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Floating Gate sensor for in-vivo dosimetry in radiation therapies. Design and first characterization.

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Abstract. A floating gate dosimeter was designed and fabricated in a standard CMOS technology. The design guides and characterization are presented. The characterization included the controlled charging by tunneling of the floating gate, and its discharging under irradiation while measuring the transistor drain current whose change is the measure of the absorbed dose. The resolution of the obtained device is close to 1 cGy satisfying the requirements for most radiation therapies dosimetry. Pending statistical proofs, the dosimeter is a potential candidate for wide in-vivo control of radiotherapy treatments.

1. Introduction

”Adequate in-vivo dosimetry would prevent most accidental exposures” states the International Commission for Radio-Protection (ICRP) in its Publ. 86 aiming to assist in the prevention of accidental exposures involving patients undergoing cancer radiotherapy from external beam or solid brachytherapy sources[1]. Similar advice is found in reports from the American Association of Physicist in Medicine (AAPM) and by the European Society for Therapeutic Radiology and Oncology (ESTRO) dealing with the use of Thermo-Luminescent Dosimeters (TLD), Radiochromic films or Diodes for in-vivo dosimetry [2], [3]. The importance of in-vivo dosimetry in radiotherapy treatments for the clinical efficacy and for the safety of the patients has been emphasized last years by the regulation agencies. It is aimed to verify that the delivered dose does not deviate from the planned treatment in more than 5%. In spite of all these recommendations, the implementation of in-vivo dosimetry is slow and limited to a few treatments (Total Body Irradiation for example) or reduced to a complementary procedure in the Quality Assurance (QA) program of the radiotherapy centers. Different detectors has been used for in-vivo dosimetry. Luminescent devices TLD, Opto-Stimulated Luminescent (OSL); Electronic devices: diode, MOSFET; Films: Radiochromic films.

In the last years a relative increase in the use of MOSFET sensors has been observed. Their main advantages are: very small volume due to the close to 20000 times the sensitivity of a ionization chamber of the same volume, robust for their manipulation, easy electronic real time reading, produced in CMOS technology allowing thus easy integration with processing electronics, suitable for intracavitary positioning and for intra-operatory and brachytherapy treatments [4].

Within the MOS sensors family, the floating gate sensor introduced a decade ago has been the subject of several studies and improvements [5-7]. Its main advantage lies in its ability to sustain an electric field in the oxide which increases the net radiation induced pair generation without the need to be externally biased. In this work we present the design, fabrication and first characterization of a floating gate device for its use in in-vivo dosimetry for radiation therapies.[*]

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2. Materials and methods

2.1 Structure and Principle of operation

The floating gate (FG) dosimeter is a MOS transistor (labeled “Reader” in Fig. 1) with an isolated/floating polysilicon gate whose potential, given by its stored charge, controls the channel current. Before measurement, charge is injected through the thin gate oxide of a second PMOS (labeled “injector”). During irradiation, charges are created in a thick field oxide under a large area of the floating gate. The electric field set up by the injected charge moves electrons and holes in opposite directions, discharging the floating gate. The reader’s drain current ID-VDS characteristics vary with FG charge and therefore with absorbed dose.

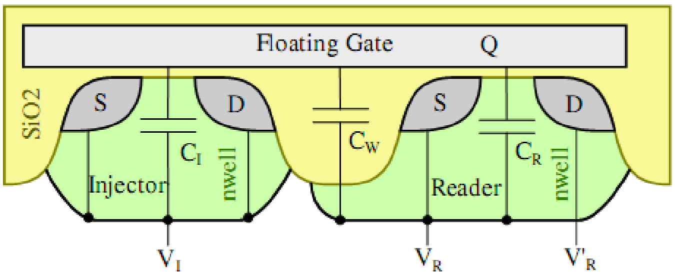

Fig. 1. Floating Gate capacitance model. CW is the capacitance between FG and the reader’s N well.

