A Low-cost Microcontrolled Dosimeter Based on CD4007 Devices for *in vivo* Radiotherapy Applications

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***Abstract*—This work presents a low-cost microcontrolled dosimeter based on CD4007 device, a popular off-the-shelf CMOS circuit. This dosimeter is aimed at *in vivo* radiotherapy applications and combines a simple and accurate readout with a small size, low-cost, and cable-free sensor. The response of this dosimeter to low-dose (10 cGy – 1 Gy) and 40 Gy irradiations were tested using X-ray (6 MV).**

Keywords—MOSFET Dosimeter; in vivo MOSFET dosimeter; radiotherapy.

I. Introduction

The main goal of radiotherapy is to deliver a lethal dose to the malignant tumor while sparing the neighboring healthy organs and tissues at risk. To accomplish this objective is fundamental that the desirable radiation dose (generated by linear accelerators (LINAC) or radiation sources) is delivered to the correct spot. For this reason, rigorous quality programs are frequently adopted by radiotherapy centers to assure that the dose precision is of the order of ±5% [1].

An important part of radiotherapy quality program is the *in vivo* dosimetry because it is the only way to monitor and verify the final dose delivered to the patient. For this reason, it is recommended that *in vivo* dosimeters should in principle be used for all patients undergoing radiation treatments [2], [3].

An ideal *in vivo* dosimeter should improve the quality of the radiotherapy service without reduce its efficiency. For example, the adoption of *in vivo* dosimetry should not represent a relevant change in the following aspects:

- **Daily number of patients treated**: radiotherapy is a well-accepted and demanding treatment; therefore, the time required to setup and read the dosimeter should not reduce the number of patients that can be treated per day.
- **Quality of the treatment**: the interaction (scattering or attenuation) between the sensor and the treatment beam should be minimum. Furthermore, the use of this dosimeter cannot reduce the patient's ability to stay immobile during irradiation (any movement of patient during irradiation can be catastrophic).
- **Cost of the treatment:** the increasing cost (dosimeter + sensors + technician hours + treatment machine downtime) should not be significant because it can reduce the number of patients that can afford (or be afforded by public health policies) the treatment.

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Considering these requirements, a promising *in vivo* dosimeter should have the following features: cable-free (no cables running from each patient to the monitor unit), small in size (more comfort to the patient and less attenuation to the radiation beam), and simple of operation and fast readout (small treatment machine downtime and less technician hours). From Table I, we can observe that the MOSFET dosimeter is the only detector (considering the most commonly used *in vivo* dosimeter: thermoluminescent (TL), diode, and MOSFET) that is able to combine these three characteristics [2],[3]. In this context, we present a low-cost microcontroller-based MOSFET dosimeter suitable for *in vivo* radiotherapy applications that combines a simple and fast readout procedure with a small in size and cable-free sensor.

TABLE I. Comparison between TL, Diode, and MOSFET in vivo dosimeters.

Dosimeters	*Cable-free*	*Small in size*	*Simple and fast readout*
TLD	YES	YES	NO
Diode	NO	YES	YES
MOSFET	YES	YES	YES

II. CD4007 MOSFET Dosimeter

In the CD4007 MOSFET dosimeter, the dose is inferred from the threshold voltage (V_T) variation. The V_T variation (in mV) is measured by the constant current (CC) reader circuit previously studied in [4],[5],[6]. During the readout, any changes in temperature must be compensated for, since V_T is dependent on temperature. For this reason, this dosimeter uses the differential measurement, *i.e.*, the V_T variation of the sensor is compared with a replica. The sensor and its replica (both CD4007 UBM devices) are selected to have matched V_T before irradiation. The CD4007UBM integrated circuit was selected as the radiation sensor because the gate oxide thickness (t_{ox}) of the transistors is 120 nm [7], which provides the sensor with two important characteristics: radiation sensitivity (ΔV_T is proportional to t_{ox}^2) suitable for radiotherapy applications, and operation with relatively reduced supply voltage since $|V_T|$ is around 1.6 V [4],[5],[6].

