Low power and low voltage V_T extractor circuit and MOSFET radiation dosimeter

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***Abstract*— This work discusses two fundamental blocks of an *in vivo* MOS dosimeter, namely the radiation sensor and the V_T-extractor circuit. It is shown that threshold extractor circuits based on an all-region MOSFET model are very appropriate for low power design. The accuracy of the extractor circuits allows using the PMOS transistors of the integrated circuit CD4007 as the radiation sensor in a dosimeter for radiotherapy applications.**

I. INTRODUCTION

In cancer treatment by means of ionizing radiation precise knowledge of the dose and location of radiation experienced by the patient is critical for efficacy of the treatment. The most direct method to provide quality assurance (QA) in radiation oncology is the monitoring of the dose delivered to the patient during radiation therapy which can only be performed using an *in vivo* dosimeter. The most important examples of *in vivo* dosimetry systems are: thermoluminescent, diode, and MOSFET dosimeters [1],[2].

Traditionally, the dosimeters most commonly used for QA in radiotherapy have been TLDs (thermoluminescent dosimeters) and silicon diodes. TLDs are small in size, accurate and wireless. TLD infers the total dose of ionizing radiation by measuring the amount of visible light emitted from a thermoluminescent crystal when it is heated. The reading process is an important drawback of TLDs because the readout must be performed off-line, data information is lost during reading process, and it is time consuming. In fact, the diode dosimeter has gained popularity due to its greater sensitivity and low processing time (seconds) as compared to the TLDs' (hours). In the diode dosimeter the radiation current is proportional to the dose rate and the total dose can be easily obtained integrating this current. The readout process of a diode dosimeter is instantaneous; however, the dosimeter must be connected with cables during radiation. The diode dosimeter measurement is sensitive to temperature variation and dependent on energy of the radiation beam. Also, diode dosimeters must be regularly and carefully calibrated [2].

Due to the reasons above mentioned, MOSFET detectors are very attractive for clinical *in vivo* dosimetry because they have qualities that are impossible to achieve with TLDs or diode dosimeters. MOSFET dosimeters provide immediate read-out (similar to diodes), and no need for wires during radiation (like TLD). Moreover, it is possible to design and fabricate the radiation sensor and electronic circuits (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 MOSFET is that its radiation sensitivity varies less than 2% for most radiation sources used in medical applications [3]. As a consequence, MOSFET is the best choice for an ideal dosimeter, which must be very small (to reduce attenuation of the radiation beam and provide comfort to the patient), accurate, low-cost and low power consumption. The temperature dependence of the reading, which is an important drawback of MOSFETs, can be overcome by electronics circuits.

This work discusses the two fundamental blocks in an *in vivo* MOS dosimeter: the radiation sensor and the V_T-extractor circuit. Three V_T-extractor circuits are analyzed emphasizing power consumption and accuracy. We also present results from experiments with ionizing radiation that showed that appropriately biased PMOS transistors from the integrated circuit CD4007 are suitable for use as radiation sensors in low-voltage and low-power dosimeters for radiotherapy applications.

II. RADIATION SENSOR

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 thick enough. Ionizing radiation also induces an increase of interface traps at the silicon-insulator interface. As a result, the variation of charge trapped in the gate oxide (ΔQ_{ot}) and in the interface traps (ΔQ_{it}) will shift the threshold voltage (V_T). The variation of V_T due to ionizing radiation is given by:

$$\Delta V_T = -\frac{\Delta Q_{ot}+\Delta Q_{it}}{C_{ox}} \quad (1)$$

where C_{ox} is the oxide capacitance. ΔQ_{ot} is positive, but, under normal operation, ΔQ_{it} is positive in a PMOS transistor

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and negative in an NMOS transistor. Due to this reason PMOS transistors are used in MOS dosimeters because they have greater sensitivity and better linearity than NMOS.

III. V_T-EXTRACTOR CIRCUITS

The radiation dose in a MOS dosimeter is inferred by the variation of the threshold voltage; therefore, it is essential to design a circuit that extracts V_T or some parameter directly linked to V_T. In this section, we analyze three V_T-extractor circuits: strong-inversion (SI), constant-current (CC), and designated as ultra low-power extractors.

