A MOSFET dosimeter built on an off-the-shelf component for *in vivo* radiotherapy applications

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***Abstract* — In this paper we detail the development of a new *in vivo* MOSFET dosimeter built on the CD4007, a popular off-the-shelf CMOS circuit. The dosimeter, which is aimed at radiotherapy applications, combines a simple and accurate readout procedure with a small, low-cost and cable-free sensor. The linearity (97.5%) and radiation sensitivity (6.8 mV/Gy) of this dosimeter were tested using X-ray (6 MV).**

***Keywords*— threshold voltage extractor circuit; MOSFET dosimeter; *in vivo* MOSFET dosimeter; radiotherapy.**

I. Introduction

The purpose of radiotherapy is to deliver a lethal dose to the tumor while sparing the neighboring healthy organs at risk. In this type of cancer treatment dose accuracy is expected to be of the order of ±5%, since certain tumors and normal tissues exhibit steep dose-response curves. Providing this accuracy is a challenging task because uncertainties are always present. For these reasons, an efficient Quality Assurance (QA) program is essential to ensure the success and quality of the radiotherapy [1].

The most direct method to provide QA in radiation oncology is the monitoring of the dose delivered to the patient, which can only be carried out by using *in vivo* dosimeters. The overall dose of a cancer treatment is usually divided into fractions of 2 Gy. The detection of a dose error early in the treatment is a warning sign for compensation in later fractions to guarantee that the total dose applied to the patient meets the specified prescription. The authors of [2] therefore recommend that *in vivo* dosimetry should be carried out at least for the first patient's treatment session.

Due to the importance of *in vivo* dosimetry, we first review here the most popular *in vivo* dosimeters (thermoluminescent, diode and MOSFET). We then present two methods to measure the MOSFET threshold voltage, which is a parameter sensitive to the radiation dose. Next, we describe the development of a MOSFET dosimeter built upon the popular CD4007 CMOS integrated circuit (IC). Finally, we show some experimental results for the dosimeter prototype.

II. *In vivo* Dosimeters

The most commonly used *in vivo* dosimeters are based on thermoluminescent, diode and MOSFET sensors [1],[3].

The thermoluminescent dosimeter (TLD) is the most popular dosimeter for QA in radiotherapy [3]. TLDs are tissue-equivalent, small in size, accurate and cable-free. The reading process consists of measuring the amount of visible light emitted from the TLD when it is heated. However, the reading procedure is an important drawback of TLDs because it occurs off-line, it is time consuming and information is lost during the reading. Additionally, the cost of the readout equipment is relatively high.

The readout process of a diode dosimeter is instantaneous; however, the dosimeter must be connected to cables during radiation and the measurement is sensitive to the temperature and dependent on the energy of the radiation beam.

MOSFET dosimeters are small in size, capable of storing the accumulated dose, can be read remotely in a non-destructive way, and cables or battery are not required during the radiation application. Considering these characteristics, MOSFET radiation detectors are the most attractive option for clinical *in vivo* dosimetry and they have features which are impossible to combine in TLDs or diode dosimeters. MOSFET dosimeters can provide immediate readout (similar to diodes) and are cable-free (like TLD). MOSFET dosimeters, as compared to TLDs, can reduce the processing time for reading from hours (or even days) to minutes. Moreover, it is possible to fabricate the MOSFET sensor and the electronic circuitry (for data processing, signal conditioning and communication) on the same chip, which allows the design of very small dosimeters. Another advantage of the use of the MOSFET is that its radiation sensitivity varies by less than 2% for most of the radiation sources used in medical applications [4]. The dependence of the threshold voltage on the temperature, which is an important drawback of MOSFETs, can be overcome by the use of differential circuits, as will be shown in Section VI.

III. The MOSFET Dosimeter

The operation of a MOSFET radiation dosimeter is based on the generation of electron-hole pairs in the gate oxide of the MOSFET structure when exposed to ionizing radiation. Electrons escape easily from the oxide but holes are trapped if the oxide is of sufficient thickness. As a result, the total charge trapped in the gate oxide (Q_o) will shift the threshold voltage (V_T). The variation in V_T due to ionizing radiation is given by

$$\Delta V_T = -\frac{\Delta Q_o}{C_{ox}} \quad (1)$$

where C_{ox} is the oxide capacitance [5].

In a MOSFET dosimeter the dose is inferred from the variation in the threshold voltage. The V_T variation, in mV, measured by an extractor circuit, is converted into a corresponding dose value, in Gy. During the dose readout, any changes in temperature must be compensated for, since V_T is dependent on temperature. Finally, the dosimeter processes and transmits the data (Fig. 1).

