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## High sensitive depleted MOSFET-based neutron dosimetry

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### Abstract

A new dosimeter based on a depleted Metal-Oxide-Semiconductor field effect transistor, sensitive to both neutrons and gamma radiation was manufactured at LAAS-CNRS Laboratory, Toulouse France. In order to be used for neutron dosimetry a thin film of lithium fluoride was deposited on the surface of the gate of the device. The characteristics of the dosimeter such as its response to neutron dose were investigated. The response in thermal neutrons was found to be high. In fast neutrons the response was lower than that of thermal neutrons but higher than the one presented in literature.

### 1. Introduction

Metal-Oxide-Semiconductor Field Effect Transistor (MOSFET) dosimeters have numerous advantages such as: low cost, small size and weight, robustness, accuracy of measurement, real-time or delayed direct read-out, information retention with small fading, possibility of integration with other sensors and/or circuitry. In addition they can be used without power supply during irradiation i.e as passive dosimeters for dose measurements of large ranges, which is very important for a dosimeter. These advantages prove that MOSFET's can be successfully applied in dosimetry. They have been used in several application fields [1,2] especially in gamma and neutron dosimetry. It was found that this kind of dosimeters are not significantly influenced by neutrons [3] and the response, if any, is mainly due to the interaction of neutrons with the packaging [4, 5]. However they can be used as a neutron dosimeter when an appropriate converter is applied [6-8]. In addition, by

using two dosimeters, with and without LiF converter, gamma rays can easily be discriminated by neutrons.

In literature thermal neutron doses measured by MOSFETs are rarely presented. The published data show that the response to fast neutrons is very low (of the order of 0.01 mV/mGy) due to the large distance between the converter and the detector [5, 8]. In addition, the lower detectable dose of these dosimeters is very high, about 1mSv. Especially for personal dosimetry the lower detectable dose is a very important parameter as it is required to be as low as possible for practical applications. Therefore, the study of the characteristics of MOSFETs have to be continued, even for lower doses, in order to be applied in gamma and neutron dosimetry.

In the current study in order to increase the MOSFETs sensitivity in neutron dosimetry LAAS have create a new set of MOSFETs and covered by a layer of LiF. These MOSFETs are of depletion type – their channel is pre-fabricated – presenting a positive threshold voltage and they have a thick gate insulator. They can be used for both thermal and intermediate-fast neutron dosimetry. The effect of neutron irradiation on the threshold voltage of these new transistors was studied in order to determine their sensitivity.

## 2. Experimentals

The p-type depleted MOSFETs with 1.6  $\mu\text{m}$  thick gate insulator studied in the present work were developed at LAAS-CNRS, Toulouse. As it is known from previous studies in the literature thick  $\text{SiO}_2$  p-MOSFETs present a high negative threshold voltage of the order of several Volts [9]. The p-MOSFETs used in the present study were fabricated following a process designed for improving both sensitivity to radiation dose and stability and operate with a positive threshold voltage. A 3  $\mu\text{m}$  thick LiF converter was deposited on the surface of the MOS gate in order to be able for neutron dose measurements. With this converter neutron doses of thermal up to fast neutrons can be determined, from the charge collection of the alpha particles' emitted via the  ${}^6\text{Li}(n,\alpha){}^3\text{H}$  reaction. The alpha particles cause electron-hole pairs in the insulator. Recombination of the generated pairs takes place and those holes which escape recombination are trapped close to the oxide-silicon interface. As a result, the positive charges which are stored in the gate oxide lead to a shift of the

transistor threshold voltage  $V_T$ . The threshold voltage shift,  $\Delta V_T$ , which is the measured quantity, depends upon the incident particle type and energy, the ionizing particle penetration into the oxide, the absorbed dose, the gate bias during irradiation, the gate insulator thickness, the temperature during measurement and processing parameters. Irradiations were performed at different positions inside the subcritical reactor of the Nuclear Physics Laboratory of the Physics Department/Aristotle University of Thessaloniki, Greece. In order to measure thermal neutrons and intermediate-fast neutrons, 2 dosimeters were irradiated at the same position inside the sub-critical reactor. The first sensors were in contact with LiF converter, while the second was additionally covered by 1mm thick Cd layer. The Cd covered detector was used to measure the response of the dosimeters to intermediate-fast neutrons. The response of the dosimeters to thermal neutrons can be obtained by subtracting the shift of  $V_T$  of Cd covered from Cd un-covered detector.

An automated instrumentation configuration based on a small microcontroller was used to collect data from multiple measurements [10]. During measurement the MOSFETs were diode connected (gate and drain grounded) while the source was fed by a constant current of 100  $\mu$ A. The difference  $\Delta V_{out}$  between output voltages, taken from the source terminal, before and after irradiation corresponds directly to the threshold voltage increment and can be connected to the dose absorbed by the device in the time interval between the two measurements.

### 3. Results and Discussion

The response of a MOSFET dosimeter can be influent by applying a voltage to the gate of the transistor during the radiation exposure. In personal dosimetry an unbiased dosimeter is preferable and for that reason in these experiments the irradiated dosimeters were chosen to be unbiased. For this exposure mode, usually called zero bias mode, the expected response of the voltage shift  $\Delta V_T$  follows a power-law [5,11]:

$$\Delta V_T = aD^b \quad (1)$$

Parameters  $a$  and  $b$  were experimentally determined. Parameter  $b$  was found to be close to the unity then the response of the MOSFETs can be expressed by parameter  $a$ .