2.2 Design considerations

Charging the floating gate occurs by Fowler-Nordheim tunnelling from the injector [8]. The expression for the tunnelling current is

$$J_{FN} = AF_{ox}^2 \exp(-B/F_{ox}) \tag{1}$$

with A and B constants. The oxide field Fox is given by

$$V_{FG} - V_I = F_{ox} t_{ox} + \psi_s + V_{FB}, \tag{2}$$

where the left hand side is the potential difference across the tunnel oxide, tox the field oxide thickness and ψ_s the band bending at the substrate surface. VFB is the flat band voltage. In order to negative charge the floating gate, the injector is negatively biased (VI < 0) causing the silicon surface to be accumulated and thus
ψ_s is negligible in last expression. The floating gate potential is given by

$$V_{FG} = \frac{C_I V_I + C_R V_R + Q}{C_I + C_R} \tag{3}$$

being CI and CR the capacitances -shown in Fig. 1- injector-floating and reader-floating, VI and VR the corresponding voltages and Q the floating gate stored charge.

For the injection to be efficient, i.e. for the applied voltage at the injector VI to fall mainly across the tunnelling oxide, VFG should be as close as possible to VR in absence of charge (Q=0). This set the condition CI<<CR. The second design condition is that all the capacitances should be as small as possible in order to maximize the electrical sensitivity, i.e. maximum dVFG/dQ, given

$$Q_{FG} = (C_R + C_W)V_{FG} + C_I(V_{FG} - V_I)\,. \tag{4}$$

Finally, as the radiation induced charge in the floating gate is proportional to the volume of the insulators in these capacitors where it is generated, we have for the radiation sensitivity,

$$S = \frac{dV_{FG}}{dDose} \propto \frac{\sum A_i t_i}{\sum A_j / t_j} \tag{5}$$

where A_i and t_i are the area and thickness of each insulator. The result of the above criteria is synthesized in Fig. 2, where using the thicknesses of the foundry process the sensitivity is represented by the level curves in the plane of the areas ratios.

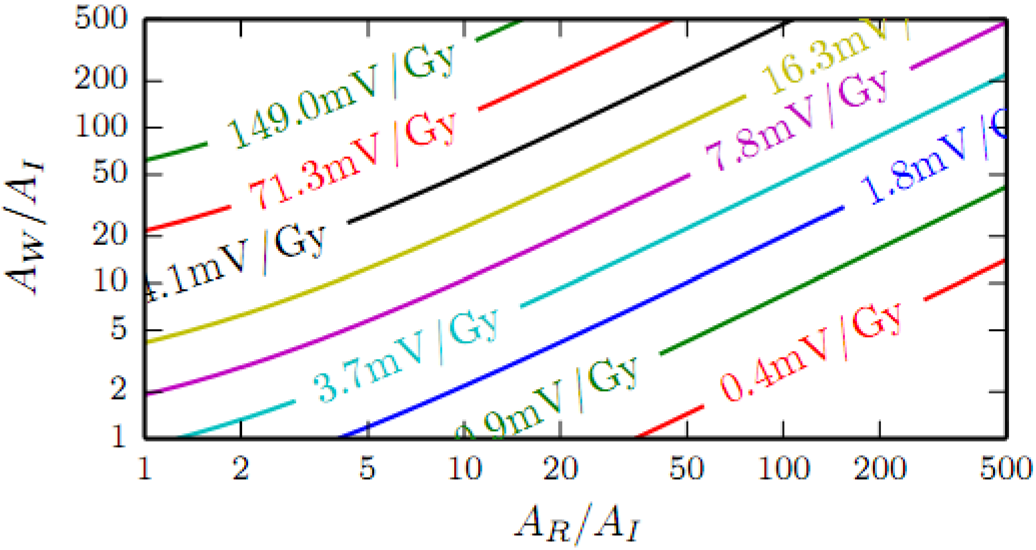

Fig. 2. The level curves of iso-sensitivity in the plane of the capacitors area ratios

Whereas the maximum sensitivity is in the upper left corner, efficient injection requires, as explained below eq.(3) $A_{R/}$ A_I>>1. We choose the ratios $A_I/A_R/A_W$: 1/50/500, being the largest area limited by the cost of the device which is proportional to its footprint on Silicon.