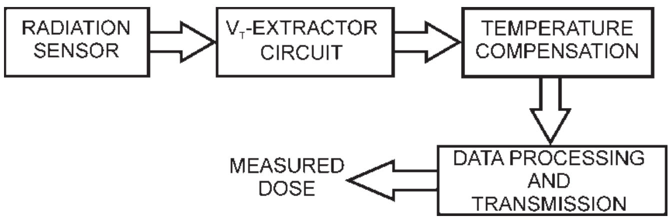

Figure 1. Flowchart of the basic building blocks of a MOSFET dosimeter.

The main characteristics of the radiation sensor and the V_T-extractor circuit are presented in the following sections. Also, we show how the dependence of the sensor readout on the temperature can be almost eliminated.

IV. THE RADIATION SENSOR

The charge Q_o trapped in the oxide is proportional to the oxide thickness (t_{ox}), while $C_{ox} \propto 1/t_{ox}$. Thus, from (1), it can be observed that the variation in V_T due to ionizing radiation is proportional to t_{ox}^2. Therefore, MOSFETs with thicker gate oxides have higher radiation sensitivity. The dosimeter we developed uses PMOS transistors of the CD4007 array. PMOS transistors have higher sensitivity and better linearity than their NMOS counterparts [5]. We selected this integrated circuit because the gate oxide thickness of the transistors is 120 nm [6], which provides the sensor with two important characteristics: radiation sensitivity of around 7 mV/Gy, which is suitable for radiotherapy applications, and operation with relatively reduced supply voltage since $|V_T|$ is around 1.6 V. Furthermore, the CD4007UBM is of very low-cost (US$ 0.5/IC) and has small dimensions (Table II).

V. V_T-EXTRACTOR CIRCUITS

The dose in a MOS dosimeter is determined from the variation in the threshold voltage; therefore, it is essential to design a circuit that extracts V_T. In this section, we compare two circuits aimed at extracting V_T, namely the constant-current (CC) and automatic V_T-extractor circuits [5], [7].

The constant-current (CC) V_T-extractor circuit employs a diode-connected transistor operating in moderate inversion (Fig. 2). It was demonstrated in [7], [8] that, when biased through a current I_D=3*I_S (I_S is the specific current, approximately 400 nA for the PMOS transistors of CD4007UBM), the threshold voltage is simply the voltage drop between source and gate. Despite offering the most direct method for extracting V_T, the CC circuit forces the transistor to operate in the saturation region. In saturation, short-channel effects (*e.g.*, channel-length modulation, drain-induced barrier lowering, and carrier velocity saturation) interfere with the value of the measured threshold voltage, thus reducing the accuracy of the V_T-extractor [7].

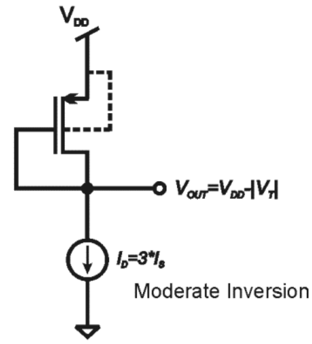

Figure 2. Schematic of the constant-current V_T-extractor circuit.

The automatic V_T-extractor circuit [7] allows the threshold voltage to be directly determined, with minimum influence from short-channel effects, since the transistor operates in the linear region with a very small drain-to-source voltage [7].

The threshold voltage of the PMOS transistors of the CD4007UBM was extracted using V_T-extractor circuits (CC and automatic) and the g_m/I_D methodology, which is a standard current-based V_T-extraction procedure [7].

It is important to note here that each CD4007 has 3 PMOS transistors which can be easily connected in series. Thus, in the V_T extraction procedure, we can study the influence of the channel length by measuring the V_T for an individual PMOS transistor ("short-channel") and for a "long-channel" transistor. The latter is composed of 3 PMOS transistors connected in series, which is equivalent to a transistor with the channel-length three times longer than an individual transistor [9].

TABLE I. THRESHOLD VOLTAGE OF PMOS TRANSISTORS OF THE CD4007UBM EXTRACTED USING EXTRACTOR CIRCUITS (AUTOMATIC AND CC) AND THE EXTRACTION METHOD (G_M/I_D).

	$\|V_T\|$	$\Delta V_T = \|V_{T(gm/ID)}\| - \|V_{T(extractor)}\|$	
Transistor	g_m/I_D	**Automatic**	**CC**
Short-channel	1.580 V	7 mV	18 mV
Long-channel	1.577 V	7 mV	11 mV

In Table I we can note a 7 mV difference in the value of V_T measured using the automatic extractor with respect to that measured applying the standard method (g_m/I_D), for both short- and long-channel transistors. Also, as predicted, the CC extractor presents a more accurate result for the long-channel device than for the short-channel device. These results show that the automatic V_T-extractor is more accurate and less susceptible to short-channel effects than the CC extractor. However, the performance of the CC extractor is also acceptable, especially for the long-channel transistor. Despite being less accurate than the automatic V_T-extractor, the CC V_T-extractor circuit was employed for the MOSFET dosimeter due to its simplicity. To improve the accuracy of the CC extractor, the radiation sensor used was a "long-channel" transistor, composed of a series association of 3 PMOS transistors. It should be mentioned here that a similar constant-current circuit is used in the MOSFET dosimeters of references [10]-[13]; however, in these CC circuits the MOSFETs usually operate in strong inversion (which leads to higher power consumption) and the voltage extracted has no physical meaning [5],[7]. Moreover, in [12] and [13] the reading procedures are not direct and require a cumbersome algorithm to determine the output voltage.

