A Commercial off-the-shelf pMOS Transistor as X-ray and Heavy Ion Detector

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Abstract. Recently, p-channel metal-oxide-semiconductor (pMOS) transistors were suggested as fit for the task of detecting and quantifying ionizing radiation dose. Linearity, small detection volume, fast readout, portability, low power consumption and low radiation attenuation are some of the pMOS advantages over PIN diode and thermoluminescent dosimeters. A hand-held measurement system using a low power commercial off-the-shelf pMOS as the sensor would have a clear advantage due to the lower cost incurred by a standard technological process. In this research work, we tested the commercial device 3N163 regarding its behaviour as an X-ray sensor, as well as its possible application as a heavy-ion detector. To study the radiation effects of X-rays, a XRD-7000 (Shimadzu) X-ray diffraction setup was used to produce 10-keV effective energy photons. Heavy ions tests involved 

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\begin{align*}
^{12}\text{C},
^{16}\text{O},
^{19}\text{F},
^{28}\text{Si},
^{35}\text{Cl},
^{63}\text{Cu},
^{107}\text{Ag}
\end{align*}
\]

beams scattered at 15° by a 275 µg/cm² gold target, which provide LETs (Linear Energy Transfer) from 4 to 40 MeV/mg/cm². The signal readout was done using a 1 GHz oscilloscope with a 10-Gsamples/s conversion rate, high enough to permit the recording of transient pulses in the drain current. In this case, an ion can cause a current signal proportional to the ion beam used. Through this study it was found that a simple commercial pMOS device can be reliably used as a detector of X-rays as well as heavy ion detector.

1. Introduction
Radiation dosimetry is a very important area to be explored because of current needs for control and monitoring of the dose of ionizing radiation to which human beings are exposed. In the last few years, it has been suggested that electronic devices could be used as radiation monitor [1,2] since the effects of the interaction of radiation with electronic devices are relatively simple and reliable. With the widespread adoption of nuclear medicine, there is a growing demand not only for X-ray and gamma ray dosimeters, but also for good particle counters. Apart from the development of dosimeters for use in medicine, there is also a growing demand for dosimeters that can be used in environments where
ionizing radiation should be monitored, as in particle accelerators, satellites, avionics, skin dosimetry and others.

A dosimeter is any device that is capable of providing a reading of the measurement of the absorbed dose deposited in its sensitive volume by ionizing radiation [3]. Recently, p-channel metal-oxide-semiconductor (pMOS) transistors were suggested as fit for the task of detecting and quantifying ionizing radiation dose. Linearity, small detection volume, fast readout, easy calibration, portability, low power consumption and low radiation attenuation are some of the pMOS advantages over other electronic devices [1,2].

In order for a pMOS device be useful as a particle identifier, it is necessary that the pMOS shows a current pulse proportional to the linear energy transferred to its sensitive volume [4]. On the other hand, it is very important that the device also recovers itself quickly after any event registered, being ready to respond to a next event. This way, the device can monitor the dose of radiation imparted to it.

The physical mechanisms that are responsible for the pMOS detection principle are based on the production of electron-hole pairs along the track of the particle. Part of the generated charge accumulates in the device oxide layers, and in its oxide-semiconductor interfaces, leading to total ionizing dose (TID) effects. Besides, the charge generated in the semiconductor bulk by the passage of a single energetic ionizing particle may be collected in the terminals of the device, giving rise to single event effects (SEE) [4-7]. The pMOS transistor designed for dose measurements, the so-called RADFET (Radiation Field Effect Transistor), is manufactured with a special process aiming to produce a thick gate-oxide leading to a large detection volume (gate-oxide), which improves the sensibility of the detector [5]. In order to achieve a better understanding of the mechanisms responsible for radiation damage due to radiation effects, and check the response to radiation of a pMOS sensor, we are studying a commercial off-the-shelf pMOS - 3N163 - exposed to X-ray and heavy ion beams.

The 3N163 device is a p-channel enhancement mode MOSFET largely used in industry for several applications, presenting the following characteristics: very high input impedance, high gate breakdown voltage, ultra-low current leakage, fast switching and low capacitance. Gate oxide thickness is the main parameter controlling the sensitivity of the transistor to radiation [1-4]. Hence, this device is very appropriate in studies of radiation effects, since after irradiation its $I_{DS}$ current is always reduced, facilitating the observation of the relationship between the accumulated dose and the change of the characteristic parameters in the device [3-6].

