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Evaluation of a low-cost commercial mosfet as radiation dosimeter

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Abstract

In this work, a low-power commercial MOS transistor was tested as a gamma radiation dosimeter. Due to the small size of its detector, low cost, reproducibility, minimal power requirements, signal conditioning and data processing, it offers excellent possibilities as a dose monitor in radiotherapy. Sensor irradiation in the unbiased mode was aimed at improving patient comfort and facilitating use. Uncertainties in the results were obtained from an exhaustive dosimetric study, following a full statistical study using Monte Carlo analysis techniques. A procedure to compensate for temperature effects was introduced in order to correct the dosimetric parameter extracted. Excellent linearity and good reproducibility were found in the accumulated threshold voltage shift as a function of the accumulated dose, up to 58 Gy (air equivalent). The uncertainty regarding sensor sensitivity was found to be less than 1% for individual device calibration. When collective calibration was carried out, the uncertainty was around 5%, accounting for a set of 31 devices. In this case, a mean value of 29.2 mV/Gy was obtained. In addition, the angular and dose rate dependencies showed good behaviour. These results suggest that the transistor studied would be an excellent candidate for use as the sensing device of a low-cost measurement system capable of in vivo dosimetry.

Keywords: MOSFET; Dosimeter; Radiation sensor; Gamma radiation

1. Introduction

Verification of the dose delivered to patients is an essential tool for controlling radiotherapy treatments. Dosimeters based on thermo-luminescent dosimeters (TLD) or PIN diodes are extensively used to measure ionising radiation. However, TLDs do not allow an immediate reading and their use is time-consuming, while PIN diodes require external connections to function. Recently, some advantages have been found in using p-channel metal-oxide-semiconductor transistors (pMOS) for this purpose. Among them, we would emphasise linearity, small detection volume, fast readout, portability, low power consumption and low radiation attenuation [1–3]. In fact, pMOS radiation dosimeters have found a wide range of applications in the fields of spacecraft, medicine, and personal dosimetry [4–8].

The sensitivity of a pMOS dosimeter basically depends on the gate oxide thickness and gate oxide growing process, the applied electric field during irradiation and the dose absorbed by the sensor [5,9–11]. Usually, a pMOS dosimeter, sometimes referred to as RADFET, has a gate oxide thickness of about 1 μm, and has been grown using a special process. During the last decade, technology in the field of dosimetry for radiation therapy has matured and several instruments with pMOS as radiation detectors have become commercially available [12,13]. These systems perform well but at a relatively high cost for the main frame and head sensors. Furthermore, they use specially-designed pMOS, with thicker gate oxides, operating with relatively large positive gate biases to ensure the efficient separation of electron-hole pairs generated within the oxide and therefore, increase sensitivity during irradiation. For this reason, the sensors require external connection during irradiations. On the other hand, floating gate MOSFETs, with no external bias supply, have also performed well as dosimeters [14,15]. However, as in the previous case, specially designed devices need to be manufactured if an efficient dosimeter response is to be guaranteed.

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In this work, we show that it is possible to use a commercially available transistor, manufactured with standard low-power enhancement mode lateral pMOS technology, as a radiation sensor for radiotherapy treatment dosimetry. Designing a low-cost hand-held measurement system using this pMOS as the sensor would have a clear advantage due to the lower cost incurred by a standard technological process. To achieve this goal, we performed an exhaustive study of the response of this commercially available pMOS transistor to gamma radiation. Aiming for simplicity and ease of use, this device was irradiated in the unbiased mode (all terminals shorted together) in order to analyse the radiation response without external connections. This makes it much more comfortable for patients than previous systems and easier for untrained staff to use. It is necessary to compensate for the well-documented low sensitivity of pMOS in unbiased mode by using an appropriately designed electronic measurement system in which the main limiting factor for resolution would be the low-frequency noise (mostly 1/*f* noise) of the sensor [16,17].

The exhaustive dosimetric evaluation of this commercially available pMOS transistor covers device parameter sensitivities, linearity, reproducibility, thermal effects and their compensation, dose and dose rate effects, angular dependence and readout polarisation conditions. We will show that its reproducible response and excellent linearity make it a good candidate for radiotherapy dosimetry use within the dose range analysed.

The structure of this paper is as follows. In the next section we explain the analysed sensor, the irradiation set-up and the extraction procedure for dosimetric parameters; we discuss the Monte Carlo technique used to evaluate the uncertainties in our results and we describe in detail the thermal compensation procedure. The results and discussion of the dosimetric evaluation will appear in Section 3. In Section 4, we summarise our main results and draw conclusions.

