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A monolithic 180 nm CMOS dosimeter for wireless In Vivo Dosimetry

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HIGHLIGHTS

- A Monolithic Dosimeter for real time dosimetry during radiotherapy is proposed.
- The proposed device is 1 mm3 in size and could potentially be body implantable.
- The device includes a radiation sensor and RF readout, operating in the MICS band.
- Detailed tests have been performed under radiation beam in a clinical environment.
- Reported sensitivity is 1 cGy over 50 Gy, with an accuracy of better than 3%.

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ABSTRACT

The design, fabrication and testing of a novel monolithic system-on-chip dosimeter fabricated in a standard 180 nm CMOS technology is described. The device, implementing a radiation sensor and an RF transmitter, is proposed to address the need for real-time In Vivo Dosimetry (IVD) of radiation during Linac radiotherapy sessions. Owing to its small size, of approximately 1 mm^3, such solution could be made in-body implantable and, as such, provide a much-enhanced high-resolution, real-time dose measurement to improve Quality Assurance (QA) in radiation therapy. The device transmits the related information on dose of radiation wirelessly to a remote receiver operating in the Medical Implant Communication Service (MICS) band. Comprehensive description of the various phases of this project, including the development of the radiation sensors and integrated RF transmitter to perform the readout, along with the final test results using a radiation beam, will be given.

1. Introduction: the in vivo dosimetry

The aim of this project was to design a monolithic system-on-chip, of approximate size 1 mm^3, capable of performing the real-time measurement of dose of therapeutic radiation delivered to it and to transmit the related information wirelessly to a remote receiver.

Its small size would render such proposed system potentially body implantable, a solution that could allow real-time In Vivo Dosimetry (IVD) during radiotherapy sessions of unprecedented accuracy, being performed directly or very near the treatment volume location.

The importance of IVD as QA tool has long been recognized in the medical community (Rosenfeld et al., 2006; Towards-safer-radiotherapy; Scarantino et al., 2006); recommendations reports for practical dosimetry (International Atomic Energy Agency, 2000; Izewska et al., 2002; International Atomic Energy Agency, 2007) and surveys on its usage in radiotherapy centers are also available (Nelms and Simon, 2007).

Monolithic wearable systems for wireless real-time measurement of dose of radiation have been proposed ((Shamim et al., 2008)). However, the only recent example of an implantable device, which was fabricated in a hybrid technology and which was

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used in clinical practice for this purpose, is reported in Scarantino et al, (2004). Test results obtained from real patients using such device (Scarantino et al., 2008, 2005) justified the development of the project here described.

A general description of the operating principle and features of the monolithic dosimeter are shown in this paper in Section 2. Subsequent sub-sections describe the various design aspects of the dosimeter blocks, including technical details of the radiation sensors and the read out section. Section 3 describes test results of the individual elements of the dosimeter. Section 4 describes the details of the final, monolithic version of the dosimeter, including the processing phases of dicing to the required size of 1 mm^3 and bump bonding on a PCB carrier for the final radiation test. In Section 5 the description of the wireless radiation test performed with Linac in a radiotherapy center along with the obtained results are shown. Finally, in Section 6, a summary of the project and conclusions are given, along with proposed ideas on how to further develop the dosimeter towards a practical implementation usable in clinical practice.

2. Monolithic CMOS system for wireless dosimetry

The block diagram of the proposed monolithic dosimeter investigated in this project is shown in Fig. 1. This System-On-Chip (SOC) device consists of three sections, all integrated on the same silicon substrate: the radiation sensor, an analog to digital converter and an RF transmitter, the output of which drives a loop antenna.

The whole device is fabricated using a standard 180 nm CMOS technology, provided by Tower Jazz Semiconductor foundry. The target size of the final SOC was chosen to be approximately 1 mm^3, a compromise between low invasivity for a potentially body-implantable device and easiness of localization using standard clinical imaging techniques (Mahadevappa, 2009).

This project covered the design, fabrication and testing aspects of the SOC only. The other elements, that would indeed be needed for an actual implementation of IVD, including an autonomous powering, a biocompatible packaging and a custom RF receiver, were not investigated.

During the final radiation tests, the powering of the device was provided by an external small battery cell and the wireless retrieval of the data from the dosimeter was implemented using an external RF receiver and a spectrum analyzer, as described in details in Section 5.