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It is important to note that only the sensing transistor is exposed to radiation whereas its replica is not. The sensor and its replica are in the same room and, thus, subject to the same temperature; as a consequence, the difference in V_T of these devices will be due to radiation only and (almost) independent of temperature [4],[5]. The principle of operation of the developed MOSFET dosimeter is illustrated in Fig. 1.

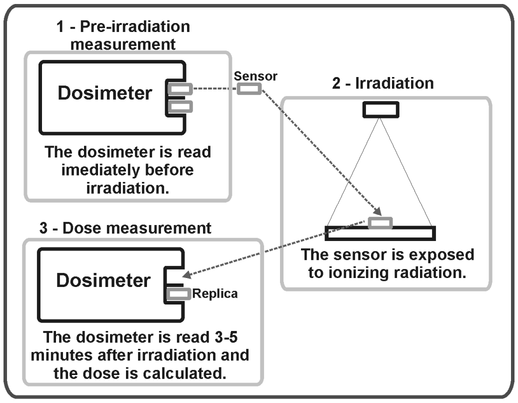

Fig. 1. Principle of operation of the CD4007 MOSFET dosimeter.

A. *CD4007 MOSFET Dosimeter Prototype*

The simplified schematic of the implemented dosimeter is presented in Fig. 2.

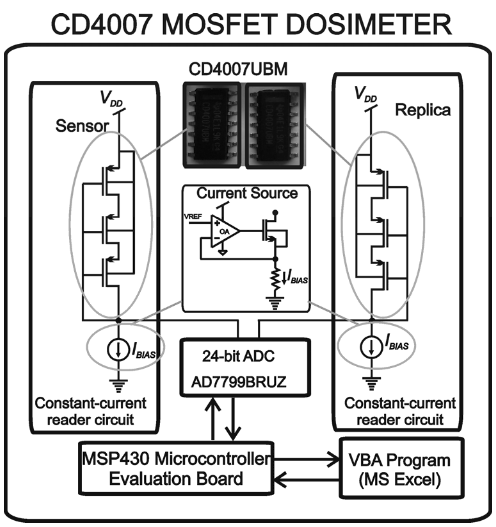

Fig. 2. Simplified schematic of the CD4007 MOSFET dosimeter prototype.

The dosimeter is powered by a USB port and controlled via a Visual Basic (VBA) code written in Microsoft (MS) Excel software. It is important to mention that the microcontroller evaluation board (MSP-EXP430G2) was used (instead of only a microcontroller device) for the following reasons: the microcontroller can be easily reprogrammed, its voltage regulator can supply stable voltage for the entire dosimeter circuitry, the UART (Universal Asynchronous Receiver/Trasmitter) communication module is already implemented, and it is very cost-effective [8]. The dosimeter sampling frequency was set to be 8.67 Hz.

The most important components used in this prototype are listed in Table II.

TABLE II. LIST OF SELECTED COMPONENTS USED IN THE CD4007 MOSFET DOSIMETER PROTOTYPE.

IC PART	*Description*	*Cost*
CD4007UBM	MOSFET array used as the radiation sensor	0.5 US$
OPA2277P	Low-offset operational amplifier used in the reader circuit	5.0 US$
AD7799BRUZ	24-bit analog-to-digital data converter (ADC)	7.5 US$
MSP-EXP430G2	Microcontroller evaluation board	10.0 US$

The main features of this prototype are:

- **Portability:** USB powered, dimensions of 10.5 cm x 12 cm x 5cm, and weighs less than 200 grams.
- **Easy of operation:** only basic MS Excel knowledge is required and the reading procedure takes less than 30 seconds;
- **Very cost-effective:** the cost of the dosimeter prototype and the radiation sensor are about 40 US$ and 0.5 US$, respectively.