2. Experimental

2.1. Sensor selection

The first step was selection of a commercially available pMOS in order to study its response to gamma radiation. We were seeking a single encapsulated transistor free from parasitic structures. This led us to discard vertical MOSFETs or power MOSFETs (these devices usually include diodes as protection devices against high voltages), which, in fact, form the majority of single encapsulated MOSFETs. In the other available transistors, oxide thickness is one of the most important parameters for radiation sensitivity. As this technological datum is rarely disclosed by the manufacturers, data sheets were analysed in order to gather information regarding oxide thickness. In the absence of parasitic structures, the comparison of maximum gate-substrate voltages before breakdown ($V_{\mathrm{GB\,MAX}}$) is an indication of the oxide thickness of different devices: the greater the absolute value of $V_{\mathrm{GB\,MAX}}$, the thicker the gate oxide. We selected pMOS model 3N163, with a transient $V_{\mathrm{GB\,MAX}} = -125$ V. This device is contained in a cylindrical hermetic metal can, type TO-72, composed of an external nickel layer 0.4 mm thick. The transistor is placed on the surface of a cubic die with an area of 0.3 mm × 0.3 mm located at the centre of the cylinder. Its structure and typical dimensions are shown in Fig. 1. The 3N163 model pMOS is available from several semiconductor manufacturers, with a unit price of less than $3.

2.2. Irradiation set-up and dosimetry

For the dosimetric evaluation, a total of 31 transistors were irradiated with an AECL Theratron 780 located at the University Hospital "San Cecilio" in Granada (Spain). This is a teletherapy unit with a ^{60}Co source. All the irradiations were carried out at a constant temperature with all four transistor terminals connected to each other, hence without bias voltage, in the 'unbiased' mode. The transistors were irradiated with a 35 cm × 35 cm field and were located at distances between 30 and 160 cm from the source, depending on the desired dose rate. The transistors analysed were divided into five groups. In each session, all the transistors in a given group were irradiated simultaneously, ensuring that all were affected by the same gamma radiation beam.

The first and most numerous group with fifteen detectors, was labelled the S group and was used to study the sensitivity, linearity, reproducibility and dose dependence of the radiation response with a normal incidence gamma ray beam. This group was irradiated with different doses of 2, 4 or 6 Gy per irradiation session, up to a limit of 58 Gy, and at a constant dose rate of 0.37 cGy/s. The remaining transistors were irradiated in several sessions and gathered in sets I, A–C. The irradiation conditions for these four sets are summarised in Table 1. As can be seen, the experimental conditions were maintained in all the sessions of each set.

The sixteen transistors not in the S group were divided into four groups. The first, with four transistors, was named group T and was used to study the dependence of the sensor response

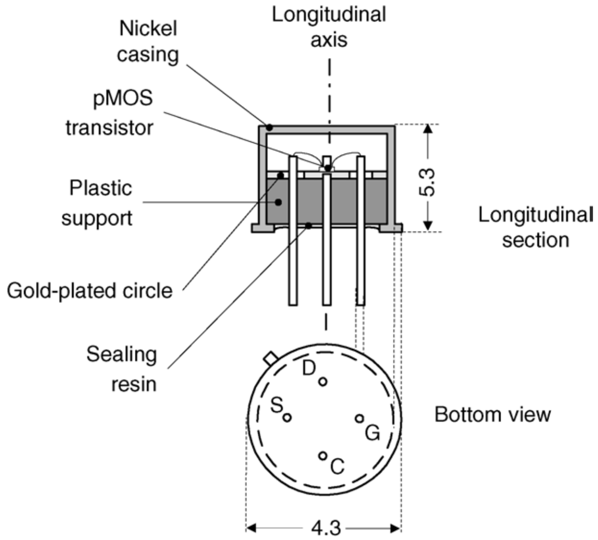

Fig. 1. Longitudinal section and button view of the 3N163 transistor. Terminal equivalence is (D) drain, (S) source, (C) substrate and (G) gate. Dimensions are expressed in millimetres.