A total of three ASIC designs were submitted to the foundry for fabrication. The first two addressed the radiation sensors and the readout section respectively. Following electrical and radiation characterization, the best performing flavors of each of these blocks were selected and in turn implemented in the third and final design. ASICs from the latest design were diced to the required size of 1 × 1 mm^3, initially wire bonded on a PCB carrier for initial tests and finally bump-bonded on a custom PCB carrier for the final radiation test with Linac.

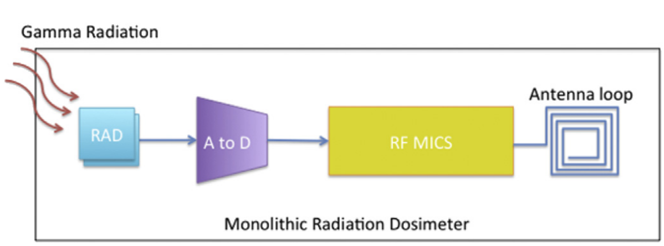

Fig. 1. Block diagram of the monolithic dosimeter.

2.1. CMOS radiation sensors

The radiation-sensing device of this dosimeter consists of an ad hoc modified CMOS Non Volatile Memory (C-FLASH NVM) cell, featuring a floating gate (FG) (Roizin et al., 2008). Additional technical details of the radiation sensor investigated in this project, along with some description of the design of the cells and initial tests results, can be found in Villani et al, (2013).

The use of the FG technology for radiation sensing has been proposed and evaluated earlier, (Tarr et al., 1998; Martin et al., 2001). For this project, a number of different flavors of C-FLASH cells were designed and fabricated, differing in size of the FG and form factor of the MOS transistors, with a view to optimizing their sensitivity to radiation and lower their output noise, Fig. 2. The latest versions of the fabricated cells also implemented, over the FG area, one of the four available metal layers from this CMOS technology, to act as an electrostatic shield and to investigate its effect on sensitivity to radiation when biased to high voltage, Fig. 3. In this technology, the distance between metal layers and FG is approximately 1 μm x metal layer level, with undoped silicon dioxide as separating dielectric. Thus, the application of 10's of volts to any of the layer would generate in the dielectric an electric field of strength of the order of 10^5 V/cm, which increases the escape recombination probability of ions immediately after their generation, (Boch et al., 2006), and, at the same time, does not exceed the breakdown voltage limit for silicon dioxide. The reduced recombination is therefore expected to increase the amount of collected charge by the FG and, thus, to increase the sensitivity. At the same time, the metal layer kept at constant potential acts as an AC ground plane, shunting externally injected noise to ground and, therefore, reducing the output noise of the cell.

Additional cells were also fabricated without FG, to evaluate the sensitivity of this CMOS technology to radiation.

As for all FG based devices, initial charging (‘programming’ i.e. charge injection in the FG via, for example, a tunneling or channel hot-electron injection process (Lacaze and Lacroix, 2014)) is required to make them sensitive to radiation.

After cell programming, the measurement of the dose of radiation received by the devices is performed, in our case, by measuring the threshold voltage shift of the PMOS transistors at the output inverter of the cell, Fig. 4. The threshold voltage is here conventionally defined as the V_{sd} measured across the transistor when its I_{sd} is set to 1 μA.

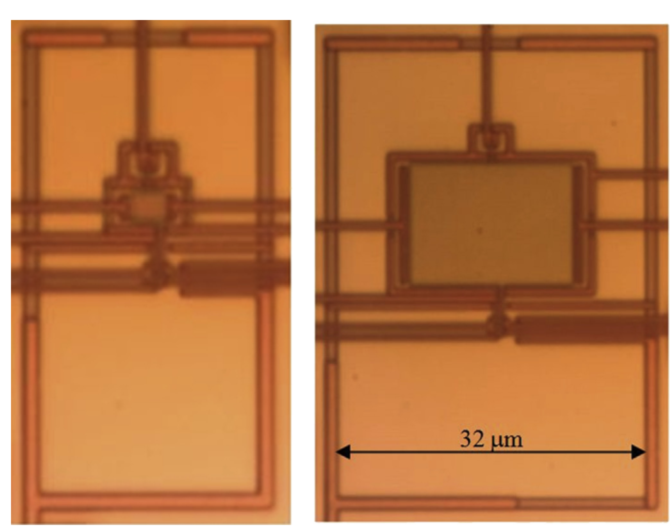

Fig. 2. Microphotographs of two fabricated C-FLASH radiation sensors, with different FG size, to investigate its effects on sensitivity to radiation.