A. Strong-inversion (SI) V_T-extractor

The threshold voltage lies between strong and weak inversion regions, where both drift and diffusion transport mechanisms are important [4]. Therefore, strong-inversion V_T-extractor circuits (see, for example, [5-6]) are inherently inaccurate because they are based on the characteristics of MOSFETs operating in strong inversion (SI), where the drift current prevails largely over the diffusion current. Another important drawback of SI V_T-extractors is the high power consumption. This characteristic is particularly important in V_T-extractors for *in-vivo* dosimeter because battery (heavy metals) and wires deflect radiation. Thus, in order to enable self-powered dosimeters, that harvest energy from ambient light or radio-frequency source, the design of low-power circuitry is mandatory.

Since biasing transistors in strong inversion have two important drawbacks; namely low accuracy and high power consumption, we will present two V_T-extractor circuits that employ transistors operating in the moderate inversion (MI) or weak inversion (WI) regions.

B. Constant-current (CC) V_T-extractor

The conventional constant current bias circuit uses a diode connected transistor operating in strong inversion (Fig.1a). The output voltage of this circuit is directly linked to the threshold voltage. Due to its simplicity, this extractor circuit is used in several MOSFET dosimeters [7],[8].

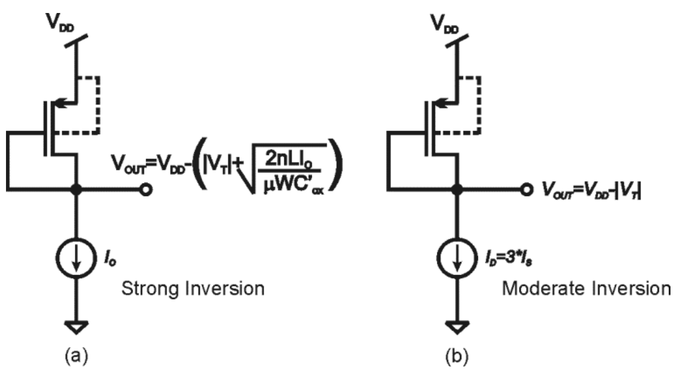

Figure 1. Schematic of the constant-current bias circuit (a) conventional (SI), and (b) low power (MI).

TABLE I. LONG-CHANNEL MOSFET EXPRESSIONS [9]. I_S IS THE SPECIFIC CURRENT, i_f IS THE FORWARD NORMALIZED CURRENT, i_r IS THE REVERSE NORMALIZED CURRENT, n IS THE SLOPE FACTOR, ϕ_t IS THE THERMAL VOLTAGE, μ IS THE MOBILITY, W IS THE CHANNEL WIDTH, AND L IS THE CHANNEL LENGTH.

Variable	Expression
Drain current	$I_D = I_F - I_R = I_S(i_f - i_r)$ (2)
Specific current	$I_S = \mu n C'_{ox} \frac{\phi_t^2}{2} \frac{W}{L}$ (3)
Source (drain)-to-bulk voltage (Unified current control model (UICM))	$V_P - V_{S(D)} = \phi_t\left[\sqrt{1+i_{f(r)}} - 2 + \ln\left(\sqrt{1+i_{f(r)}} - 1\right)\right]$ (4)
Pinch-off voltage	$V_P \cong \frac{V_{GB}-V_T}{n}$ (5)

The conventional current bias circuit can be improved to obtain directly the threshold voltage as the output (Fig.1b). The improved MI CC V_T-extractor circuit extracts the threshold voltage in a very direct way and can be demonstrated (using Eqs. (2)-(5)) that the output voltage V_{OUT} is given by [4],[10]

$$V_{OUT} = V_{DD} - |V_T| + n\phi_t\left(\sqrt{1+i_f} - 2 + \ln\left(\sqrt{1+i_f} - 1\right)\right). \quad (6)$$

We have from (6) that biasing the transistor with I_D=3*I_S (i_f=3) V_{OUT}=V_{DD}-|V_T|. Fig. 2 shows that we can reduce the thermal dependence of V_{OUT} choosing an appropriate biasing current; however at the expense of a high current.

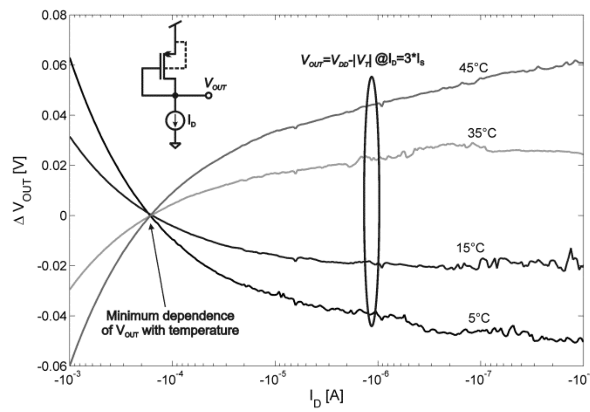

Figure 2. Variation of the output voltage (V_{OUT}) with respect to the measurement at 25°C for the PMOS transistor of integrated circuit CD4007. The values of the current that give V_{OUT}=V_{DD}-|V_T| and the minimum temperature dependence are -1.2μA (I_S=-0.4μA) and -150μA, respectively.