Table 1
Irradiation set-up for studying angular and dose rate dependence with T, A1–A3 transistor groups

Session group	Session number	T		A1		A2		A3	
		Dose rate (cGy/s)	Incidence angle (°)	Dose rate (cGy/s)	Incidence angle (°)	Dose rate (cGy/s)	Incidence angle (°)	Dose rate (cGy/s)	Incidence angle (°)
I	1	2.75	0	2.75	0	2.75	0	2.75	0
A	2	0.77	0	2.75	±30	2.75	±60	2.75	±90
	3	0.77	0	2.75	±30	2.75	±60	2.75	±90
	4	0.77	0	2.75	±30	2.75	±60	2.75	±90
B	5	2.75	0	2.75	±60	2.75	±90	2.75	±30
	6	2.75	0	2.75	±60	2.75	±90	2.75	±30
	7	2.75	0	2.75	±60	2.75	±90	2.75	±30
C	8	6.95	0	2.75	±90	2.75	±30	2.75	±60
	9	6.95	0	2.75	±90	2.75	±30	2.75	±60
	10	6.95	0	2.75	±90	2.75	±30	2.75	±60

on the dose rate. To carry this out, three values of the dose rate, different from the S group dose rate and commonly used in radiotherapy, were fixed by placing the pMOS at various distances ranging from 30 to 160 cm from the ^{60}Co source.

Three additional groups, each with four transistors, were used to study the dependence of the sensor response with the incidence angle of the radiation. This is an important issue because in actual practice and for a variety of reasons, the relative orientation of a given sensor to the radiation beam axis may vary between two irradiation sessions, and different sensors can show a different orientation even in the same session. The three groups selected to analyse the angular dependence were labelled A1–A3. Within each group, two transistors were irradiated, rotating 180° around the longitudinal axis in the horizontal plane in relation to the other two (see Fig. 1). In this study, the head of the Theratron 780 was rotated between 0 and 90° relative to the normal incidence. Subsequently, six pMOS received the gamma-ray beam at 30, 60 and 90°, and the other six at −30, −60 and −90° in relation to the former. This was repeated three times per angle in a different order for each group. A first 4 Gy irradiation, (session I), with a normal incidence had been applied beforehand in order to equalise initial conditions for later irradiations. In subsequent sessions, the direction of the gamma ray beam was varied as described above, and doses of 3 Gy per session were applied. For those irradiations in the angular study, the dose rate was 2.75 cGy/s.

The dose and its uncertainty were obtained according to the following method. Up to the date of the present investigation, the dose rate determined in reference conditions [18] has been measured five times. As a result of these measurements and at the reference date (12 July 2002), it has been established that the dose rate at the maximum and in the beam axis, for a source-to-sensor distance of 80.2 cm, is $D_0 = 3.07 \pm 0.02$ cGy/s. In addition, the time delay (input–output time) is $t_{\text{io}} = -0.22 \pm 0.02$ ms. This value must be added to the time calculated in order to determine the required dose.

As this value of the dose corresponds to measurements in water, we converted it to the experimental conditions (the sensors were irradiated in air). To do this, we made two different estimations. In the first, the reference value was corrected for the thickness of the material involving the sensitive volume in the transistor, the dimensions of the irradiation field and the dispersion in the head of the irradiation unit. In the second, field factors measured in water at maximum depth were used to correct the dose reference rate for the field used, and finally, we considered the modifications due to the effect of the phantom (needed in water measurements) and to the absence of dispersion in air. The results obtained with the two methods were $D_{0,\text{exp}} = 3.07 \pm 0.05$ cGy/s and $D_{0,\text{exp}} = 3.08 \pm 0.05$ cGy/s, respectively.

In addition, we performed a set of measurements using cylindrical ionisation chambers in order to obtain the ratio between the reference readings and experimental conditions. This allowed us to obtain a value $D_{0,\text{exp}} = 3.03 \pm 0.03$ cGy/s. These experimental results were in agreement with the two prior estimations and we therefore considered the mean value $D_{0,\text{exp}} = 3.06$ cGy/s as the reference value, with a total uncertainty (three times the standard deviation) of 0.13 cGy/s. More details about this standard method to calculate the absorbed dose can be found elsewhere [19,20].

2.3. Extraction of the dosimetric parameters

In order to quantify the radiation response, the pMOS transistor transfer characteristics were measured. In particular, the drain current, I_{DS}, as a function of the gate voltage, V_{GS}, was obtained for each transistor before and after each irradiation session, using a semiconductor parameters analyser HP-4145B controlled by a personal computer. To avoid electromagnetic interference during measurement of the curves, transistors were placed in a shielded text fixture HP 16085A. To determine which transistor polarisation condition would be the most suitable (better sensitivity, linearity and reproducibility) during the readout operation, these curves were extracted in both a saturation regime, with gate and drain shorted, and a linear regime with a drain-source voltage $V_{\text{DS}} = -100$ mV. Substrate and source terminals were shorted in both cases.

