Novel Silicon Microdosimeter based on 3D Cylindrical Structures

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ABSTRACT

A new design of a solid-state-detector based on silicon microfabrication is provided in this work in order to create a novel microdosimeter. This microdosimeter improves the performance of existing microdosimeters using three-dimensional microfabrication technology development. The microdosimeter could help to obtain biophysical parameters necessary to elucidate the relative biological effectiveness in hadrontherapy as well as the equivalent dose of those radiations present in nuclear medicine, aerospace exploration, nuclear facilities, particle accelerator and aviation, among others.

Keywords: microdosimetry, radiation silicon detectors, hadrontherapy

1 INTRODUCTION

Microdosimetry deals with the study of the distribution of energy deposition in microscopic volumes in biological material, as well as its relationship in physical/chemical and biological consequences. This dosimetry field is essential for both radiation therapy and radiation protection and requires appropriate instrumentation to carry out measurements at the micrometric level, in particular for cellular or subcellular structures. The device that is able to assess the especific energy within these structures when organisms are irradiated is called microdosimeter. Special considerations have to be taken into account to design a microdosimeter. For example, first the microsensor should have a cross-section size in that range of the mammalian cellular nucleus (few micrometers). Secondly, since the cellular volume may be approximated by a cylindrical shape, it is required to fix a sensitive size of the microsensor with a well-defined cylindrical volume [1].

One of the fields with more microdosimetric applications is the radiation therapy. Radiotherapy (RT) is a type of cancer treatment where the tumors are irradiated with ionizing radiation while keeping the risk organs near the tumor with tolerable dose. The RT has achieved great success in the cure or palliation of various cancers (alone or in combination with chemotherapy, surgery, or both). However, there are certain types of tumors of high radio-resistance RT whose treatment is more effective to therapies that make use of particles of high linear energy transfer (LET). These are included within the category of hadron beam therapies that use protons and heavy ions such as carbon, helium, oxygen, etc. Hadrontherapy has several advantages over conventional radiotherapy [2]: it has more radiobiological effectiveness and higher accuracy in the dose distribution, and therefore it allows a greater preservation of the health tissue placed around the tumor volume. This is possible because the density of ionization which produces an ion beam is greater than that generated by photons, especially at the end of the range of such particles (Bragg peak) [3]. In radio/hadrontherapy, the radiation treatment planning (RTP) is used to determine the dose distribution to be applied to a tumor volume. In the case of hadrontherapy, the RTP is hampered due to the strong influence of the structure of the trace on the therapeutic effectiveness. Treatment with non-optimized dose may lead to serious side effects to the patient, such as loss of functionality of tissues or even secondary tumors induced by radiation. The main objective of this work is to develop a novel microdosimeter to carry out microdosimetric studies in order to improve the treatment of cancers using hadrontherapy.

Drawing upon the idea proposed by Parker et al. [4] for processing columnar electrodes within the semiconductor substrate instead of being implanted in the surface to manufacture radiation detectors, the Spanish National Center of Microelectronics (IMB-CNM, CSIC) has developed and increased this 3D-concept of radiation solid-detectors for the last years. Actually IMB-CNM has proposed new designs of 3D technology for radiation detectors to be used in different research fields, e.g. plasma diagnostics [5], high-energy physics [6], or neutron detection [7] among others. Most of them are based on three-dimensional diodes (3D columnar structures with PN junctions) on ultrathin SOI silicon wafers fabricated with optimized micromachining techniques. These detectors have a sensitive volume of silicon of few microns thick (Fig.1) that makes the contribution of direct interactions of photons in silicon negligible at high energies, their membrane structure avoids the backscattering contributions from the supporting silicon wafer and the confinement of the electric field given by the columnar electrodes reduces charge sharing. All these characteristics could make the 3D devices useful to be applied in microdosimetry. Based on these 3D diodes, but extending its initial configuration, we propose a microdosimeter formed by a matrix of independent microsensors (simulating each cell) with well-defined micrometric cylindrical shape and with a volume similar to those of cellular structures (Fig. 2a). In order to achieve this, IMB-CNM is developing a new type of three-dimensional diode with cylindrical etchings that match the sensitive volume that simulates a cellular structure (Fig. 2b). Hence, when a particle passes through the microsensor of the silicon, it ionizes the matter and creates free electron–hole (e–h) pairs that are proportional to the deposited energy transmitted by the radiation to the silicon. This energy, ε, divided by the 'mean cord length' of the cylindrical diode, i.e.

$$\bar{l} = 4\frac{V}{S} \qquad (1)$$

where V is the volume irradiated of the microscopic target and S the area of such volume area, defines the associated stochastic linear energy (y) in an irradiated microvolume:

$$y = \frac{\varepsilon}{\bar{l}} \qquad (2)$$

which is a microdosimetric magnitud that would allow us to generate biophysical data (e.g. Linear Energy Transfer (LET), Relative Biological Effectiveness (RBE) or dose equivalent) needed for radiation effect models used in radio/hadrontherapy treatment planning software.