The power consumption of the MI constant current V_T-extractor (i_f=3) is greatly reduced in comparison with the SI V_T-extractor (i_f≥100). On the other hand, the accuracy is an important drawback of V_T-extractors in Fig.1 because the transistor operates in the saturation region, where short-channel effects interfere with the value of the measured threshold voltage [4].

C. Ultra low-power V_T-extractor circuit

To circumvent the drawbacks (high power consumption and low accuracy) of the previous V_T-extractors, a new topology which uses the transistor in the linear region in moderate inversion to allow for ultra-low-power operation (Fig.3), was proposed in [4].

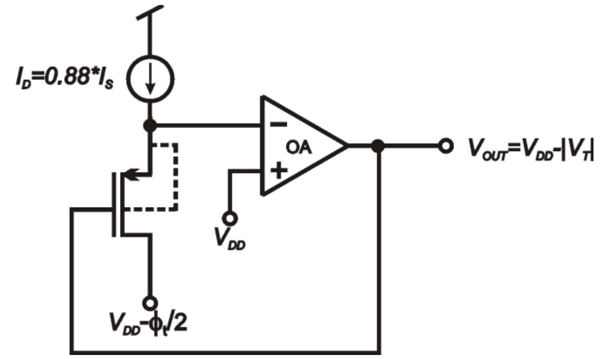

Figure 3. Schematic of ultra-low-power V_T-extractor circuit [4].

In this circuit, since the MOS transistor operates at low current levels and in the linear region, it is less affected by second order effects (*e.g.*, channel-length modulation, drain-induced barrier lowering, and carrier velocity saturation) [4].

Using (4) and (5) we have that for i_f=3, V_P=0 and $|V_{GB}|$=$|V_T|$. The value of V_{DS} is closely related to i_r and these values can be calculated using (4). Table II shows some values of V_{DS}, i_f, and i_r that can be used in the extractor circuit of Fig. 3.

TABLE II. BIASING VALUES FOR THE LOW-POWER V_T-EXTRACTOR

$\lvert V_{DS}\rvert$	i_f	i_r	$I_D=I_S*(i_f-i_r)$
$\phi_t/2$	3	2.12	0.88*I_S
ϕ_t	3	1.46	1.54*I_S
$2\phi_t$	3	0.63	2.37*I_S

This V_T-extractor circuit allows the direct determination of the threshold voltage with minimum influence of second-order effects and reduced power consumption (transistor operates in MI). It should be noted that this circuit can be fully integrated. The biasing signals, proportional to I_S and ϕ_t, can be generated using self-cascode MOSFETs (SCM) [11].

IV. Experiment with Ionizing Radiation

In order to evaluate the radiation sensitivity of MOS transistors experiments with ionizing radiation (X-rays of 6MV) were carried out.

ΔQ_{ot} and ΔQ_{it} are proportional to the oxide thickness (t_{ox}) and $C_{ox} \propto 1/t_{ox}$, thus we have from (1) that the variation of V_T due to ionizing radiation is proportional to t_{ox}^2. Therefore, the use of a transistor with thick oxide is important for the increase of radiation sensitivity. On the other hand, thick oxide transistors should operate with high voltage. Oxide thicknesses in the range of 50-150nm seem adequate to obtain the required sensitivity and (relatively) low voltage operation. Due to these reasons were used transistors from the integrated circuit (IC) CD4007 since this IC has a gate oxide thickness of 120nm [12].

The integrated circuit was submitted to a total radiation dose of 200 Gy divided in 7 fractions (Table III). The temperature was fairly constant (=22°C) during the experiment; therefore, the thermal dependence of the MOS electrical parameters (e.g., V_T, mobility) can be disregarded.

Figure 4. Experimental setup used in the experiment with ionizing radiation and detail on the prototype.

In this experiment NMOS and PMOS transistors were used in the unbiased and biased (V_{GS}=9V-NMOS and V_{SG}=9V-PMOS) conditions. Electrical measurements were performed using the CC V_T-extractor circuit (Fig.1b). The variation of V_{OUT} with the ionizing radiation dose for these transistors is presented in Fig.5 and Fig.6.