The common first order model equations [21]:

$$I_{DS} = \frac{\beta}{2}(V_{GS} - V_T)^2 \qquad (1)$$

in the saturation regime, and

$$I_{DS} = \beta\left[(V_{GS} - V_T)V_{DS} - \frac{V_{DS}^2}{2}\right] \qquad (2)$$

in the linear regime, were fitted to the experimental transfer curves in order to extract the threshold voltage, V_T, and the β factor, these being the radiation-dependent parameters to be evaluated. These fits were carried out, using the least-squares method, in the region where the channel was in the strong inversion condition and the second-order effects remained negligible [21]. In Fig. 2, typical transfer characteristics for pre-irradiated and irradiated transistors in saturation and linear regimes are shown. The horizontal lines indicate the current range where the fit was carried out.

In order to calculate the mean values and uncertainties of the dosimetric parameters, V_T and β, a statistical technique based on the Monte Carlo method was applied [22]. For every acquired point of each of the experimental transfer characteristics $I_{DS} - V_{GS}$, a new point was randomly generated according to the normal distribution centered on the original point and with a standard deviation provided by the uncertainty specifications of the semiconductor parameters analyser. The new $I_{DS} - V_{GS}$ curve was then fitted as described above and, new values of V_T and β were obtained. We repeated this process a thousand times per experimental curve. The values of V_T and β thus obtained followed normal distributions, with mean values that we considered as the final results of the fit. Uncertainties were taken to be three times the corresponding standard deviations. Quadratic error propagation was considered whenever required. Moreover, the shift of the parameter values due to their thermal dependence was compensated for, as shown below. In the following, all the results of threshold voltages are shown in absolute values, both in the text and in the figures.

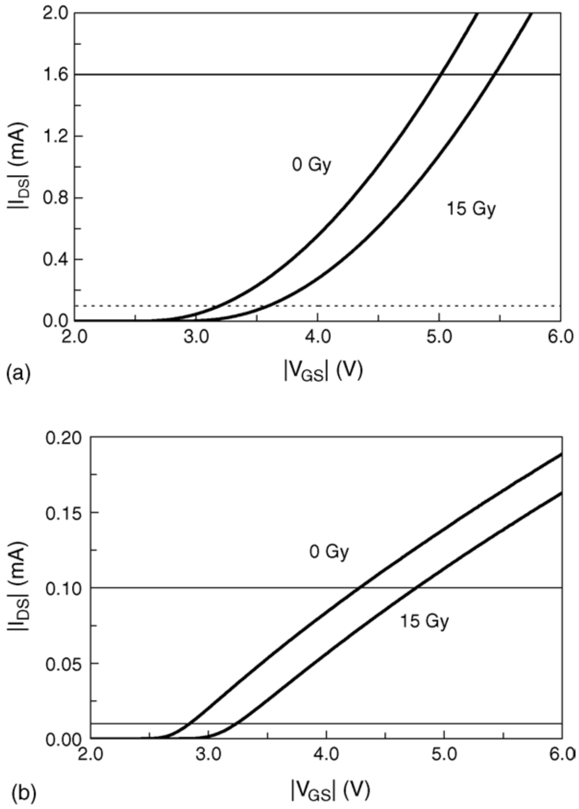

Fig. 2. Transfer characteristics, I_{DS}–V_{GS} in (a) saturation and (b) linear regimes of the pMOS transistor before and after irradiation. Horizontal lines demarcate current intervals from which pMOS parameters have been extracted.

2.4. Temperature effect compensation

The accurate study of the response to radiation of pMOS transistors requires a careful characterisation of the thermal dependence of the dosimetric parameters [15,23]. This is especially important when the sensor is in unbiased mode, as occurs in this case, because of the relatively low sensitivity of the dosimetric parameters anticipated in this operational mode. To study this point, V_T and β were obtained for several pMOS at different temperatures ranging between 25 and 45 °C. The results obtained are shown in Figs. 3a and b as a function of the temperature. As can be seen, both parameters show a linear dependence with temperature. We performed a linear fit according to the equations

