

An electronic dosimeter for diagnostic X-ray beams based on a differential amplifier circuit with MOSFETs

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Abstract—It is known that the device MOSFET works as a dosimeter in radiation beams for cancer radiotherapy. Basically, the radiation beam generates defects in a way that produces in the MOSFET the variation in its threshold voltage, V_T , which is proportional to the accumulated radiation dose. Recently, MOSFETs were also tested under X-ray beams commonly used in the energy range applied to medical diagnoses, which is lower energy than radiotherapy. Indeed, it was already shown that the MOSFET drain current varies with the radiation dose for energies in the range applied to diagnostic radiology. In this paper, an innovative method based on a differential amplifier circuit with two electronically matched MOSFETs is presented. Therefore, before irradiation the differential output voltage signal, $V_{dif} = 0$. Actually, it is a differential amplifier circuit with one of the MOSFETs shielded from the ionizing radiation beam. Therefore, if such a circuit is irradiated the difference between I_{D1} and I_{D2} , from MOSFET1 and MOSFET2 respectively, will result $V_{dif} \neq 0$. To evaluate the response of this electronic dosimeter it was tested under a diagnostic radiology beam typically used in clinics to take radiography of patients. The results showed that the proposed dosimeter works and varies linearly with the radiation dose. The technology developed in this paper will allow research to be carried out for optimizing such electronic dosimeter to make it a wearable device and can be able to use it by workers exposed to ionizing radiation in nuclear power plants or even in outer space.

Keywords — X-ray, Detector, MOSFET, Dosimeter.

I. INTRODUCTION

MOSFET has been used as an X-ray detector for over 40 years, mainly as a dosimeter in radiation beams normally used for cancer radiotherapy [1-2]. Basically, the radiation beam generates defects in the silicon oxide of the device in a way that produces in the MOSFET variation in its threshold voltage, ΔV_T [3], which is proportional to the accumulated radiation dose. Generally, ΔV_T varies by tens or hundreds of mV per unit dose (Gy) delivered to the patient. Recently, MOSFET was tested under X-ray beams commonly used in the energy range applied to medical diagnoses [4-6],

which is lower energy than radiotherapy. Also, unlike the method used in radiotherapy, the measurement technique is based on variation of the drain current, I_D . Indeed, it was previously shown that the drain current varies with the radiation dose for energies in the range applied to diagnostic radiology [4]. In this work, knowing that the so-called differential amplifier circuit provides an improvement in the characteristics of a typical amplifier, an innovative dosimetry technique is proposed. Actually, the motivation for developing this work comes from the fact that a simple and versatile circuit can be used in workers' uniform in nuclear power plants or even by astronauts in outer space, that is, providing a circuit optimization process it can become a wearable electronic system.

II. MATERIAL AND METHODS

A. Differential amplifier circuit

The proposed circuit is similar to a typical operational amplifier. Actually, it is a differential amplifier circuit with one of the MOSFETs shielded from the ionizing radiation beam as shown in Fig. 1. The circuit has two electronically matched MOSFETs: T_1 and T_2 . In this way, initially, the differential output voltage signal (V_{dif}) will be zero before irradiation or even can have any offset, which can be canceled by varying R_{D1} or R_{D2} , for example. As previously shown the MOSFET drain current (I_D) varies each time the device is exposed to diagnostic X-ray beam [4]. Therefore, if the differential amplifier circuit is irradiated the difference between I_{D1} and I_{D2} , from T_1 and T_2 respectively, will produce $V_{dif} \neq 0$. The signal V_{dif} passes through an instrumentation amplifier (IA) to be digitized by an ADC circuit to be registered in a memory block (MB). In that way, one can have the dose history of a patient or worker on a chip card.

B. MOSFET

A printed circuit board (PCB – Fig. 2) was made to connect the two transistors. The MOSFETs were selected from a sample of 50 MOSFETs to obtain matched devices. To analyse the new dosimeter, two PCBs were assembled to perform experiments in duplicate. The chosen MOSFET for this research was FQP2N06C, Infineon®, just based on the fact that such a device has already been used previously [4].

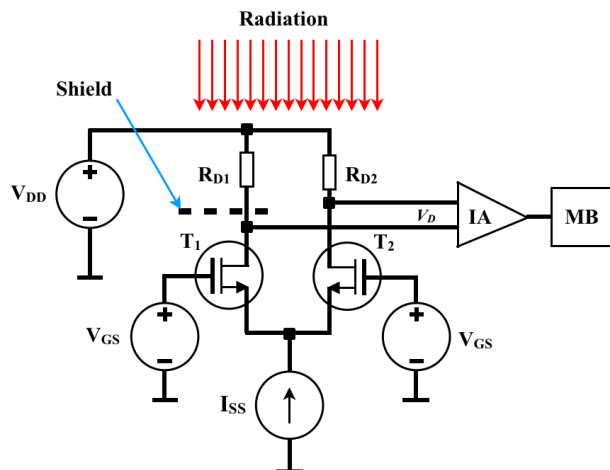


Fig. 1. Electronic dosimeter based on a differential amplifier circuit. T_1 and T_2 are electronically matched MOSFETs; V_{dif} is the differential output signal to be amplified by an instrumentation amplifier (IA); the signal is digitized by an ADC and registered in the memory block (MB).