B. *Electrical Test*

Two tests were performed to evaluate the dosimeter. In the first test, the inputs terminals of the dosimeter were grounded. Afterwards, a standard pre-irradiation measurement (*i.e.* the differential measurement of two matched CD4007UBM devices) was performed. In these tests, each measurement was repeated 700 times (Fig. 3).

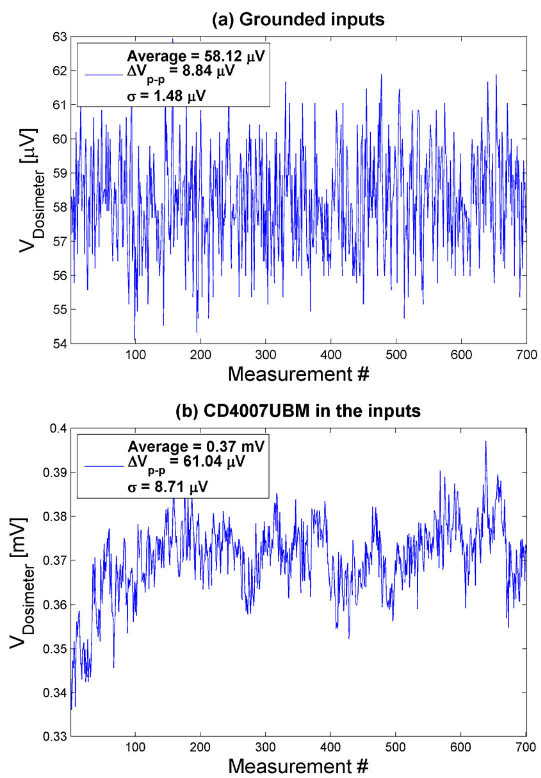

Fig. 3. Results of the prototype tests: (a) with grounded inputs and (b) standard pre-irradiation measurement (using CD4007UBM devices).

The effective peak-to-peak resolution ($R_{p\text{-}p}$) can be defined as [9]:

$$R_{p\text{-}p} = log_2(V_{FS}/\Delta V_{p\text{-}p}) \quad (1)$$

where V_{FS} and $\Delta V_{p\text{-}p}$ are the full-scale voltage and the dosimeter output peak-to-peak variation. The full-scale voltage (= $V_{DD}/2$ = 1.765 V) is internally measured by the dosimeter.

The results presented in Fig. 3 show that the peak-to-peak resolutions of the dosimeter are about 17.6 bits (= log_2(1.765 V/8.84 μV)) and 14.8 bits (= log_2(1.765 V/61.4 μV)) for the configurations presented in Fig.3 (a) and (b), respectively. As a consequence, for a standard irradiation of 2 Gy ($\Delta V_{Dosimeter}$ = 13 mV) the inaccuracy due to the dosimeter circuitry is expected to be of the order of 0.5% (61.4 μV/13 mV). The dosimeter resolution with the inputs grounded (17.6 bits) is very close to the ADC reference value 18.5 bits (=log_2(2.5 V/6.86 μV)) [9]. Furthermore, the dosimeter offset voltage is about 58 μV.

III. Materials and Methods

This section presents the main characteristics of the experiments with ionizing radiation carried out to evaluate the performance of CD4007 MOSFET dosimeter. In these experiments, the sensor (CD4007 UBM) was irradiated by 6 MV x-ray beams (field of 10 cm x 10 cm and dose rate of 400 monitors units per minute) generated by the Elekta (model Axess) linear accelerator (Fig. 4). We used slabs of acrylic and solid water, a water-equivalent material. All experiments with ionizing radiation were performed at the Radiotherapy Center of the Hospital do Coração (HCor) in São Paulo (São Paulo State – Brazil).