$$V_T(T) = V_T(T_0) + \alpha_V(T - T_0) \qquad (3)$$

and

$$\beta(T) = \beta(T_0) + \alpha_\beta(T - T_0) \qquad (4)$$

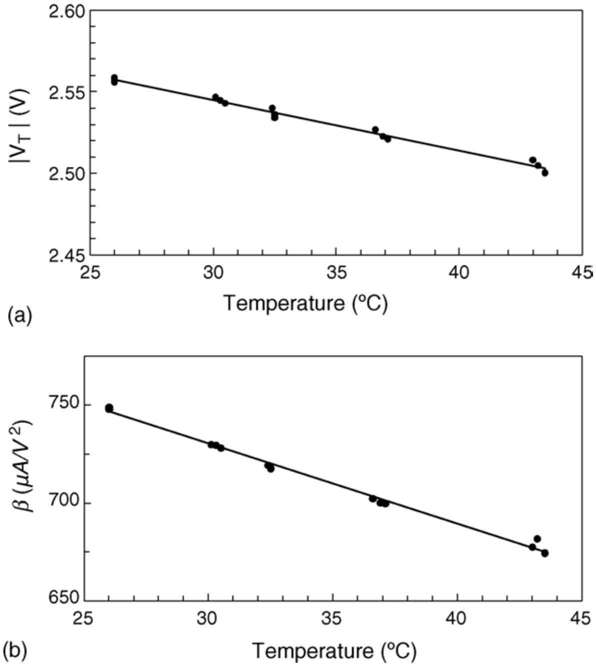

Fig. 3. Dependence of (a) threshold voltage and (b) β on the temperature.

where $T_0 = 25\,^{\circ}\mathrm{C}$. The results of these fits gave us

$$\alpha_V = -3.5 \pm 0.4\,(\mathrm{mV}/^{\circ}C), \quad V_{\mathrm{T}}(T_0) = 2.56 \pm 0.06\,(\mathrm{V}) \tag{5}$$

and

$$\alpha_\beta = -3.9 \pm 0.6\,(\mu\mathrm{A/V^2\,^{\circ}C}), \quad \beta(T_0) = 755 \pm 15\,(\mu\mathrm{A/V^2}) \tag{6}$$

The uncertainty of the temperature coefficients, α_V and α_β, was taken to be the maximum between experimental error, obtained by applying the Monte Carlo method to each transistor, and three times the standard deviation derived from the distribution results of the transistor set quoted in (5) and (6). The temperature was monitored with a resolution of 0.1 °C during the extraction process of V_{T} and β, and the corresponding linear correction, using the coefficients α_V and α_β, was applied to compensate for the values obtained, with reference to $T_0 = 25\,^{\circ}\mathrm{C}$.

The effect of temperature during irradiation was considered negligible because the temperature in the irradiation room was fixed at 25 °C in all the irradiation sessions.

3. Results and discussion

3.1. Sensitivity, linearity and reproducibility studies

In this section, we describe the results of the response to radiation of transistor group S. All the irradiations of the pMOS in this group were carried out with normal incidence. We studied the sensitivity, linearity, reproducibility and dose dependence of the dosimetric responses of V_{T} and β, when extracted in saturation and linear regimes during readout.

3.1.1. Response to radiation of the β factor

In Fig. 4, the accumulated $\Delta\beta$ shifts in the saturation regime are shown, corrected for temperature, as a function of the accumulated dose, D, received by four pMOS transistors. This trend was also found in the other transistors analysed and in the linear regime. A monotonous and non-linear decrease, in agreement with the results of other studies, was obtained [9,24,25] and can be explained by the fact that irradiation increases the density of interface states and oxide charge, reducing hole mobility in the conduction channel through a coulomb interaction.

The non-linear response of the sensor is not a problem in a modern instrumentation system. However, the uncertainty obtained is of the same order of magnitude as the shifts of mean value in the dose range studied, much larger than that shown by V_{T}, as demonstrated in the next section. In addition, as shown below, reproducibility is not as clear as with threshold voltage. Therefore, we can conclude that β appears not to be an appropriate choice of dosimetric parameter. In the section that follows, we will focus our attention on the threshold voltage shift.

3.1.2. Response to radiation of threshold voltage

Fig. 5 shows the accumulated threshold voltage shifts, ΔV_{T}, versus D, the accumulated dose received, for all the pMOS of the S group. Uncertainty bars have been omitted for clarity. To obtain these values, the threshold voltage was measured before and after each irradiation. The data in Fig. 5 were measured in a saturation regime but the results obtained in a linear regime are similar. As expected, the threshold voltage increases in absolute value when the accumulated dose in the pMOS increases. The data show excellent linearity and reasonably good reproducibility up to a total dose of 58 Gy (which is around the total dose used in typical radiotherapy treatments).

The results for a particular pMOS transistor (number 15) in saturation regime are plotted again with black circles in Fig. 6. The solid line represents the linear fit of the mean values, while open circles show the sensitivity at each irradiation session. The radiation sensitivity of the pMOS transistors was defined in the usual way, as the ratio between the accumulated threshold voltage shifts and the accumulated dose received:

$$S_V = \frac{\Delta V_{\mathrm{T}}}{D} \tag{7}$$

As we can see in Fig. 6, the sensitivities found for this particular pMOS present low uncertainty and good linearity.

