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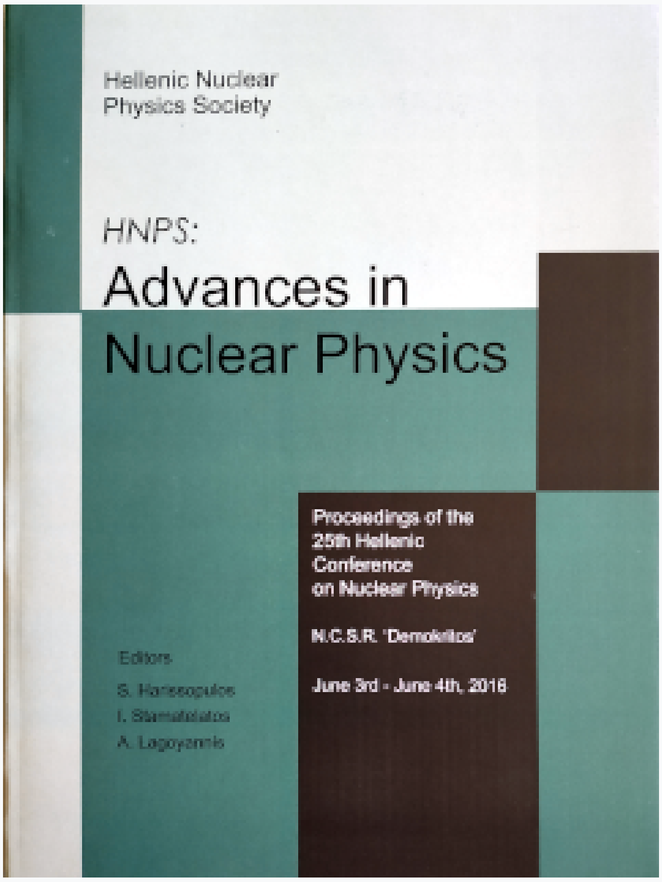

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A STUDY OF THE RESPONSE OF DEPLETED TYPE p-MOSFETs TO ELECTRON DOSES

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Abstract

A study of depleted pMOSFETs characteristics performed with electrons, at energies ranging from 6 to 15 MeV delivered by Linac medical accelerator. The depleted pMOSFETs present high sensitivity to electron doses. Linear threshold voltage shift with dose was measured for all the electron's energies studied. A small decrease of the response was observed with dose rate during irradiations which can be attributed to ELDRS effects.

1. INTRODUCTION

Silicon is an active material of radiation detectors and the basic material of electronic devices used in the fabrication and development of electronic circuits. The present technology is evolving towards the creation of faster and less power consuming devices of increasingly small sensitive volume and higher density circuits, achieving new submicron technology with an increase in the number of the memory elements. These devices are then used for applications in several fields including particle physics experiments, reactor physics, nuclear medicine, cosmic rays and trapped particles of various origins in interplanetary space and/or Earth magnetosphere **[**1]**.** The continuous evolution of mission requirements and their electronic technologies for spacecraft, combined with the need to meet the space environmental constrains, particularly radiation, constitutes challenges for component engineers and designers, especially for space craft dosimetry [2,3].

In medicine, Diagnostic Radiology often involves the use of ionizing radiation to acquire images for disease diagnosis and treatment [4, 5, 6]. Recent advantages in imaging technology have led to an increase in the use and application of medical imaging. There has been, so, an increase in population radiation dose as a result, related to the exposure of patients during routine examinations.

Among the wide variety of radiation detectors available for dose measurement the most commonly used include Thermoluminescent dosimetry (TLD), Silicon

Diodes and Metal-Oxide-Semiconductors Field Effect Transistors (MOSFETs). The MOSFET dosimeter advantages, in comparison with other dosimetric systems include immediate read out (real time measurement) of the dosimetric information while they can be used in passive mode [7]. They have extremely small size of the sensor element, wide dose range, very low power consumption and they present compatibility with microprocessors.

This work refers to the study of electron's dosimetry with depleted p-MOSFETs. The dosimeter has been used with success to neutron dosimetry with appropriate converters [8, 9]. The interest to measure radiation dose from electrons is mainly due to their application in medicine and space activities where the field of radiation is complex constituting by radiation of low and high LET radiations. The application in medicine referred to the fact that small superficial cancerous lesions are typically treated with electrons [4, 10, 11]. The knowledge of the precise radiation dose delivered to the treatment volume is crucial. The dosimetry of such small electron fields requires dosimetric measurements with small area detectors, as the MOSFETs detectors of high performance. The space application of MOSFETs to space dosimetry concern the possible biological effects induced by radiation, among them by electrons in astronauts. Electrons have a considerable contribution in the outer radiation belt of Van Allen belts region inside the Earth magnetosphere having energies distributed up to 10 MeV. In the inner radiation belt there are fewer electrons, of lower energy, up to 0.5 MeV [1]. Although the radiation weight factor is low, they release radiation dose mainly for missions of long duration and during extra vehicular applications.