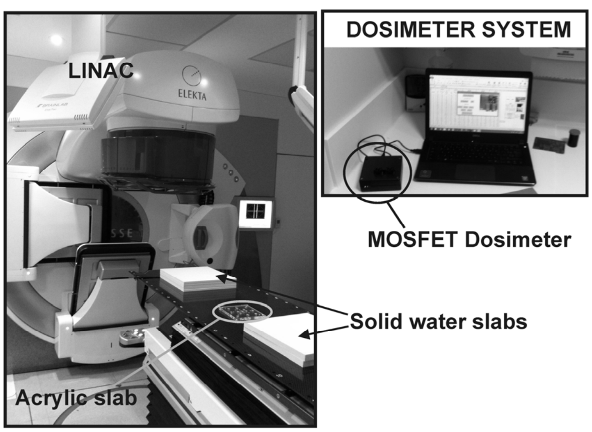

Fig. 4. Materials and equipments used in the experiments with ionizing radiation.

A. *40 Gy (20 x 2 Gy) measurements*

The dosimeter response to a total dose of 40 Gy was evaluated through the experimental arrangement shown in Fig. 5. In this experiment, five MOSFET sensors were irradiated 20 consecutive times with a dose per session of 2 Gy. It is worth to note that the total dose of a cancer treatment is usually divided into 2 Gy fractions; therefore, this experiment tends to simulate a treatment of 40 Gy equally divided in 20 sessions. The solid water slab of 1.5 cm was used over the MOSFET sensors to provide the appropriated buildup.

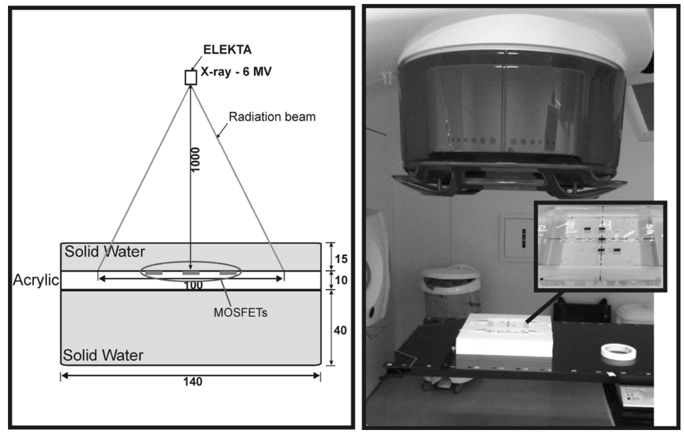

Fig. 5. Illustration and photo of the experimental arrangement used to study the response of the CD4007 MOSFET dosimeter to an accumulated total dose of 40 Gy. All dimensions in milimeters and drawn not to scale.

B. *Low-dose measurements*

In this experiment, three MOSFET sensors were irradiated simultaneously with the following doses: 10 cGy, 20 cGy, 50 cGy, and 100 cGy. Each irradiation was repeated three times, with the exception of the 10 cGy irradiation that was repeated five times. As a result, all sensors were irradiated with a total dose of 5.6 Gy. This experiment used the same experimental arrangement previously presented in Fig. 5.

IV. Experimental Results

This section presents the results of the experiments with ionizing radiation.

A. *40 Gy (20 x 2 Gy) measurements*

The result of five CD4007UBM sensors irradiated with an accumulated dose of 40 Gy is presented in Fig. 6.