1.1. Radiation Effects in Electronic Devices

When electronic devices are exposed to ionizing radiation, it may experience parametric variations and even failures. The effects caused by ionizing radiation can be transient or permanent. Transient effects may provoke momentary failure, for example, changes on stored data or even peaks of electrical current that might damage the electrical circuit. These are the motivations of the growing interest in this research area, since energy absorption, carrier generation, recombination, and transport, charge trapping, and defect formation influence the effects provoked by ionizing radiation [3-7].

Total ionizing dose (TID) effects are related to the amount of energy (dose) absorbed by the material. Particles with low linear energy transfer (LET), i.e. low electronic mass stopping power, and electromagnetic radiation, tend to contribute more to these effects. When photons interact with the device oxides, they create electron-hole pairs in the material, mainly by photoelectric effect. In a typical oxide, electrons can escape swiftly to the positive electrode while holes move slowly towards the negative electrode by a hopping mechanism. The slow motion of the holes increases the
probability that they are trapped by defects in the bulk of the oxide or near the oxide-semiconductor interface. This positive charge concentration may change the basic operating characteristics of the device [4, 6, 7]. In the context of radiation sensor applications, a p-channel transistor has an advantage over an n-channel transistor: because of the hole trap mechanism, the current always decreases in a p-channel transistor and its threshold voltage always become more negative, as shown in Figure 1. Therefore, these parameters vary monotonically, in stark contrast with the behavior of an n-channel transistor. In an n-channel transistor, competition between the effects of charge trapped in the oxide and charge trapped in the oxide-semiconductor interface leads to a non-monotonic variation of the electrical parameters of the device.

![Graph showing the effect of ionizing radiation on the behavior of the p-MOSFET](image)

**Figure 1.** Effect of ionizing radiation on the behavior of the p-MOSFET when electric charges are trapped in the gate oxide and the Si/SiO\(_2\) interface.

Single Event Effects (SEE) are induced by the travel of a single energetic particle across the active region of a semiconductor device. There is a variety of effects depending on the geometrical and physical characteristics of the device and the location in the device where most of the charge is generated, for instance. In this paper, we will concentrate on single event upset (SEU). In a SEU, the charge generated in the sensitive volume of the device is collected, leading to a current pulse of short duration. This effect begins with energy deposition that results in charge generation (electron-hole pairs) in some target medium, either owing directly to the incident particle (direct ionization) or via secondary daughter products (indirect ionization). Electrons and holes move by diffusion and drift through the semiconductor until they are collected in the terminals, giving rise to a current pulse. The electric charge collected is proportional to the linear energy transfer (LET) by the ion on the device [8]. Figure 2 shows the typical pulse generated by SEU in a pMOS.
2. **Experimental Setup**

In this section we present the experimental setup used in the irradiations with X-rays and with heavy ion beams as well as a brief description of the preparation of the devices used in the tests. It is worth noticing that X-rays were used for tests of the device as a dosimeter and that the tests with heavy ions probed the suitability of the device as a particle counter.

2.1. **Preparation of the devices**

The DUTs used in this study were 3N163 pMOS transistors, as shown in Figure 3. Preparation of the devices consisted mainly in removing the metallic layer that protects the devices, reducing any interference this could have on the absorbed dose. The removal was done mechanically. Besides, this process also allows the heavy ions to reach sensitive parts of the device.

![Figure 3. Picture of the DUT 3N163.](image)

2.2. **X-ray Irradiation**

The DUT was submitted to an X-ray beam of 10-keV effective energy, produced by a *XRD-7000 diffractometer* (Shimadzu) of the Centro Universitário da FEI. This diffractometer was calibrated with an ionization chamber and the X-ray dose rate in silicon was calculated using air and silicon mass attenuation coefficients. For the irradiation procedure, the dose rate was set to about 16 rad/s with an accumulated dose of 1500 krad. During the irradiation, the DUT was placed perpendicular to the X-
ray beam; it was operating in the linear region, using a drain voltage $V_D = 0.1 \, V$, and a gate voltage $V_G$ near the threshold voltage $V_T$. The $V_G$ value was calibrated experimentally, since it depends on the transistor type, through a precision potentiometer, connected to the transistor gate terminal. Readouts were done by monitoring the voltage $V_D$ on the drain, in order to observe possible deviations caused by the radiation effects on the transistor. These voltage values are acquired through a set of amplifiers, which wrap the signal acquisition system for the values that are within the full scale of the A/D system (0 V - 1.5 V). The information is collected and stored by an MSP 430 microcontroller (MCU), which is performed through software. Details about the bias circuit and signal measurements are shown in reference [9]. Figure 4 shows the MOSFET under test using X-ray radiation.