3. Measurements and results

3.1. Charging the floating gate dosimeter

The floating gate was charged forcing a tunnel current across the capacitor Ci provided by a Keithley 220 current source connected between the terminals Vi and Vr of the injector and reader transistors. The drain current at the reader transistor and the injected charge were monitored during the tunnel injection. A schematic of the injection configuration is given in Fig. 3.

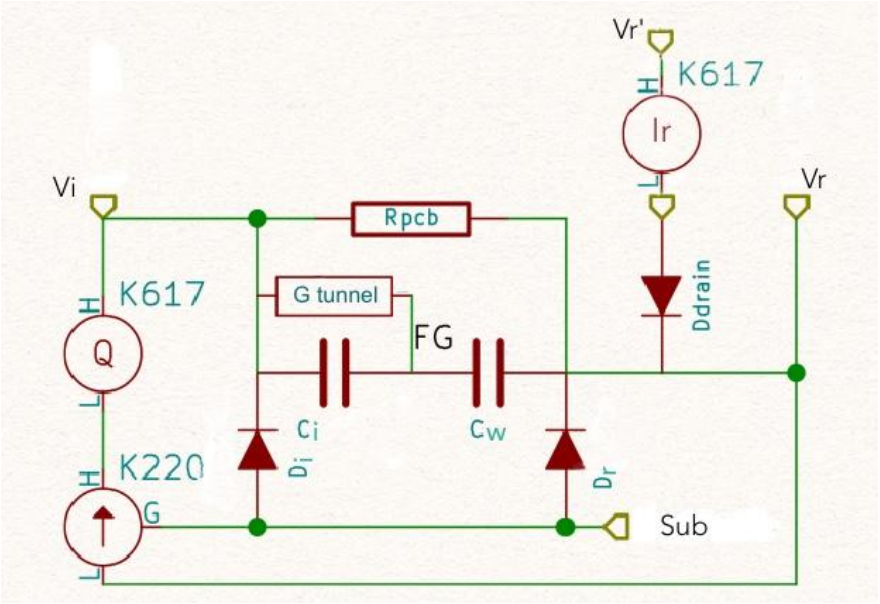

Fig. 3. Details of the injection setup. K220 is the Keithley 220 current source, there are two K617, Keithley 617 electrometer, one measuring the injected charge Q, the other one monitoring the drain current of the reader transistor Ir. G tunnel represents the tunnel conductance of the oxide in the Ci capacitor. The possible leakage paths for the injected current through Rpcb representing the pcb where the chip is mounted, and the diodes Di and Dr are blocked by applying to the substrate the same injecting voltage Vi through the guard terminal G of the K220.

The result of charging the floating gate are shown in Fig. 4. The drain current Id vs drain-source voltage Vds is measured after controlled injection pulses. The control is carried out by measuring the same drain current at fixed Vds and stopping the injection once the current reaches desired levels.