2. EXPERIMENTAL

The p-MOSFETs used in the present study are of depleted type and were fabricated at LAAS-CNRS, Toulouse, France, following a process designed for improving both sensitivity to radiation dose and stability. The sensitivity of the dosimeter is one of the main objectives when designing MOSFETs for radiation dosimetry purposes. One of the possible ways to enhance the sensitivity is by increasing the gate oxide. For this reason the MOSFETs used in this study they have fabricated with thick gate insulator of 1.6 μm. They have 3 μm of LiF deposited on the surface of the MOS gate in order to be used especially for neutron dosimetry [9, 12, 13]. The devices can operate in real time mode as well as in passive with high performance.

An automated instrumentation configuration based on a microcontroller, a memory and A/D converters has been designed and fabricated at the Electronics and Computer Laboratory of the University of Thessaloniki [14]. The device retained the time of the run as well as the threshold voltage V_t at each time of measurement. The system was able to measure the threshold voltage shift due to radiation dose with precision of the order of 100 μV. The storage of measurements was set to one second. The dose induced in SiO_2 is based on appropriate calibration of the threshold voltage shift as function of the dose, in known neutron fields as well as in photon and electron beams.

The pMOSFET devices used in this experiment were irradiated with electrons at the Linac of Anticancer Theageneio Hospital of Thessaloniki at the isocentre. The beam was collimated in circular shape of 4cm in diameter and was oriented perpendicular to the SiO_2 surface. The irradiations were performed at the isocentre. The response of the device was studied at 6, 8, 10, 12 and 15 MeV electrons with a dose rate of 4 Gy/min. Measurements were taken with the device operated in real time mode. Dose rate effects were studied with 6 MeV electrons at 1, 2 and 4 Gy/min.

3. RESULTS AND DISCUSSION

Radiation creates electron-hole pairs in the gate oxide, electrons are swept of the gate oxide, but the holes drift towards oxide/Silicon interface and get trapped near the interface, giving rise to oxide charge and interface traps. The trapped charges affect the gate voltage by reordering of charges. The measurement of the threshold voltage shift is proportional to the absorbed dose [6, 15-17].

The threshold voltage shift, ΔV_t, which is the measured quantity, depends on the dose collected in the SiO_2. The dose collected is a function of the a) the incident particle type and energy according to the energy deposition, (dE/dx) b) the ionizing particle penetration into the oxide c) the absorbed dose, D, d) the gate bias during irradiation and e) the gate insulator thickness [12, 18-20].

In the present experiment zero bias was used. For this case there is no evidence of "strechout" in the sub-threshold characteristics. Thus for zero biased devices trapped oxide charge predominates and the response of a p-MOS dosimeter is measured by the voltage shift ΔV_T which is related to the absorbed dose as [15, 21]:

$$\Delta V_t = aD^b \qquad [1]$$

The quantity ΔV_t indicates the difference V_t-V_{to}, where V_t and V_{to} are the pre and post irradiation threshold voltage respectively. The power **b** refers to the degree of linearity and depends on the oxide thickness, the internal electric field and the mode of operation. In the case where parameter b is close to the unity, the behavior of ΔV_t relative to the absorbed dose is linear thus the parameter **a** represents the sensitivity of the MOSFET dosemeter.

The threshold voltage shift, ΔV_t, depends on the oxide thickness, t_{ox} [7, 8]:

$$\Delta V_t^2 \approx 2.2 \cdot 10^{-3} D^{0.4} t_{ox}^2 \qquad [2]$$

as well as the type and energy of radiation. In the above relation D represents the absorbed dose.

In **table 1** the parameters **a** and **b** (relation (2)) corresponding to the experimental conditions are given. The values of the parameter **a** derived by fitting the experimental data of ΔV_t –Dose curves, are shown in **Fig. 1** for each energy of electrons. The total shift of the threshold voltage ΔV_t is a linear function of the dose collected by the interactions of electrons with the oxide (parameter b, Table 1).

Table 1. The values of the p-MOSFETs response and their degree of linearity, parameter b, versus electron dose. The fitting quality gives $R^2 > 0.99$

E, MeV	*a, mV/Gy*	*b*
6	66.20 ± 0.11	0.96 ± 0.01
8	91.36 ± 0.08	0.95 ± 0.01
10	101.93 ± 0.08	0.95 ± 0.01
12	124.43 ± 0.76	1.03± 0.02
15	177.36 ± 0.76	1.02 ± 0.03

A linear behavior is also measured in pMOSFETs irradiations with electrons [10] and protons [22, 23]. In photon irradiations MOSFETs present also linear behavior [15, 17, 19, 21, 24, 25].

