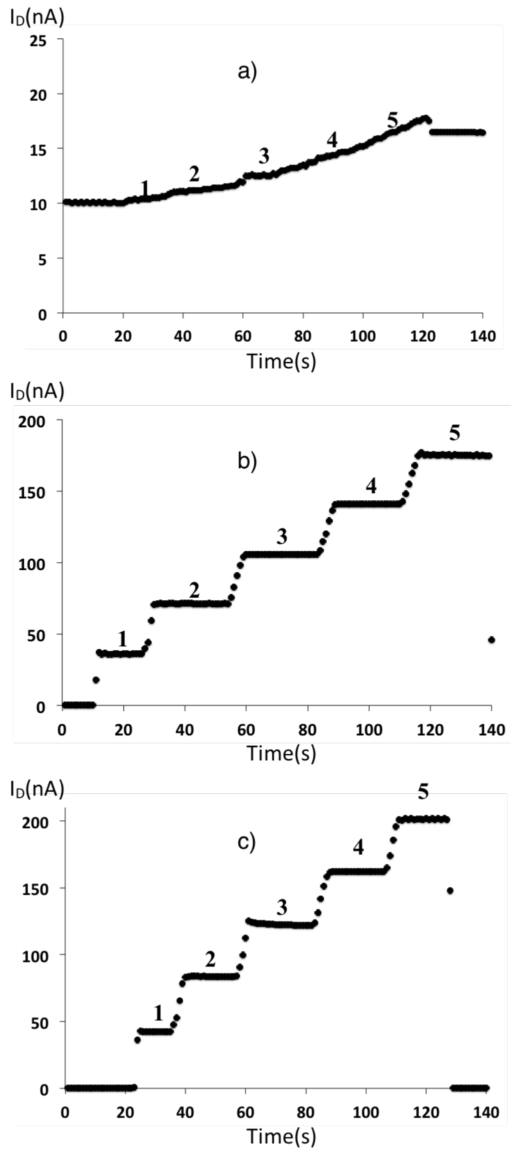

Fig. 6. Real-time measurements of I_D for each $\dot{D}_k$ where k is the index in the Table I. MOSFETs: a) BSS138; b) FQP12N60C; c) BUZ91A.

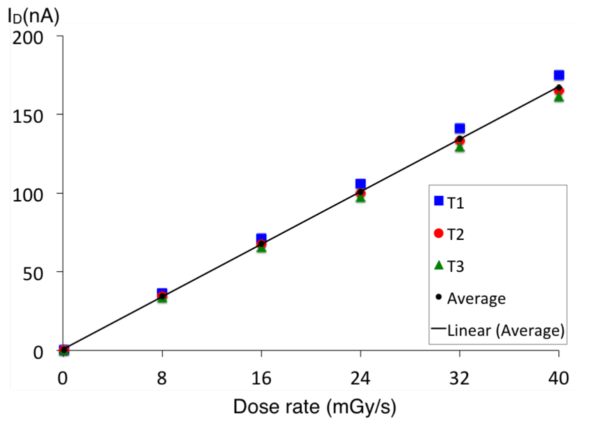

Fig. 7. $I_D \times \dot{D}$ response for three samples of FQP12N60C MOSFET. The average, in black, has the equation $I_D = I_0 + S \cdot \dot{D}$, where I_0 = 0.7 (nA) is the initial value of I_D, S=4.176 (nA/mGy·s^{-1}) is the average sensitivity coefficient, and the line has a determination coefficient of R^2=0.99991.

The linear coefficients of each power MOSFET response will depend naturally on the bias and the type of transistor. In fact, every device will have its own sensitivity coefficient, or conversion factor for calibration purposes, as any type of dosimeter has. In order to estimate the useful life of the power MOSFET in diagnostic radiology, consider that the dose of a lung X-ray examination should be about 0.5 mGy, according to the standards guide of the IAEA. In such a case, after 1,000 X-ray examinations, which corresponds to about one month of use in a typical clinic, the device would receive 0.5 Gy dose. Actually, it is the dose during the 3rd irradiation of the device (Fig. 6b) and we can observe that I_D=106±0.2 (nA) practically does not vary in 20 s. Therefore, this result demonstrates that a MOSFET can be used to estimate the dose (in real-time) via the drain current measurements, if it is previously calibrated.

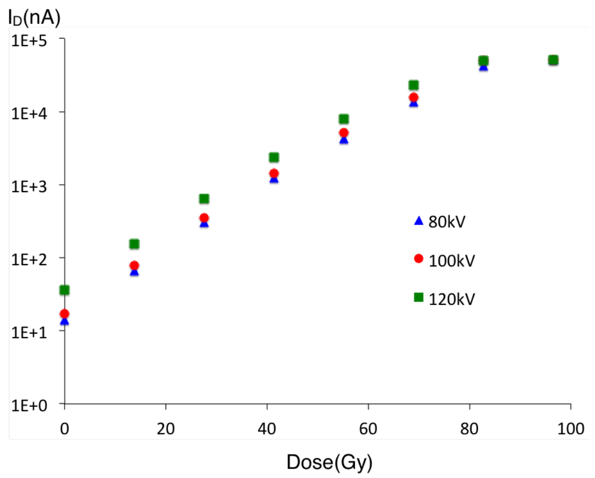

Fig. 8. The drain current I_D as a function of the received dose D for three samples of FPQ12N60 MOSFETs. Each device was submitted to three different spectrum originated from 80 kV, 100kV and 120 kV.

Finally, the radiation dose responses of three N channel MOSFETs whose are submitted to 1 mm Al plate filtered X-ray photon beam can be seen in the Fig. 8. There also is the result of the analysis of how changes in the tube potential (±20%) can modify the response of the MOSFET. We can observe that the drain current is lower if 80 kV tube potential is selected, whereas I_D is higher if the spectrum is originated from 120 kV. This proves that the measurement process has to take into account that a MOSFET must be probably calibrated with respect to the tube potential. Notice that the initial values are different and therefore the curves do not match perfectly, although we know that each device has its own calibration. It can also be observed that after the dose value reaches 70 Gy the dose-response presents saturation. However, for the lung X-ray examination, this may mean that the transistor could operate about more than 100 thousand times.

IV. Conclusions

Unlike the known conventional method for measuring the radiation dose, from the threshold voltage measurements, this paper brings an innovative measurement process, which consists of evaluating the drain current of the MOSFET. Two types of devices were used: a signal transistor and the power transistor. The results found lead us to conclude that with power MOSFET it is easier to measure the radiation dose-response. Actually, the results showed that there are two ways to estimate the dose in X-ray beam: the first is to measure the drain current in real time; and the second one is to correlate the I_D value with the received dose by the power MOSFET. Finally, the dose response indicates that variations in the spectrum lead to variations in the output current of the device. We conclude that the proposed method is feasible to estimate the dose in filtered X-ray photon beam, which is normally used in diagnostic radiology.

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