VI. Temperature Desensitization

The threshold voltage of a transistor is strongly associated with the temperature. Thus, a temperature variation can be falsely understood by the dosimeter as a dose variation. Consequently, the error originating from temperature variations needs to be minimized.

Figure 3 shows the variation in the voltage sensed in terms of the bias current of a diode-connected transistor. In particular, the variation in V_T (bias current of $3{*}I_S$) with temperature is around 2 mV/°C. Taking into account the PMOS transistor radiation sensitivity of 7mV/Gy, the thermal drift of the sensor corresponds to an error of around 0.3 Gy/^{o}C; therefore, it is crucial to find a way to reduce the effect of the dependence of the sensed parameter (V_T) on the temperature.

Two approaches are generally used to minimize this dependence: transistor biased at the current (I_{MTC}) for minimum temperature coefficient (MTC) and differential measurements [10],[13],[14].

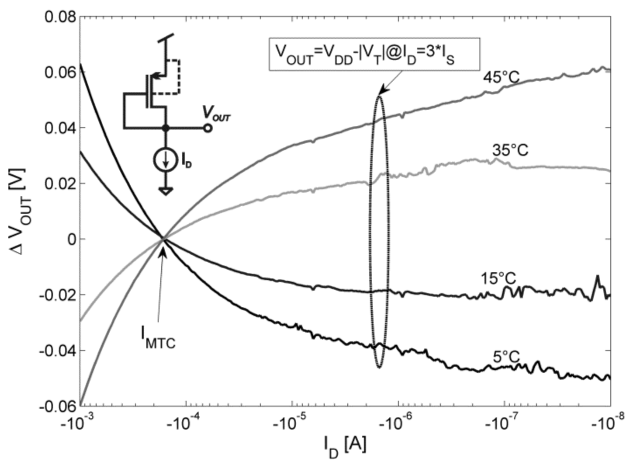

Figure 3. $\Delta V_{OUT} = (V_{OUT})_{25°C} - (V_{OUT})_T$ for PMOS transistor (CD4007UBM). The current values that give $V_{OUT}=V_{DD}-|V_T|$ and the minimum temperature dependence (I_{MTC}) are -1.2 µA (I_S=-0.4 µA) and -150 µA, respectively.

Biasing the diode-connected transistor at $I_D=I_{MTC}$ ($I_{MTC} \approx 370{*}I_S$) causes high power consumption and reduces the accuracy of the CC extractor (short-channel effects increase with the current). Moreover, for a bias current $I_D=I_{MTC}$, the output voltage of the CC extractor is no longer equal to the threshold voltage.

Considering these factors, we chose the differential approach, where the main drawbacks (increase in the number of components and need for matched MOSFETs) can be easily overcome. The CD4007 MOSFET dosimeter developed in this work uses two matched CD4007UBM ICs, one of them as the radiation sensor and the other as the sensor replica, as shown in the inset of Fig. 4. In the differential approach, only the sensing transistor is submitted to radiation whereas its replica is not. After a radiation session, the dose is computed from the difference (V_{out1}-V_{out2}) in the threshold voltages of the two transistors. Since both the sensor and its replica are in the same room and, thus, subject to the same temperature, the difference in the threshold voltages of the devices will be due to radiation only and (almost) independent of temperature.

In order to check the influence of the temperature on the differential measurements, we employed the schematic shown in the inset of Fig. 4. The differential measurements over three decades of current showed a thermal coefficient of around 20 µV/°C, which means that the error due to temperature drift is approximately 3 mGy/°C for our sensor.

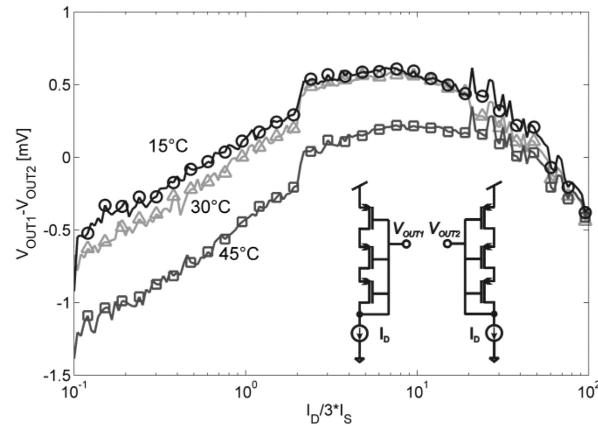

Figure 4. Differential measurement of the output voltage as a function of bias current at 15°C, 30°C, and 45°C. The maximum variation in the differential voltage is 0.7 mV for a temperature variation of 30°C.