The response of the depleted pMOSFETs used in the experiment behaviors with high sensitivity comparing to the enhancement type pMOSFETs irradiated with electrons. Note that published data correspond mostly to devices operating in biased mode [10, 21, 26] while our results were taken at zero bias. The response measured in the present experiment is higher than the published results for photons and electrons of high energy for various types of MOSFETs operating in unbiased mode.

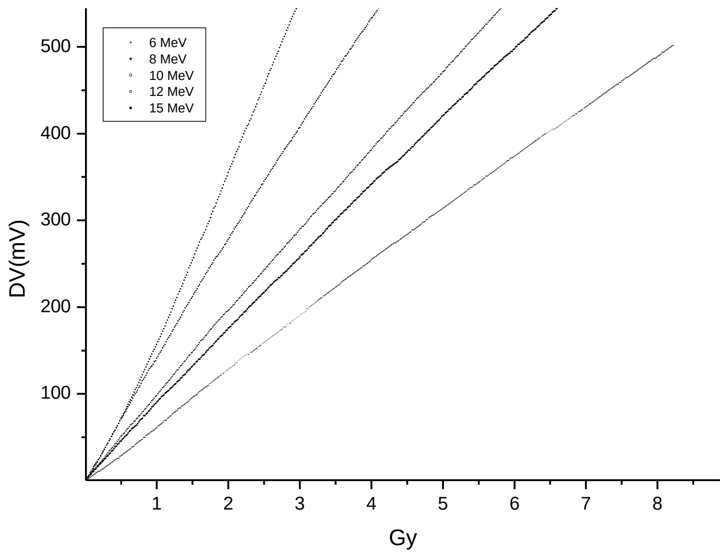

Figure 1. The threshold voltage shift of the dosemeters as a function of the dose for various electron beam energies

In the present experiment an increase of the response with electron's energy was measured, **Fig. 2.** For the irradiations employed ionization process, in the gate oxide, is dominant (as a direct interaction of electrons) and the storage of positive oxide charge contributes mainly to the threshold voltage shift. This quantity is depended on the quality of the incident radiation and can be understood considering that particles with higher energy loss (or LET) will leave along their path a high density of electron-hole pairs. Electrons having low energy loss (and LET) give a relatively low sensitivity comparing to the proton one (or higher LET particles).

The increase of sensitivity with electron's energy, as it is observed in the present experiment, can be connected to electron's stopping power behavior with energy [29]. The electron's energies used correspond to the increasing part of the stopping power curve which presents a minimum around 1 MeV. Thus for lower electron energies the behavior of the response with energy is expected to be inversed. Such effects are observed during measurements in irradiations with electrons from beta sources [30]. The same behavior is clearly observed in irradiations with protons and depends on the LET of the proton beam, i.e. the range of energies under study [22, 23].

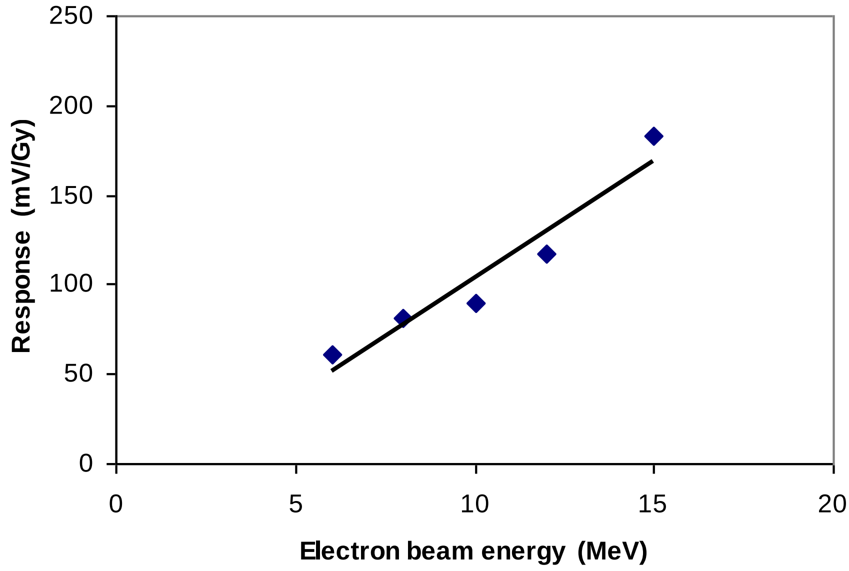

Figure 2. The Linearity of the dose response as a function of the energy of the electron beam

4. DOSE RATE EFFECTS ON DEPLETED PMOSFETS RESPONSE.

A small increase of the response with decreasing dose rate (at low dose rates) is observed in the depleted pMOSFETs of the present study. For the study electrons of 6 MeV was used. Dose rate effects are not observed in most of the published data referred to electron irradiations probably because the experiments were performed in biased mode operation or they correspond to thin oxide devices. In most of publications dealing with photon and electron irradiations a dose rate dependence of the response is not measured [10, 15, 17, 26, 31]. Small changes in sensitivity were reported in irradiations with photons [32]. Clear dose rate dependence is presented in irradiations with photons of ^{60}Co. This work refers to implanted nMOSFETs [33]. In irradiation with electron beams an indication for small dose rate dependence is observed in Ref. [4].