Fig. 2. PCB assembled to connect T_1 , T_2 and the IA circuit. T_2 connector, which is not shielded from radiation, is positioned outside the PCB area. The output signal, V_{dif} , can be evaluated by a typical multimeter or directly recorded in a microcontroller to be displayed on a small LCD screen.

C. X-ray equipment, radiation pulses and procedures

X-ray pulses were generated from a Polymat 30/50 Plus clinical equipment, Siemens[®]. The pulse duration was set to be 1600 ms to minimize the uncertainties. To assess how the dosimeter works in the energy range applied to radiodiagnosis the X-ray tube potentials were set to be the following values: 77kV, 102kV and 125kV, in order to make a comparison with other recent publications. Also, to evaluate the influence of the X-ray tube current two experiments was carried out by selecting two workloads in the control panel of the X-ray generator: 100mAs and 200mAs. Therefore, each X-ray pulse yields the radiation dose as shown in Table I. The dosimetric circuit was positioned at approximately 32.5 cm from the radiation focus. For each X-ray tube peak potential and for each selected workload value, measurements of the V_{dif} variation were made with two assembled PCBs. An EFF1705

source-meter, Scient[®], was used for real-time measurements of V_{dif} . Before carrying out the experiments described above, dosimetry of each X-ray pulse was performed using a 10X5-6 ionization chamber, Radcal[®], which is the reference detector and it has an uncertainty of 0.02 mGy.

TABLE I
RADIATION PULSE DOSE AS A FUNCTION OF X-RAY TUBE PARAMETERS

Peak kilovoltage (kV)	Workload (mAs)	Radiation pulse dose (mGy)
77	100	39.84
102	100	68.31
125	100	97.78
77	200	75.96
102	200	131.29
125	200	188.49

III. RESULT AND DISCUSSIONS

Firstly, Fig. 3 shows the result of the X-ray pulse dosimetry. The size of the marker corresponds to uncertainties in the x and y axes, which is less than 2% in both. As can be seen in the potential range applied to diagnostic radiology, the dose rate is practically linear because of the inherent filtration of clinical X-ray equipment. For this reason, the peak potential of $\approx 100\text{kV} \pm 25\%$ was chosen to carry out the V_{dif} measurement experiments for the two chosen workloads: 100 mAs and 200 mAs (Fig. 4 and Fig. 5), *i.e.*, the photonic intensity doubles in value when the X-ray tube current is doubled, since the pulse duration is held constant. It can be seen that the increase in V_{dif} is practically doubled when the dose rate doubles. This last result shows the variation in V_{dif} for only three X-ray pulses and there is no offset canceled in the circuit. A sequence of 10 X-ray pulses with a peak potential equal to 102kV for the two workloads are shown in Fig. 6 and Fig. 7, respectively, where there is offset canceled. It can be observed that in any case of dose rate corresponding to 100 mAs and 200 mAs, the increase in V_{dif} is a linear function of the dose with coefficients $R^2=0.99892$ and $R^2=0.99854$, respectively. Then each X-ray pulse generates a small step in V_{dif} .

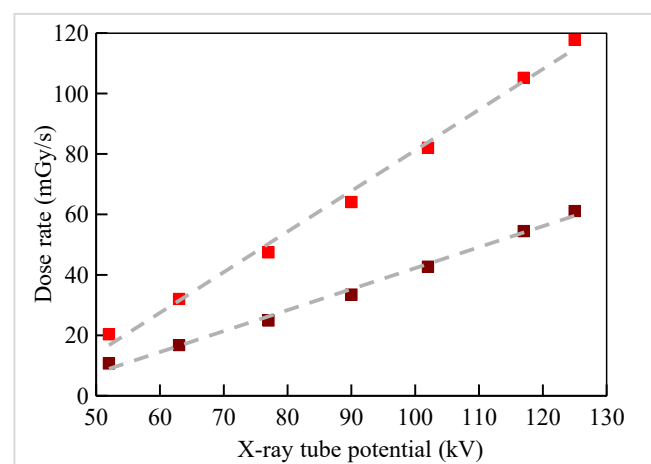


Fig. 3. Dose rate at 32.5 cm from the X-ray tube focus as a function of the X-ray tube potential and parameterized by the workload: 100 mAs (maroon) and 200 mAs (red).