At this point, two dosimeter calibration procedures were carried out. In the first, termed individual calibration, the mean value and the uncertainty of the sensitivity are calculated sepa-

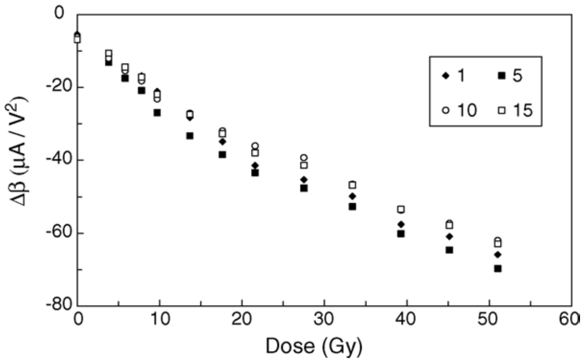

Fig. 4. Mean values of accumulated β shifts vs. the total dose received for four transistors of the S group. This data was obtained from the saturation characteristics. Uncertainty bars have been omitted for clarity.

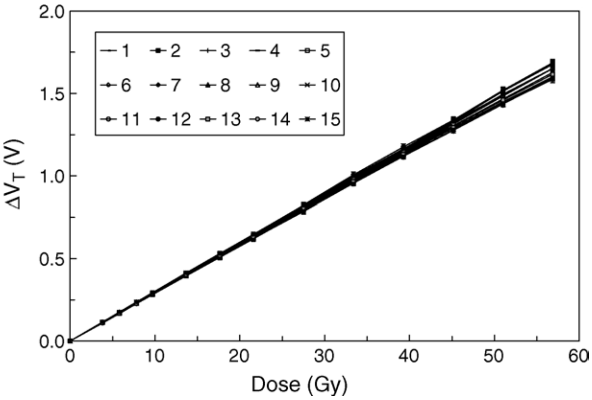

Fig. 5. Mean values of the accumulated threshold voltage shift as a function of the accumulated dose received for all transistors of the S group are shown as symbols. These data were extracted from the saturation characteristics. Uncertainty bars have been omitted for clarity.

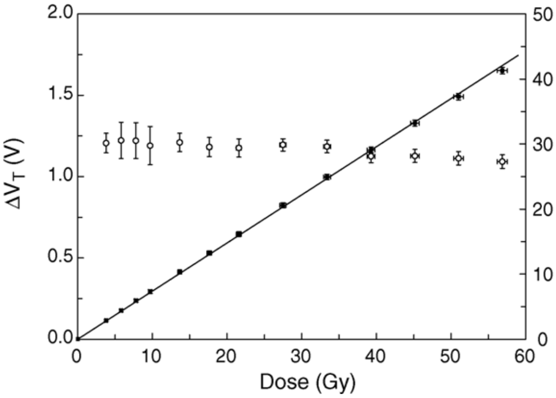

Fig. 6. Accumulated threshold-voltage shift vs. accumulated dose received (filled circles) and sensitivity per session (squares) for transistor number 15 of the S group, in saturation. Uncertainty bars are three standard deviations of data.

rately for each pMOS according to the Monte Carlo procedure. These results are summarised in Table 2, in saturation and in linear regimes. In the second, termed collective calibration, the mean value and uncertainty of the sensitivity of the whole transistor group is calculated from the distribution of sensitivities at each individual calibration. Of course, there is less uncertainty with the first procedure, which implies a calibration for each sensor, whereas with the second procedure the calibration task is reduced with a probable degeneration in sensor accuracy in relation to individual calibration.

As we also show in Table 2, the individual uncertainty is somewhat lower if the readout is done in a saturation regime. Therefore, this regime seems to have the advantage of allowing us to obtain more accurate results for individual sensors, due to the fact that in a linear regime there is the additional uncertainty of the drain-source voltage, which does not exist in a saturation regime. This allows us to manage with only two terminals for the sensor since the gate and the drain can be shorted, and does not bias the drain-source structure during the readout operation. In this case, a sensitivity of around, $S_V = 29$ mV/Gy is obtained and an individual uncertainty of ±0.2 mV/Gy (three times the standard deviation), less than 0.7% of error in the final reading under normal incidence. Therefore, with individual detector calibration, in these conditions, an error rate less than 1% is perfectly feasible.

