Applied Radiation and Isotopes 132 (2018) 1–5

Contents lists available at ScienceDirect

Applied Radiation and Isotopes

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

VDMOSFET as a prospective dosimeter for radiotherapy

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HIGHLIGHTS

- VDMOSFETs are suitable as dosimeters for radiation therapy.
- VDMOSFETs exceed RADFETs in sensitivity.
- VDMOSFETs are similar to RADFETs in the signal fading.

ARTICLE INFO

Keywords:
MOSFET
VDMOSFET
Dosimetry
Signal fading

ABSTRACT

Performance of a commercial *p*-channel power vertical-double-diffusion metal-oxide-semiconductor field-effect transistors (VDMOSFETs) as a γ-radiation dosimeters were studied. The devices were irradiated with ^{60}Co to 10–50 Gy at the gate biases ranging from 0 to 5 V, and subsequent dosimetric signal fading was monitored during room-temperature storage without a gate bias for 100 days. A linear relationship was found between the threshold voltage shift and the radiation dose for all values of the gate bias. Furthermore, a power-law relationship between the radiation sensitivity and the gate bias during the irradiation was revealed. The radiation sensitivity of these devices is higher than that of RADFETs with 100-nm-thick oxide gate layers manufactured by the Tyndall National Institute in Cork, Ireland. Room-temperature signal fading for VDMOSFETs is similar to that for RADFETs, i.e., the threshold voltage shift decreases slowly. A continuous annealing of VDMOSFETs at 150 °C for 27 days results in a significant decrease of the threshold voltage shift, especially during the first 7 days.

1. Introduction

Verification of doses delivered to patients is an essential process in radiotherapy treatments. The detectors most commonly used *in vivo* are thermoluminescence dosimeters (TLDs), semiconductor diodes and the metal-oxide-semiconductor field effect transistors (MOSFETs) (Cheung et al., 2003; Knoll, 2000; Siebel et al., 1990). The TLDs are tissue equivalent, fairly small, well characterized, commonly used detectors, which do not require voltage during measurements. However, they are not suitable for remote measurements, the readout of their dosimetric information is destructive, and the cost of the readout equipment is relatively high. Semiconductor diodes are another option for *in vivo* real-time dosimetry. However, they require a sensitive electrometer for readouts and additional operations to read the accumulated dose. Although diode dosimeters are sensitive to temperature and energy of the radiation beam, the necessary correlation and calibration factors are generally well known (Rosenfeld, 2006; Tung et al., 2008; Siebel et al., 1990).

Radiation-sensitive *p*-channel MOSFETs (also known as RADFETs or pMOS dosimeters) can also used not only in *in vivo* dosimetry (O'Connell et al., 1996; Kron et al., 2002; Currara et al., 2016), but also in personal radiation protection dosimetry (Sarrabayrouse et al., 2004), space radiation monitoring (Jaksic et al., 2002), and food irradiation applications (Faigon et al., 2008). These devices offer a number of advantages over other dosimeters (Black, 2003; Pejovic, 2016). The most important of them are immediate and nondestructive readout, easy calibration, permanent dose storage, reasonable sensitivity and reproducibility, small volume and weight, robustness of use, and accuracy of the dose measurements (Price et al., 2004; Nurul Amin et al., 2011).

Furthermore, RADFETs could be used in either active or passive mode (Pejovic, 2015a). In the active mode, the RADFETs need to be biased, but they do not need any voltage bias in the passive mode. However, disadvantages of RADFETs are that they require separate, individual calibrations in the fields of different modalities and energies, and are relatively expensive. Moreover, these dosimeters have a limited dynamic range of measurable doses because of the Si–SiO_2 interface charge saturation, which depends on the type and sensitivity of the

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http://dx.doi.org/10.1016/j.apradiso.2017.11.001
Received 17 March 2017; Received in revised form 31 October 2017; Accepted 1 November 2017
Available online 02 November 2017
0969-8043/

RADFETs. Once the upper limit of linearity between threshold voltage shift and the radiation dose is achieved, the RADFET needs to be replaced. It should be mentioned, however, that recent studies have shown that these devices can be recovered for re-use by storing them at elevated temperatures (Pejovic et al., 2013a, 2013b; Pejovic, 2013a, 2013b) or by annealing with current (Alshaikh et al., 2014; Luo et al., 2014).

The trend in investigations in the recent decades was towards the use of low-cost commercial *p*-channel MOSFETs as dosimeters in radiotherapy. It was shown that the power *p*-channel MOSFETs 3N163 could be used as dosimeters for measuring radiation doses up to 55 Gy without gate bias (Asensio et al., 2006). These devices have sufficient sensitivity along with satisfactory linearity and angular dependence of the response, which constitute the most important performance characteristics. A possibility of using commercial vertical diffused MOS transistors, also known as double-diffused MOS transistors or simply DMOS, as dosimeters for electron and photon doses up to 25 Gy was also investigated (Martinez-Garcia et al., 2014; Martines-Garcia et al., 2016). The investigated devices were DMOS BS250F, ZVP3306, and ZVP4525. It was also shown (Martinez-Garcia et al., 2014) that the *p*-channel MOS transistors from the integrated circuits CD4007 could be used as dosimeters. Results of a comparative study of RADFETs with the 100-nm-thick gate oxide layers manufactured by Tyndall National Institute (Cork, Ireland) and the commercial *p*-channel power vertical-double-diffused MOSFETs (VDMOSFETs) IRF9520 are given elsewhere (Pejovic, 2015b); they include sensitivities to γ-ray radiation in the dose range of 100–500 Gy. An important result was that the threshold voltage shift for the same radiation dose was higher for VDMOSFETs than for RADFETs.

