Sensors and Actuators A 210 (2014) 175–181

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

journal homepage: www.elsevier.com/locate/sna

General purpose MOSFETs for the dosimetry of electron beams used in intra-operative radiotherapy

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ARTICLE INFO

Article history:
Received 31 October 2013
Received in revised form 12 February 2014
Accepted 13 February 2014
Available online 2 March 2014

Keywords:
MOSFET
Dosimeter
Intra-operative radiotherapy
Electron beams

ABSTRACT

The experimental response of different commercial metal-oxide-semiconductor transistors to electron beams in order to check their capabilities as radiation sensors for intra-operative radiotherapy treatments is studied. The main characteristics of the radiation response, such as sensitivity and reproducibility, have been determined using measuring algorithms previously developed by our research group for photon beams and which allow, among other advantages, the thermal compensation of the devices. Reproducing typical intra-operative radiotherapy treatment sessions, several vertical and lateral p-channel transistors in different configurations (single and two stacked transistors, unbiased and biased during irradiation) have been studied. Non zero temperature coefficients are presented in the analyzed vertical transistors (BS250F, ZVP3306 and ZVP4525) and their responses show a linear behaviour with a low dispersion in the results obtained for all the studied devices. Though all of them appear to be reliable for electron dosimetry, the best candidates are the transistors included in the well known integrated circuit CD4007, due to its higher sensitivity and better thermal compensation. In this case, a sensitivity of 13 ± 1 mV/Gy to 6 MeV electron beams has been measured with two stacked devices in biased mode. Linearity and uncertainty are comparable to that of commercial dosimetry sensors, while sensitivity is smaller.

1. Introduction

Intra-operative radiotherapy (IORT) is a technique in which therapeutic levels of radiation are applied to a target area while it is exposed during surgery. IORT is a complementary technique to surgery, used just after removing the tumour, with the patient lying on the stretcher, and aiming at destroying the remaining cancer cells on the edge of the tumour [1]. In IORT electrons beams or low-energy X-rays are used as ionizing radiation sources and the absorbed doses range from 10 Gy, in combination with external radiotherapy treatments, up to 30–35 Gy, in case of a single irradiation session. The beam energy depends on the depth of the tumour.

IORT requires an accurate dosimetric control. In vivo dosimetry of radiotherapy treatments can be carried out using different types of sensors: ionization chambers, thermoluminescent crystals (TLDs), diodes and metal-oxide-semiconductor field effect transistors (MOSFETs) [2,3].

In the last few decades, commercial dosimetry systems for photon beam radiotherapy, based on p-channel MOSFETs (pMOSs) have been developed. These devices show a number of advantages over traditional dosimetry systems in medical applications [4,5]. The most important ones are an immediate and non-destructive readout, a low power consumption, an easy calibration, a permanent storage of doses and a reasonable sensitivity and reproducibility [6–10]. Recently, reliable MOSFET dosimetry systems for IORT have been analyzed [11,12].

MOSFETs commonly used in dosimetry systems are the so-called RADiation sensitive Field-Effect Transistors (RADFETs). The sensing principle of these devices is based on the electron–hole pairs that are radio-induced in the gate-oxide of the transistor and create additional oxide trapped charge, producing a threshold voltage shift, ΔV_T. RADFETs are manufactured using a special process to achieve a thick gate oxide that increases the sensitivity at higher cost than general purpose MOSFETs. In order to find a cheaper alternative, it is worth to study the behaviour of low-cost (<1$) general purpose commercial MOSFETs as dosimeters. In previous studies

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http://dx.doi.org/10.1016/j.sna.2014.02.019
0924-4247/

[13–16], the response to gamma radiation of this kind of MOSFETS was analyzed. To our knowledge, this characterization has not been extended to electron beams [10,17,18].

In the present work, the response of different models of low-cost commercial pMOS transistors that could be good candidates as radiation sensors for electron beams are studied. As in many cases, IORT involves a single irradiation session, the sensitivity of the dosimeter must be higher than in case of conventional external treatments, in order to guarantee a reliable measurement of the delivered dose. During the IORT, the thermal contact between the MOSFET and the patient's body may not be good nor repetitive, therefore temperature compensation is needed to reduce errors in the reading process. Commercial MOSFETs show usually small oxide thicknesses and biased and stacked configurations are expected to increase the sensor sensitivity [2,6,9,19–22]. In the present work different biased (with different gate voltages) and single and stacked (with two transistors) configurations have been analyzed, with four configurations for each one of the different pMOS models considered.