Table 2
Individual sensitivities and uncertainties (three times the standard deviations, S.D.) for each transistor of the S group analysed, in saturation and linear regimes

Transistor	Saturation		Linear	
	Sensitivity (mV/Gy)	3 S.D. (mV/Gy)	Sensitivity (mV/Gy)	3 S.D. (mV/Gy)
1	28.5	0.2	29.7	0.3
2	29.2	0.2	28.8	0.3
3	29.3	0.2	28.8	0.3
4	29.6	0.2	29.0	0.3
5	28.6	0.2	29.4	0.3
6	29.2	0.2	29.0	0.3
7	28.5	0.2	29.8	0.3
8	29.6	0.2	29.6	0.3
9	28.7	0.2	29.9	0.3
10	29.1	0.2	30.6	0.3
11	28.4	0.2	29.7	0.3
12	29.8	0.2	29.6	0.3
13	28.9	0.2	30.1	0.3
14	29.2	0.2	29.1	0.3
15	29.6	0.2	30.7	0.3

Fig. 7 shows the result of collective calibration from individual sensitivities, measured in a saturation regime. These individual parameters are plotted with symbols, whereas the solid line in the figure shows the mean value of the sensitivities of the fifteen transistors in this group (the collective sensitivity) while the dashed lines indicate the interval of three times the standard deviation of this set of data, which we assume to be the collective uncertainty. According to our results, processing the individual sensitivities statistically, we obtain:

$$S_V = 29.2 \pm 1.5\,(\mathrm{mV/Gy}),$$

for the collective sensitivity under normal incidence. Therefore, considering a mean sensitivity of 29.2 mV/Gy for any pMOS transistor, the error introduced in the worst case is 5%. This result leads us to believe that the choice of this particular low-cost transistor is acceptable for the verification of the most commonly absorbed doses in patient treatments. The relatively low sensitivity could be amplified with an appropriate electronic design of the readout circuitry, where the final resolution is the low frequency noise of the sensor and not the instrumentation noise. In addition, the response transistor is independent of the dose per session in the range analysed. Irradiations of 2, 4 and 6 Gy were applied without a change in the final sensitivity.

From our study, it seems clear that this commercially available pMOS, using an appropriate measurement system, could be a suitable choice as a gamma radiation dosimeter. Depending on the accuracy required, individual or collective calibration could be chosen. In the former case, the uncertainty falls below 1% and in the latter is around 5% when the dosimetric parameter is extracted in a saturation regime. These errors are reduced even further if the sensor is treated as disposable for typical radiotherapy treatments of 20 or 30 Gy, a realistic option, given its low cost.

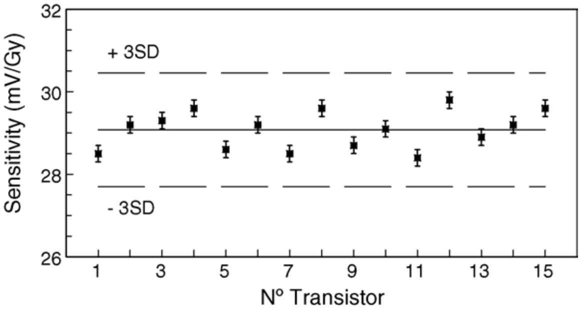

Fig. 7. Individual sensitivities for each transistor of the S group are plotted as symbols. The solid line is the collective mean sensitivity value and the dashed lines represent an interval of ±3 standard deviations around this mean. Uncertainty bars represent ±3 standard deviations around the individual mean obtained for each single transistor.

3.2. Dose rate dependence

In practice, the distance from the radiation source of different sensors varies and the activity of the source may also vary between different irradiations. These variations produce differences in the dose rate at which the dosimeters are irradiated and, as a consequence, it is essential to study the dose rate dependence of the detectors proposed. As stated above, analysis of the dose rate effects in the transistors was carried out by submitting the four transistors in the T group to the experimental procedure in the unbiased mode, as described in Table 1. Apart from the initial session I, three different dose rates were applied to the group, each repeated three times. Following a similar procedure to that described in the previous section for S group pMOS, the mean sensitivities were calculated. In this case and in the angular dependence study, the V_T value was measured before and after irradiation, so that the sensitivities of each session rather than the accumulated ones were studied. The results obtained for transistor 18 are plotted in Fig. 8, and the collective sensitivity of the S group at 0.37 cGy/s has also been included for comparison. These radiation sensitivities correspond to the saturation regime; the sensitivities obtained in the linear regime were similar. The three remaining transistors in this group showed the same behaviour. As shown in Fig. 8, small changes in sensitivity are seen in the range analysed. A standard deviation of 1.0 mV/Gy was obtained for this dose rate range. This value is similar to that of previous studies [26].