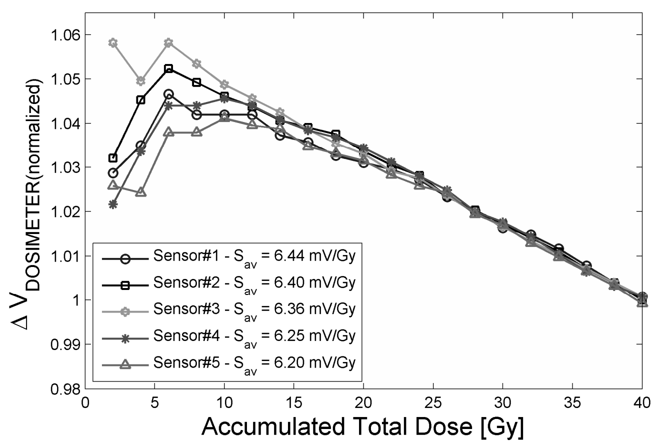

Fig. 6. Normalized variation of the dosimeter output voltage ($\Delta V_{DOSIMETER(normalized)}$ = ($\Delta V_{DOSIMETER}$ /(Accumulated Total Dose * S_{av})) as a function of the accumulated total dose. The average sensitivity (S_{av}) was evaluated dividing $\Delta V_{DOSIMETER}$ by the total dose (40 Gy).

From Fig. 6, we have that the average sensitivity differs less than 4% (6.20/6.44 = 0.963) for the five radiation sensors.

Furthermore, we can observe that especially for doses greater than 10Gy the normalized response tends to decrease following a linear behavior. Consequently, a curve of reference can be used to compensate this sensitivity reduction (about 4% for doses between 10 and 40 Gy), as shown in Fig. 7.

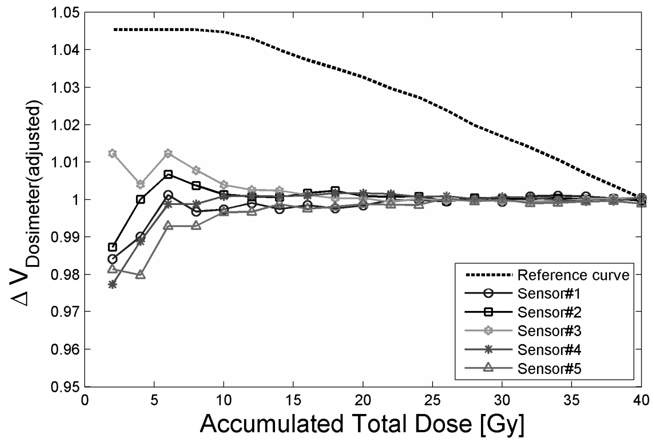

Fig. 7. Ajusted variation of the dosimeter output voltage ($\Delta V_{DOSIMETER(adjusted)} = (\Delta V_{DOSIMETER(normalized)}$ /Curve of reference)) as a function of the accumulated total dose.

From Fig. 7, we have that the adjusted dosimeter response over a 40 Gy irradiation varies less than 4% (-2.5% to +1.5%). This result shows that the dosimeter precision is suitable for radiotherapy applications, which requires a dose precision of the order of ±5%.

B. Low-dose measurements

The normalized radiation sensitivity of three CD4007UBM devices irradiated with low doses is presented in Table III.

TABLE III. NORMALIZED RADIATION SENSITIVITY ($S_{NORMALIZED} = \Delta V_{DOSIMETER(NORMALIZED)} * S_{AV}$) FOR EACH IRRADIATION DOSE. THE AVERAGE SENSITIVITY FOR SENSORS #1, #2, #3 ARE: 6.73 MV/GY, 6.62 MV/GY, 6.73 MV/GY, RESPECTIVELY.

SENSOR	***5*10cGy***	***3*20cGy***	***3*50cGy***	***3*1Gy***
#1	0.922	1.013	0.997	1.012
#2	0.931	1.011	0.990	1.014
#3	0.948	0.974	0.996	1.016

Table II shows that the average sensitivities (excluding 10 cGy irradiations) have small variations: 1.6%, 1.5% and 4.2% for the sensors #1, #2, #3, respectively. However, considering the 10 cGy irradiations this deviation increases and reaches 9% for the sensor #1. This behavior was expected because the $\Delta V_{Dosimeter}$ after a 10 cGy irradiation is of the order of 650 μV, which is only ten times greater than the dosimeter peak-to-peak variation presented in Fig. 3b. Consequently, this low-dose measurement can be affected by dosimeter resolution. Providentially, low dose irradiations (less than 1.0 Gy/session) are not a common practice in radiotherapy.