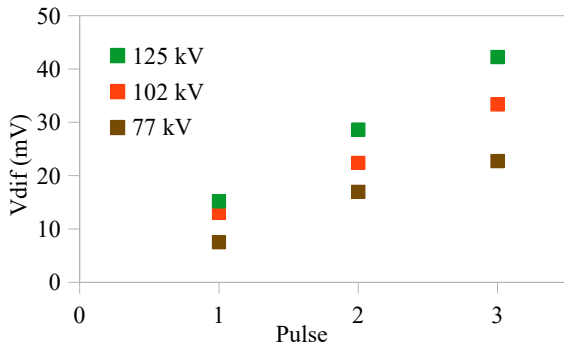


Fig. 4. Variation in V_{dif} (there is no offset canceled) for three X-ray pulses with potential corresponding to $\approx 100\text{kV} \pm 25\%$, the workload is 100 mAs.

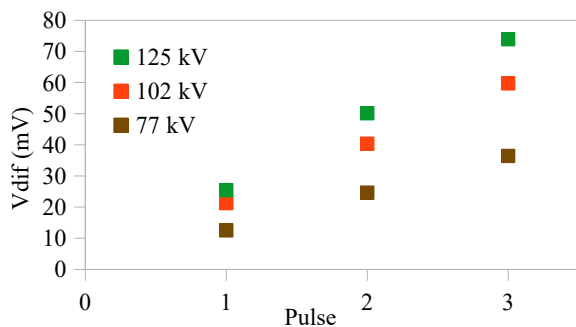


Fig. 5. Variation in V_{dif} (there is no offset canceled) for three X-ray pulses with potential corresponding to $\approx 100\text{kV} \pm 25\%$, the workload is 200 mAs.

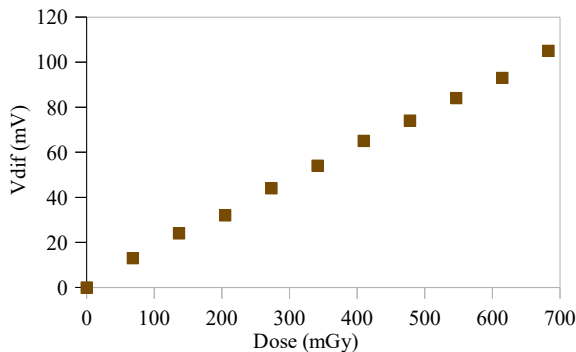


Fig. 6. Variation in V_{dif} (there is offset canceled) for a sequence of 10 X-ray pulses with a peak potential equal to 102kV@100 mAs, $R^2=0.99892$.

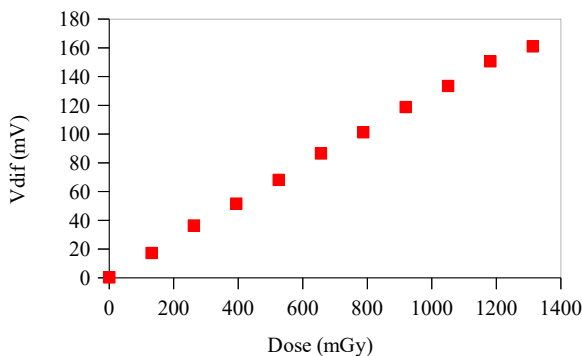


Fig. 7. Variation in V_{dif} (there is offset canceled) for a sequence of 10 X-ray pulses with a peak potential equal to 102kV@200 mAs, $R^2=0.99854$.

One can observe that the step of the curve in Fig. 5 practically doubles in value compared with Fig. 4, since it corresponds nominally to twice the value of the dose received by the circuit regardless of the potential applied to the X-ray tube. Note that the same happens for irradiation repeated 10 times in each workload. In other words, each X-ray pulse regularly generates steps in the dose range up to 1.4 Gy. From the point of view of lung radiography, which is the most frequent in radiography examinations and corresponds to a dose lower than 1 mGy [7], if the circuit does not present saturation, it would be possible to use the circuit more than 1,400 times in the radiography clinic. Actually, the MOSFET used in this circuit showed linearity with doses of up to 70 Gy (see Fig. 8 in [4]) and by canceling the offset or even adjusting it to a certain negative value, the circuit can have a much higher voltage compliance for V_{dif} . Therefore, the new dosimeter can be reused more than 70000 times. In addition, the IA circuit can also be adjusted to increase the voltage compliance of the differential circuit. As the circuit proposed in this article is not complex, it is suggested that an optimization study can be carried out to become a wearable circuit and then be printed on patients' clothing, or on the uniforms of nuclear power plant workers, or even astronauts. In a microcontrolled system, it is possible to easily have the dose history of the patient or worker exposed to radiation. Such a system has already been applied for a patent in 2021 and the application has already been published by the Brazilian patent office recently [8].

IV. CONCLUSIONS

Based on the results found, the innovative differential circuit with MOSFET works as a linear dosimeter in the X-ray range applied to diagnostic radiology. The useful life of such an electronic dosimeter will be a function of the dose rate to which the circuit is exposed and also depend on the voltage compliance of V_{dif} . Therefore, this will depend on the type of MOSFET, its response as a function of dose and even on the circuit adjustments, that is, applying a negative offset to gain compliance in V_{dif} . Actually, as the circuit is shielded from radiation, it is only necessary to change the irradiated device to reuse the electronic dosimeter.

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