In order to detect neutrons, the p-MOSFETs with LiF converter were irradiated by thermal and intermediate-fast neutrons in calibrated neutron mixed fields. For the conversion of neutron fluence to ambient dose equivalent, appropriate conversion coefficients neutrons to  $H^*(10)$ , for thermal and intermediate-fast neutrons, was used [12]. The threshold voltage shift, of the MOSFET dosimeters with LiF converter was measured. The corresponding component to gamma rays was subtracted from the total MOSFETs response.

In each position of irradiation the calibrated neutron field contains an almost equivalent number of intermediate-fast and thermal neutrons. The LiF converter mainly was used for thermal neutron detection, because of the high Li (n, a) reaction cross section in thermal neutrons (about  $10^3$  barns for  $^6\text{Li}$ ). However the same converter can also be applied for the detection of intermediate-fast neutrons although the reaction cross section is much lower than the corresponding to thermal neutrons, but not negligible, of the order of 1 barn. Therefore two MOSFET dosimeters with LiF layer were irradiated in each position. The one of them was additionally shielded with Cd layer of 1 mm in thickness, which absorbs the 90% of thermal neutrons. By this detector arrangement it is possible to take information about the response of the dosimeters to intermediate-fast neutrons. While from the subtraction of the voltage shift of the Cd covered dosimeter from the Cd un-covered one the response to thermal neutrons can be deduced. The threshold voltage shift as a function of neutron dose, for both thermal and intermediate-fast neutron components, is presented in Figs 1.a and 1.b respectively. A power function fitted the response curve and the results are presented in table 1. Parameter b for thermal neutrons was found to be close to 1, ( $1.13 \pm 0.001$ ), indicating the linear behavior of the threshold voltage variation with neutron dose. In the case of fast neutrons the fitting of the response curve was performed after the subtraction of gamma ray contribution. Parameter b was found to be around 1, ( $0.97 \pm 0.002$ ) which was very close to the behavior of irradiated MOSFETs by gamma rays.

The response of the dosimeters to thermal neutrons was found by the same practice as in the previous experiments [11]. Its value was found to be 1.58 mV/mSv (8.13 mV/mGy), much higher than their response to intermediate-fast neutrons which is 0.017 mV/mSv (0.22 mV/mGy). These values show that the response of the MOSFETs was improved compared to the response obtained in previous studies in which LiF powder was deposited on the gate surface [13]. This response is also higher

than previously reported in the literature with different neutron converters such as Gd in which the sensitivity to thermal neutrons was found to be 1.5-1.6 mV/mGy [7]. Although pin diodes are not of the same construction their response presented lower than that of the MOSFETs studied in this work (40 k $\Omega$ .cm, 5 V/Gy especially for thermal neutrons) [14].

The almost linear behavior of the MOSFETs response curve to intermediate-fast neutrons can be shown in fig. 1b. The sensitivity resulted by the estimated parameter  $a$ , was found to be  $0.0165 \pm 0.001$  mV/mSv. This value was clearly lower than that obtained for thermal neutron, Table 1. The effect can be attributed to the lower  ${}^6\text{Li}$  (n,  $\alpha$ ) reaction cross section at intermediate-fast neutrons. The new p-MOSFETs are operating in depletion mode compared to the enhancement mode ones studied in previous experiments and they present a response lower than the one reported for fast neutrons using a polyethylene converter (0.01 V/Gy) [5].

## Conclusion

p-MOSFETs are promising devices for their use in radiation dosimetry. In order to improve their characteristics and prolonged their use in neutron dosimetry new p-MOSFETs were fabricated at LAAS-CNRS Toulouse, France. They had 1.6  $\mu\text{m}$  thick gate oxide and positive threshold voltage. To enhance the sensitivity to neutrons a layer of 3  $\mu\text{m}$  LiF was evaporated on the surface of the transistors gate. These dosimeters working in the unbiased mode present high response to thermal neutrons, which is about two orders of magnitude higher than the measured one for intermediate-fast neutrons.

An important result deduced from this study is the almost linear response of the new p-MOSFETs observed. This behavior is valid for a wide neutron dose range, from  $\mu\text{Sv}$  up to Sv giving good flexibility to use p-MOSFETs in personal dosimetry as well as for environmental monitoring. Further study dedicated to the lower detection limits has to be done in order to be used for personal dosimetry.

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**Table 1.**

**Characteristics of the new depleted MOSFET dosemeters**

<i>Type of radiation</i>	<i>Applied current</i>	<i>Response ( mV/mSv)</i>	<i>Response ( mV/mGy)</i>	<i>b parameter</i>
Thermal neutrons (up to 1eV)	100 $\mu$ A	$1.580 \pm 0.002$	$8.13 \pm 0.01$	$1.13 \pm 0.001$
Intermediate-fast neutrons ( above 1 eV)	100 $\mu$ A	$0.017 \pm 0.001$	$0.22 \pm 0.13$	$0.97 \pm 0.002$

### Figure Captions

**FIG 1a.** The response of the depleted p- MOSFET dosemeters to thermal neutrons.

**FIG 2b.** The response of the depleted p- MOSFET dosemeters to intermediate-fast neutrons