![Figure 4. X-ray System of the Centro Universitário da FEI.](image)

2.3. **Heavy Ion beam irradiation**

Tests on Single Event Effects were performed on the 8 MV Pelletron Accelerator of São Paulo University that provides heavy-ion beams in a wide range of masses and up to 75 MeV of energy. In tests with the 3N163 pMOS transistor for verification of their behavior as a detector of heavy ions, beams of $^{12}$C, $^{16}$O, $^{19}$F, $^{28}$Si, $^{35}$Cl, $^{63}$Cu and $^{107}$Ag were scattered at $15^\circ$ by a 275 $\mu g/cm^2$ gold target, which provide LETs from 4 to 40 MeV/mg/cm$^2$. All tests were performed in a vacuum chamber, as shown in Figure 5.
The signal readout was done using a 1 GHz oscilloscope with an ADC of 10 Gsamples/s which allowed us to register short-duration drain current pulses. Beam monitoring was done using surface barrier detectors. More details of the experimental apparatus can be seen in references [10,11].

3. Results

3.1. The device as a dosimeter

Figure 6 shows the monitoring of drain current as a function of the accumulated dose in the DUT 3N163. The fitted trend lines allow us to interpret this result as a calibration curve in X-ray radiation doses [9]. Besides, it provides a way to perform real-time radiation dose monitoring. The best fit found for the current it is very close to a linear relation with dose as it can be seen in the figure when comparing with the fit using a straight line.

In accordance with that reported in reference [9], through this study it is possible to observe the behaviour of a device widely used in industry when subjected to ionizing radiation of the X-ray, whereas the drain current decreases as a consequence of the cumulative dose. With these obtained results, it was possible to develop a study that suggests the use of this type of transistor as a simple, efficient and inexpensive dosimeter, since it requires less complex electronics, and can be widely used in radiation studies in various fields such as medicine, radiation protection and reliability evaluation.
Figure 6. Linear response of the drain current as a function of the total ionizing dose accumulated in DUT 3N163.

3.2. The device as a particle counter

The charge collected on each current pulse generated by the passage of an ion through the device was determined from the analysis of the voltage pulses as a function of time. Figure 7 shows different pulses recorded by the oscilloscope for four different ion beams: $^{16}$O, $^{19}$F and $^{28}$Si. It is possible to observe that the time duration and the shape of peak voltage vary with the ion beam. The voltage peaks related to the silicon ions are higher than the other peaks, while the peaks for oxygen are less resolved. To calculate the charge collected by the terminals of the DUT, only the first peak of each signal was considered, i.e., only the prompt charge collection was estimated in this work.
Charge collected by the terminals of the 3N163 when exposed to different heavy ions is presented in Figure 8. It is important to note that since the device is a simple p-type CMOS transistor, the charge collected is, to a very good extent, proportional to the ion LET. In Table I, the values of energy for each ion used in this experiment are presented.

| Ion   | Energy (MeV) |
|-------|--------------|
| $^{12}\text{C}$ | 45.00 (3)     |
| $^{16}\text{O}$ | 52.50 (3)     |
| $^{19}\text{F}$ | 42.00 (3)     |
| $^{28}\text{Si}$ | 66.00 (3)     |
| $^{35}\text{Cl}$ | 75.00 (3)     |
| $^{63}\text{Cu}$ | 82.00 (3)     |
| $^{107}\text{Ag}$ | 97.50 (3)     |
Cross section for the occurrence of an upset as a function of the incident ion LET for the 3N163 transistor is shown in Figure 9. The results indicate that $^{12}$C ions produce less upset events than the higher LET, heavier ions. For a LET above 10 MeV/mg/cm$^2$, approximately, SEE cross section achieves a roughly constant value of $\sigma \approx 2.5 \times 10^{-5}$ cm$^2$ [10]. The results indicate also there is a same proportionality factor in the number of SEU and the incident number of heavy ions from LET around 10 MeV/mg/cm$^2$ to LET=40 MeV/mg/cm$^2$, allowing to use the 3N163 pMOS transistor as a LET independent particle counter.
4. Conclusions

This work shows strong indications that it is possible to develop a low-cost, yet efficient, radiation monitor instrumentation using a commercial pMOS transistor. The tests performed indicate that the device is capable of measuring the total dose accumulated, and also of monitoring the number of impinging particles. The relationships between drain current and accumulated dose, and between collected charge and linear energy transfer, were observed during the tests. Additionally, a cross section for the occurrence of SEE was determined for the 3N163 transistor. New radiation tests should be performed to evaluate the behavior of this mechanism to other accumulated dose ranges.

5. References

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