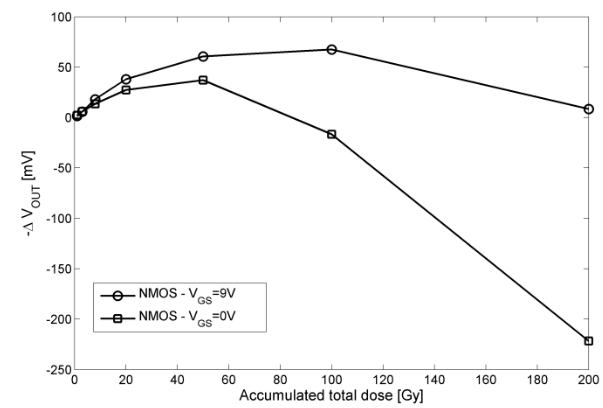

Figure 5. Variation of the output voltage as function of the total accumulated dose for NMOS transistors from the IC CD4007.

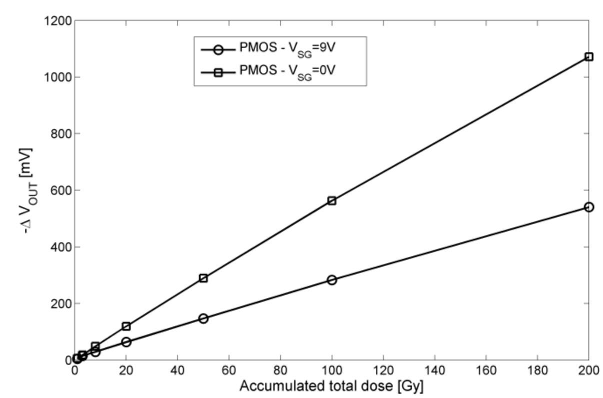

Figure 6. Variation of the output voltage as function of the total accumulated dose for PMOS transistors from the IC CD4007.

Fig.5 and Fig.6 show that PMOS transistors have greater sensitivity and better linearity than NMOS transistors. Also, we can see that the unbiased PMOS transistor has the greatest sensitivity and good linearity; therefore this transistor is the most appropriate to be used as a radiation sensor. Table III shows that the unbiased PMOS transistor has an average radiation sensitivity of 5.36mV/Gy over a wide dose range (doses up to 200Gy, which is more than two times the total dose used in cancer treatment).

TABLE III. ΔV_{OUT} FOR PMOS TRANSISTOR OF THE IC CD4007 IRRADIATED WITH DOSES UP TO 200GY (X-RAYS OF 6MV).

Fraction	***Dose per fraction (Gy)***	***Accumulated Total Dose (Gy)***	***PMOS V_{SG}=0V***
			$-\Delta V_{OUT}$ ***(mV)***
1	1	1	6.3
2	2	3	17.5
3	5	8	48.3
4	12	20	119.1
5	30	50	289.1
6	50	100	563.2
7	100	200	1071.3

To evaluate the time stability of V_{OUT} of the selected transistor (unbiased PMOS), after the exposure to 200Gy, 3 measurements (after 3, 10 minutes and 12 hours) were made. The results presented in Table IV show that the variation of V_{OUT} with time is about 2.0mV and 8.0mV after 10 minutes and 12 hours, respectively.

TABLE IV. TIME STABILITY OF THE PMOS TRANSISTORS OF CD 4007.

Time after irradiation	***Accumulated Total Dose (Gy)***	***PMOS V_{SG}=0V***
		$-\Delta V_{OUT}$ ***(mV)***
3 minutes	200	1071.3
10 minutes	200	1073.7
12 hours	200	1063.0

The characteristics (sensitivity, linearity and time stability) presented by the unbiased PMOS transistor from IC CD4007 make this transistor suitable to be used as a radiation sensor in radiotherapy applications. Another interesting characteristic of this transistor is that its pre-irradiated V_T is about -1.6V, therefore all the necessary electronics circuits can be designed in a standard 3.3V standard CMOS process (e.g., CMOS 0.35µm). It should be noted that using the low-power V_T-extractor circuit of Fig.3 the current consumption of the PMOS transistor used as a radiation sensor is only 350nA (I_S=-0.4µA).

V. CONCLUSIONS

We showed why a new generation of threshold voltage extractor circuits can greatly improve MOSFET radiation dosimeters. The new circuit techniques allow designing very low power circuits and low voltage MOSFET radiation sensors.

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