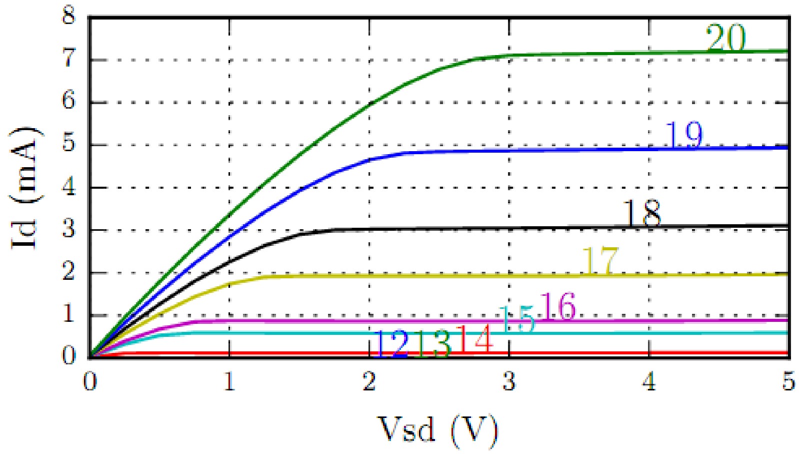

Fig. 4. Drain Current vs. Drain-Source Voltage after successive injection pulses

3.2.- Irradiating the floating gate dosimeter

After the device was charged at the maximum level of the Fig. 4, it was exposed to a 90Sr source with a dose rate of about 0.5 Gy/min measured with a ionization chamber. Along the irradiation the drain current at a fixed drain-source voltage was tracked as shown in Fig. 5.

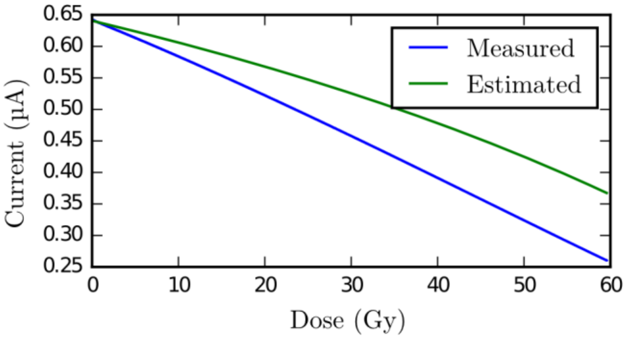

Fig. 6. Drain Current vs. Dose at Vds=0.1 V.

3.3 Sensor resolution

The measured current is almost linear with dose exhibiting the sensor a sensitivity of 6.5 uA/Gy. In order to establish the sensor resolution a figure of noise is needed. It was taken from the statistic of repeated measurements as shown in Fig. 6.

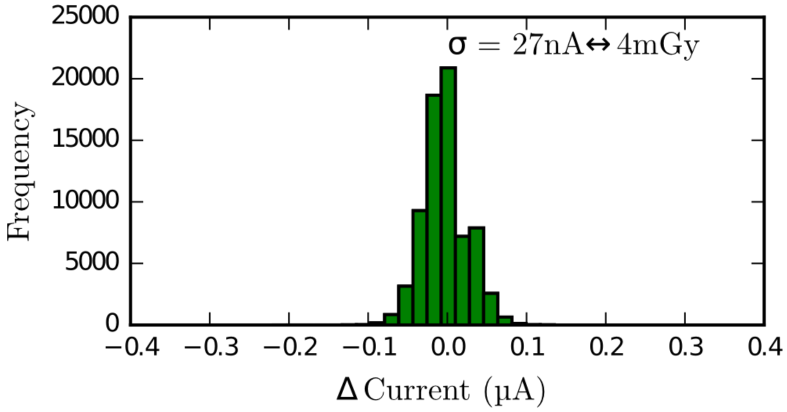

Fig. 6. Estimation of the noise. Distribution of the differences between successive current readings. The standard deviation in the distribution is equivalent to 4 mGy.

Conclusion

A floating gate dosimeter was designed and fabricated in a commercial CMOS process. First characterization of its performance was done. The resolution obtained from the estimation of noise is 4 mGy for one standard deviation. A safe figure of four standard deviations gives a noise equivalent dose of 1.6 cGy. Following the 5% accuracy required by the control agencies, the sensor complies with the requirement for radiotherapy control for doses greater than about 30 cGy. This is a fairly good performance given that in standard treatments doses of the order of 1 Gy per session are delivered.

The presented results are preliminary ones. Pending further tests, the presented device is a potential candidate to be used in in-vivo dosimetry for Radiation Therapies.

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