VII. Experiment with Ionizing Radiation

In order to evaluate the radiation response of the CD4007 MOSFET dosimeter, experiments with ionizing radiation (X-ray of 6 MV) were carried out at the Centro de Pesquisas Oncológicas (CEPON), Florianópolis-Brazil. The measurement procedure consisted of reading the differential output voltage immediately before irradiation and then reading it again after each irradiation session.

A. Manufacturer & packaging

The radiation sensitivity of CD4007UBM IC was compared with two other electrically equivalent integrated circuits. As can be observed in Table II, the other two ICs each have only one characteristic (packaging type or manufacturer) in common with the CD4007UBM.

TABLE II. Manufacturer and packaging information for the following integrated circuits: CD4007UBM, CD4007UBE, and MC14007UG.

Integrated Circuit	Manufacturer (Packaging)	Area (Thickness)
CD4007UBM	Texas Instruments (SOIC)	38 mm^2 (1.75 mm)
CD4007UBE	Texas Instruments (DIP)	120 mm^2 (5 mm)
MC14007UG	ON Semiconductor (SOIC)	38 mm^2 (1.75 mm)

Two CD4007UBE, four CD4007UBM and five MC14007UG integrated circuits were exposed simultaneously to a total dose of 20 Gy. The variation in the threshold voltage (V_T) after irradiation of 20 Gy is reported in Table III.

TABLE III. V_T VARIATION, AFTER IRRADIATION OF 20 GY, FOR THE CD4007UBE, CD4007UBM, AND MC14007UG (X-RAY OF 6 MV).

Integrated circuits	*ΔV_T (mV)*	*Average sensitivity (mV/Gy)*
CD4007UBE	142.3	7.1
CD4007UBM	136.6	6.8
MC14007UG	79.6	4.0

The comparison between these three equivalent integrated circuits indicates that the CD4007UBM is the best option as a radiation sensor because it combines high sensitivity and small dimensions.

B. Sensitivity fluctuations

For the experimental determination of the sensor sensitivity, five CD4007UBM sensors were irradiated individually with an accumulated total dose of 10 Gy, divided into 5 fractions of 2 Gy.

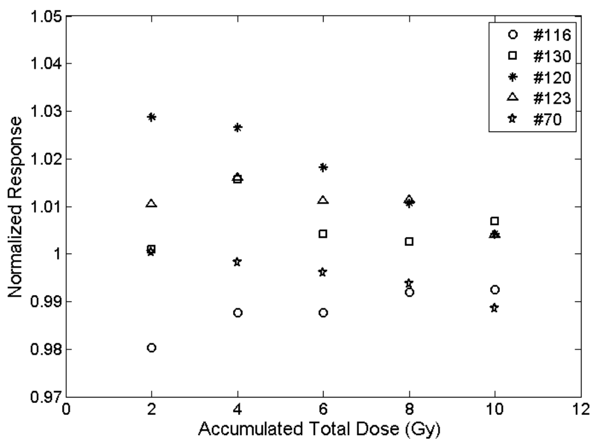

Figure 5. The CD4007UBM sensitivity - normalized response of 5 different radiation sensors as a function of the accumulated total dose.

Figure 5 shows the sensor sensitivity by way of the normalized response. The normalization factor is equal to the average sensitivity of the five sensors for an accumulated total dose of 10 Gy. For the five samples that we measured, the maximum normalized variation of the sensitivity was less than 3%. In addition, the relative difference between the maximum and minimum values for the sensitivity was less than 2.5% for all samples.

VIII. SUMMARY AND CONCLUSIONS

In this paper we have discussed the fundamental aspects - sensitivity of MOSFET radiation sensors, accuracy of V_T extraction circuit and temperature desensitization – associated with the development of a MOSFET dosimeter. The dosimeter we developed uses a small, low-cost and cable-free (during irradiation) sensor which is suitable for *in vivo* measurements. Furthermore, experimental measurements showed that this dosimeter has a linearity of 97.5% (for total dose of 10Gy) and its radiation sensitivity is roughly 7 mV/Gy.

The use of the CD4007UBM as the radiation sensor does not preclude a hybrid solution (commercial and custom ICs assembled together in a small printed circuit board). For the dosimeter we can use bare dies of CD4007UBM (die area around 1 mm^2) together with the necessary electronics implemented in a standard 3.3 V CMOS process (*e.g.*, 0.35 μm), which is capable of handling the output voltages of the CD4007 radiation sensor.

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