The behavior of the MOSFETs response against dose rate as it is measured in the present experiment is given in **Fig. 3.** The linear behavior of the dose response curves is conserved with the dose rate. The decrease of the response with dose rate is connected to ELDRS effects. Recent studies [**34, 35]** indicated that specific p-channel MOSFETs exhibits ELDRS effects in the space radiation environments. The radiation damage for pMOSFETs between high and low dose rates is different, so influences the calibration which in laboratories is performed in higher dose rates. As a result corrections are necessary for space applications were dose rates are very low.

Both effects, of energy and dose rate dependence of the response are connected also to the thickness of the oxide layer (equation 2) as the energy deposition by electron's follow the stopping power behavior. In MOSFETs with thin oxide layers these effects are of less importance.

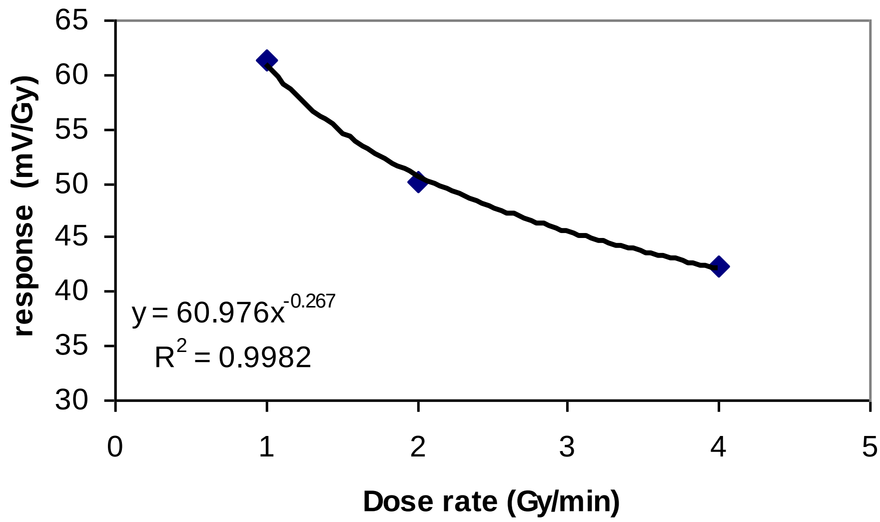

Figure 3. The dose response as a function of the dose rate of the electron irradiation

4. CONCLUSION

The dose response of the depleted pMOSFETs (with Li deposition) was studied in case they irradiated with electrons of energies ranging from 6 to 15 MeV.

The variation of the threshold voltage as function of the absorbed dose presented linear up to about 10 Gy for all the energies of electrons studied in agreement with previous studies with photons and electrons.

The response of the depleted type of p-MOSFET dosemeters presented higher than the published responses of the enhancement type devices. This result was expected according to the mechanism of the depleted devices operation. A detailed description is given by Mathur [36,37]. The response values of the depleted pMOSFETs to electrons are of the same order with those of low energy photons and fast neutrons. The magnitude of the dose response is expected to be increased even more, about one order of magnitude, if a bias applied in the source of the dosemeters during the irradiation.

A linear dependence of the dose response from electron's energy is measured. This behavior of pMOSFETs, when irradiated by electrons, is connected to the absorption of electron's energy in the oxide and follows the curve of stopping power with energy.

The dose response of the dosemeter as function of the dose rate was also investigated for 1, 2 and 4 Gy/min for electrons of 6 MeV. A small dependence of the dose response on dose rate during irradiation is observed. This behavior is connected to the thick gate oxide as well as to ELDRS effects.

Although the devices used in the present experiments were fabricated especially for neutron measurements, where they show high response, mainly to thermal neutrons, they present advantageous characteristics as the high response, the perfect linearity and reproducibility so that they can be used in dose measurements from other type of radiations. Their use in medical applications, however after an appropriate calibration, is indicated as the treatment plans includes accurate electron energy and dose rate.

The radiations of low LET present low dose rates in space and they participate with an important amount to the total dose measured. Space dosimetry with the depleted pMOSFETs (with Li deposition) can successfully be applied because in addition to their high response in neutrons respond also well in photons and electrons [38]. Also they fulfill all the technical requirements for dose measurements in space.

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