3.3. Angular dependence

To determine the angular response of the 3N163 pMOS, we measured the threshold voltage shifts produced by gamma exposure with different incidence angles. The study was developed for the twelve pMOS in groups A1–A3, submitted to the experimental conditions quoted in Table 1. In this experiment, we investigated whether hysteretic behaviour was present or whether detectors had some memory of past irradiations related to different incidence angles of the gamma beam. The sensitivity of each transistor was calculated in linear and saturation operating conditions, and the mean value for every transistor in each irradiation condition was extracted. The results were similar in the two operation regimes. The sensitivities found for transistors 20 and 21 are displayed in Fig. 9 as a function of the incidence angle. Results are plotted for two transistors rotated 180° in the horizontal plane, as described in the irradiation set-up section. The remaining pMOS showed a similar angular dependence. A standard deviation of 0.5 mV/Gy is obtained from −90 to 90° of incidence, corresponding with an uncertainty of 5%. This uncertainty is similar to or even below that of other pMOS dosimeters [5–7,27,28]. Moreover, no memory effect is observed when irradiating in a different order with different incidence angles.

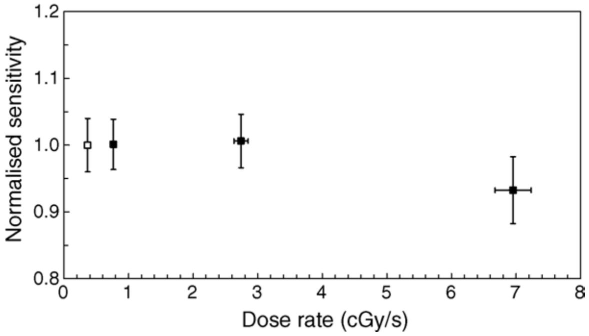

Fig. 8. Sensitivities of the threshold voltage shift as a function of dose-rate for the number 18 transistors (filled symbols). Sensitivity for transistor 15 of the S group is shown as an outline symbol for comparison. The results are extracted from the saturation curves and normalised to the sensitivity value obtained for the lowest dose-rate.

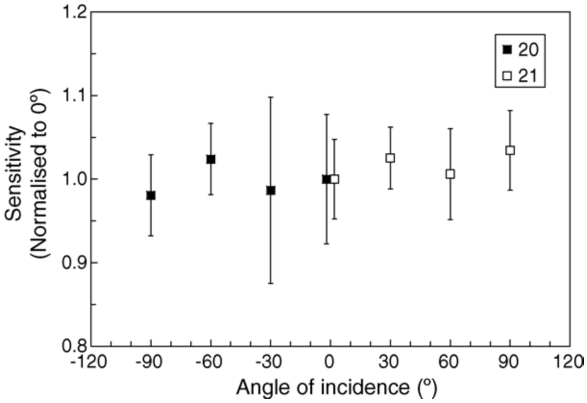

Fig. 9. Sensitivities of the threshold voltage shift for the number 20 (filled symbols) and 21 (outline symbols) transistors, as a function of the angle of incidence of the gamma ray beam. Results are normalised to the 0° response. The data are extracted from the saturation curves.

4. Conclusions

An exhaustive evaluation of the response of a commercially available pMOS, the 3N163 model, to gamma radiation was carried out in the unbiased mode. The main advantage of this device is that its manufacture uses standard low-power MOS transistor technology, hence its low cost in comparison with RADFETs, which require the introduction of additional steps. Our aim was patient comfort and ease of use by untrained personnel, with irradiation of the sensor in the unbiased mode. Our results were obtained after a complete statistical treatment based on the Monte Carlo method, and all uncertainties were calculated as three times the data standard deviation in linear and saturation operation regimes. A thermal compensation procedure was applied in order to correct the transfer characteristics. Excellent linearity and good reproducibility were found for this device, with a mean sensitivity value of 29.2 mV/Gy, and an uncertainty of less than 1% for individual sensor calibration or around 5% for collective sensor calibration for the 31 analysed MOSFETs. Moreover, the angular and dose-rate dependencies are similar to those of other, more specialised pMOS dosimeters. These results suggest therefore, that this transistor would be an excellent candidate as the sensor of a low-cost system capable of measuring the gamma radiation dose. To summarise, this radiation sensor could be placed on patients without the need for wires, and the threshold voltage shift, which is indicative of the dose absorbed, could be measured after the completion of each irradiation session with a reasonable degree of confidence.

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