The aim of this work was to investigate performance characteristics of the commercial *p*-channel power VDMOSFETs IRF9520 as dosimeters for photons in the dose range from 10 to 50 Gy. We investigated the linearity of the dose response and its sensitivity to the gate bias values during irradiations. Annealing of irradiated VDMOSFETs at room temperature and at 150 °C without a gate bias was also investigated to evaluate the stability of the dosimetric information in a long term.

2. Effects of ionizing radiation and postirradiation annealing on MOSFETs

The basic function of MOSFETs as ionizing radiation dosimeters is to convert the threshold voltage shift ΔV_T induced by radiation into the absorbed radiation dose D (Holmes-Siedle, 1974; Sarrabayrouse and Siskos, 1998). ΔV_T is defined as the change of threshold voltage V_T from the corresponding value in the unirradiated state V_{T0} (Frohlich et al., 2013):

$$\Delta V_T = V_T - V_{T0} = A{\cdot}D^n, \tag{1}$$

where A is a constant and n is the degree of linearity. The value n depends on such factors as the voltage applied during irradiation, the thickness of the oxide layer, and the absorbed radiation dose (Pejovic et al., 2012; Pejovic, 2016).

The sensitivity of MOSFETs to radiation is based on the formation of electron–hole pairs in the oxide layer under irradiation and generation of a positive trapped charge and the interface traps (Rosenfeld, 2002; Lipovetzky et al., 2007). A fraction of the holes that escape the initial recombination with electrons migrate towards the SiO_2–Si interface and get captured by the traps, which results in an increase of the positive charge. The trapping rate depends on the applied electric field (gate bias), the number of empty traps, and the capture cross-section area (Benson et al., 2006). The formed plane of the positive charge effectively changes the current in the channel of the MOSFET, which results in the corresponding change in the gate bias voltage ΔV_T (i.e., a shift in the threshold voltage) to restore the initial constant current through the channel (Rosenfeld, 2002). The current in the channel is very sensitive to the positive buildup charge as it is located very close to the channel. The interface trap generation is commonly accepted to be associated with intermediate processes involving the holes captured and released, and the migration of the hydrogen ions in the oxide (Fleetwood, 2002). Both the trapped positive charge and interface traps affect the threshold voltage shift in the *p*-channel MOSFETs in the same direction. Hence, the *p*-channel MOSFETs offer advantages over the *n*-channel MOSFETs when used as radiation dosimeters.

The sensitivity of MOSFETs can be controlled by the gate bias during the irradiation. MOSFETs can be biased (active mode) or unbiased (passive mode) during an irradiation. In the active mode, a positive voltage difference is applied between the gate and the bulk terminals, thus decreasing the probability of recombination of the radiation-induced electrons and holes in the gate oxide (Pejovic et al., 2011, 2014). An increase in the sensitivity can also be achieved by an increase in the gate oxide thickness (Pejovic, 2015a; Pejovic et al., 2013a, 2013b) and adjustment of the device processing conditions (Sarrabyrouse and Gessinn, 1994).

In addition to being sensitive to radiation, MOSFETs must also be stable over time after irradiation, i. e., the change in ΔV_T at room temperature must be only insignificant for a long period to preserve the dosimetric information. That is crucial because the dose cannot always be read immediately after irradiation. During annealing at room temperature, the density of the trapped positive charge decreases due to electrons tunneling from Si to SiO_2 (Pejovic et al., 2016). These electrons get captured and neutralized by the positively charged oxide traps, which adversely affects the threshold voltage shift.

3. Materials and methods

The experimental samples were commercial *p*-channel power VDMOSFETs IRF9520 manufactured by International Rectifier (El Segundo, CA, USA) with the continuous drain current of 6.8 A at room temperature and the drain-to-source breakdown voltage of − 100 V. These devices, produced by the standard poly-Si gate technology, had a gate oxide thickness of 100 nm and a hexagonal cell geometry. The initial threshold voltage of the virgin devices V_{TO} was − 2.6 V. The cross-section of the two half-cells of the *p*-channel VDMOSFET is described elsewhere (Davidovic et al., 2016).

The VDMOSFETs were irradiated at room temperature up to 50 Gy to silicon oxide at a dose rate of 0.02 Gy/s using a ^{60}Co source (Pejovic et al., 2016). Before the irradiation, the VDMOSFETs were divided into five groups. Every device in each group had a specific gate bias during the irradiation, namely, 0, 1.25, 2.5, 3.75, or 5 V. The variation of the sensitivity of the nominally identical devices was within 5% in all cases. After the irradiation, the VDMOSFETs were kept at room temperature for 100 days without a gate bias (all the terminals were grounded). Subsequently, the annealing process was continued at 150 °C for 27 days, also without a gate bias, in the HERAEUS HEP2 system (Thermo Fisher Scientific, Waltham, MA, USA), which provided stable temperature of 150 ± 0.5 °C.

The threshold voltage was determined from the transfer characteristics in the saturation, i.e., from the intersection of the V_G axis and the extrapolated linear region of the $(I_D)^{1/2} - V_G$ curve (I_D is the drain current, and V_G is the gate voltage) (Pejovic, 2016). A DC characterization of the devices before and after the irradiation and annealing was performed with the Keitly Semiconductor Characterization System Model 4200 (Pejovic, 2015a, 2017).

4. Results and discussion

Fig. 1 shows a relationship between the threshold voltage shift ΔV_T and the radiation dose D for the VDMOSFETs irradiated without a gate bias (V_{irr} = 0 V). Fig. 2 shows the same relationship for the devices irradiated under the gate bias V_{irr} = 5 V. These figures also show previously published results for RADFETs with a 100-nm-thick gate oxide layer manufactured by the Tyndall National Institute (Pejovic, 2015a).