2. Materials and methods

2.1. MOSFET selection and configurations and irradiation setup

The first step was the selection of commercially available pMOSs in order to study their response to electron beams. The pMOSs availability in the market is huge, and there are transistors with different structures and configurations. The response to ionizing radiation is expected to be affected by the physical structure of each transistor; therefore it is worth to analyze the response of different models. A very important consideration is that pMOSs must be used without metal encapsulation, because, as it is well known, electron beams cannot be applied over metals during radiotherapy treatments. This is due to the fact that electron are absorbed by thin layers of metal or plastic, without reaching the patient [3].

A common structure in the case of general purpose transistors is the vertical diffused MOS, also called double-diffused MOS or simply DMOS, which are mainly used with power MOSFETs. During the last two decades some authors have studied the performance and capabilities of the DMOS in a radiation environment [23–26]. Special attention was paid because some of these transistors include body diodes as parasitic devices. Among the commercially available transistors, we had considered those designed for small signal, having no metal encapsulation and the maximum gate-source voltage (this last as an indication of a relatively thicker gate oxide). The models of this type selected were the very common DMOS models BS250F, ZVP3306 and ZVP4525, all of them manufactured by Diodes Incorporated (Plano, USA).

Among the integrated circuits with pMOS transistors, we decided as a candidate the well-known lateral CD4007. We did not find significant differences between the two versions (surface-mounted and through-hole no metal package) of this device. This integrated circuit is composed of six transistors, three nMOS and three pMOS, and is available from several semiconductor manufacturers. In the present study devices manufactured by Texas Instruments (Dallas, USA) and NXP Semiconductors (Eindhoven, Netherlands) were chosen.

In our study we built up sensor modules including a single pMOS (see Fig. 1) or two stacked pMOSs (see Fig. 2). Therefore, the module consisted of one or two pMOS and one, two or three junction field-transistors (JFETs), with the corresponding discharging resistor, depending on the particular configuration. In the readout, the pMOS transistors operated in the saturation region and it was necessary to maintain short-circuited the gate and the drain terminals. This short-circuit was produced by cutting the JFETs. In the case of the configuration including two stacked pMOS devices, the drain and source connected to JFETs belong to different transistors (see Fig. 2b and d). To open the source and the drain terminals, these JFETs had to be cut-off. During the radiation process, all the terminals were short-circuited except the biased terminals of the transistor: the source and the gate. Therefore, it was necessary to open the

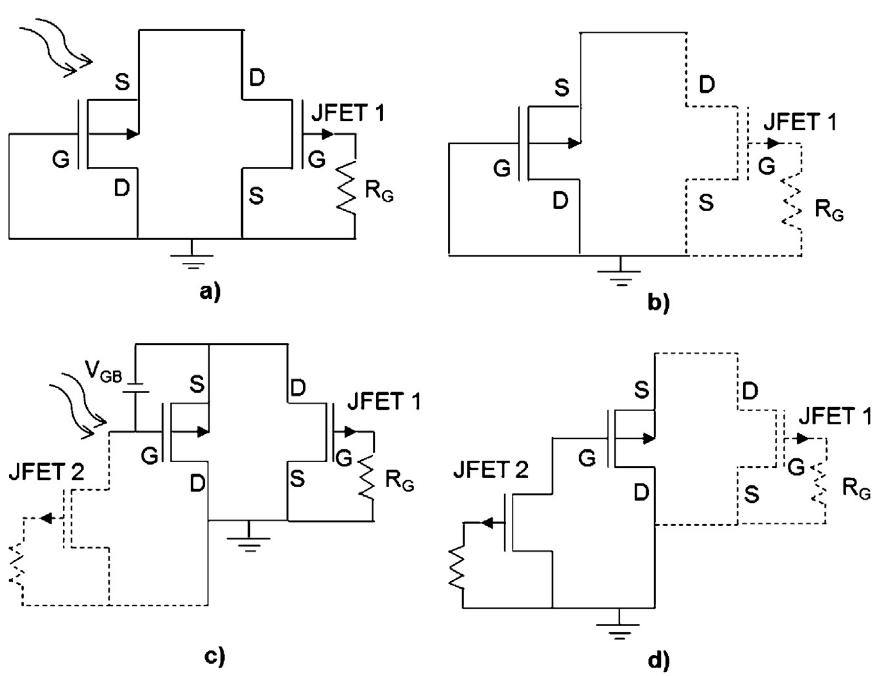

Fig. 1. Sensor module configurations with a single pMOS. (a) Unbiased mode: during radiation period the JFET is on and the terminals are short-circuited all together. (b) Unbiased mode: during readout process the JFET is cut-off. (c) Biased mode: during radiation period JFET2 is cut-off with a bias source between the gate and source. (d) Biased mode: for readout process JFET2 is on and JFET1 is off.