V. CONCLUSIONS

In this paper we detailed the development of a low-cost microcontroller-based MOSFET dosimeter which uses the CD4007UBM device as the radiation sensor. The sensor is cable/battery-free during irradiation and has small dimensions (area of 38 mm^2 and thickness of 1.75 mm). These characteristics contribute to very low attenuation of the radiation beam, to the patient's comfort, and to rapid setup [4]. Also, the dosimeter readout procedure is quick (take less than 30 seconds), very simple (can be carried out anywhere by any professional with basic knowledge in MS Excel), and accurate (a maximum average sensitive variation of 4.2% for low-dose irradiations (20 cGy to 1Gy)). Moreover, the variation of the adjusted response over a total dose irradiation of 40 Gy is less than 4%.

The CD4007 MOSFET dosimeter is of very-low cost, the prototype was built for less than US$ 40. It is important to note that the prototype is not exposed to radiation; therefore, its expected lifetime is of a regular consumer electronic, usually few years. Furthermore, the low price of the sensors (US$ 0.5 each) combined with their reduced dimensions, which aid their storage, allows the use of one (or more) sensor(s) to track the radiation dose given to a patient throughout the treatment. Considering these important characteristics, the MOSFET dosimeter presented in this article is a very appealing and cost-effective option for *in vivo* radiotherapy applications.

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REFERENCES

[1] J.A. Purdy, E. Klein, S. Vijayakumar, C.A. Perez, and S.H. Levitt, "Quality assurance in radiation Oncology" in *Technical basis of radiation therapy: Practical clinical applications*, C.A. Perez, S.H. Levitt, J.A. Purdy and S.Vijayakumar, 4th Ed. Berlin: Springer-Verlag, 2006, pp 395-422.

[2] A.B. Rosenfeld, "Electronic dosimetry in radiation therapy," *Radiation Measurements*. vol.41, Suppl. 1, S134-S153, 2006.

[3] "Development of procedures for in vivo dosimetry in radiotherapy,", *International Atomic Energy (IAEA) and International Society for Radiation Oncology*, IAEA Human Health Reports, no.8, 2013.

[4] O. F. Siebel, J.G. Pereira, R.S. Souza, F.J. Ramirez-Fernandez, M.C. Schneider, and C. Galup-Montoro, "A very-low-cost dosimeter based on the off-the-shelf CD4007 MOSFET array for *in vivo* radiotherapy applications," *Radiation Measurements*, vol. 75, no. 1, pp. 53-63, 2015.

[5] O.F. Siebel, J.G. Pereira, M.C. Schneider and C. Galup-Montoro, "A MOSFET dosimeter built on an off-the-shelf component for *in vivo* radiotherapy applications," *Proceedings of the 5th IEEE Latin American Symposium on Circuits and Systems (LASCAS)*, pp.1-4, 2014.

[6] O.F. Siebel, M.C. Schneider, and C. Galup-Montoro, "Low power and low voltage VT extractor circuit and MOSFET radiation dosimeter," *Proceedings of the 10th IEEE International New Circuits and Systems Conference (NEWCAS)*, pp.301-304, 2012.

[7] D.P. Foty and S.L. Titcomb, "Thermal effects in n-channel enhancement MOSFET's operated at cryogenic temperatures," *IEEE Transactions on Electron Devices*, vol. 34, no.1, pp. 107-113, 1987.

[8] "MSP-EXP430G2 LaunchPad Evaluation Kit - User's Guide", *Texas Instruments*, 2010.

[9] C. Slattery e M. Nie, "A reference design for high-performance low-cost weigh scales," *Analog Dialogue*, vol.39, no.4, pp.13-18, 2005.