2 MICRODOSIMETER FABRICATION AND RESULT

We have proposed and manufactured a novel microdosimeter as the base detector for this microdosimetric application [8]. These devices are fabricated on four types of SOI wafers with a high resistivity n-type substrate and with active volumes of 3 µm, 6, 10 and 20 thick for each type of wafer. The collecting electrodes are columns etched through the silicon instead of being surface implants like in the standard planar diodes, which allows a much lower capacitance and thus a lower electronic noise compared to a planar sensor of the same thickness. The sensors are designed at IMB-CNM (CSIC) and fully fabricated at the Institute's clean room facilities. Figure 3 shows the microdosimeter layout where the p-and-n electrodes and the metal strips that connect them with the contacts are displayed: the p-electrodes have a 4 µm diameter and it is surrounded by holes-n annulus of 3 µm thick with 2, 5, 10 and 20 µm depth (for each type of wafer) distributed in a square geometry. In the same wafer are distribuited microdosimeters with 25, 50, 100 and 200 µm pitches, P (distance between p-columns) and with 9, 10, 15, 20 and 25 µm of internal diameter (D), in order to include a greater number of cell distribution and sizes. The p–type electrode is patterned in a square geometry and an ionic implantation with boron (p+) is performed. The annulus is etched using the deep reactive ion etching (DRIE) technique, then it is partially filled with polysilicon doped with phosphorus (n+) to form the p–n junction. The top of the holes are metalized with aluminum and each electrode is connected with a thin aluminum layer to provide the electrical contact.

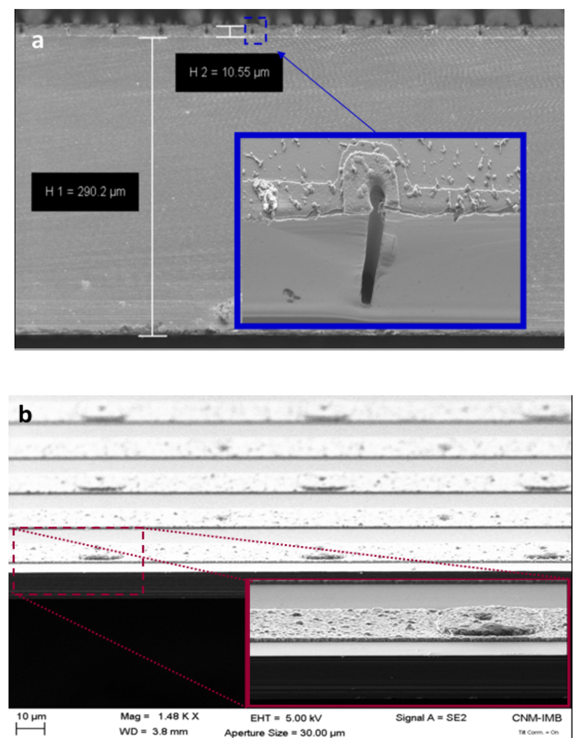

Figure 1: (a) SEM image of a the cross–section of 290 µm-thick support wafer and the 10 µm–thick high resistivity n–type active silicon with the columnar electrodes distributed along the top surface. The amplified image is a columnar electrode of 10 µm thick. (b) View of the front–face with the metal strips that connect the columnar electrodes of the same type.

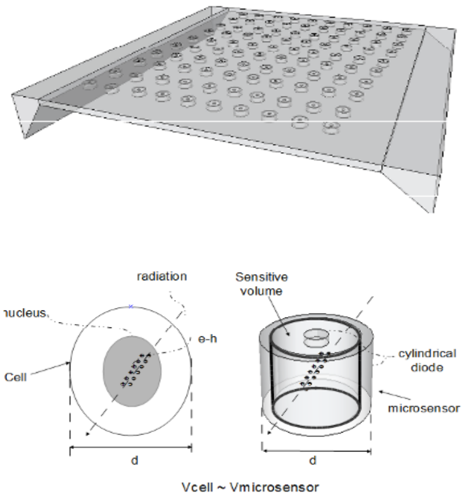

Figure 2. (a) Scheme of a microdosimeter, with an array of 10x10 microsensors, manufactured in a SOI wafer whose support piece is etched. (b) Sketch of a simplified cell and unit-cell (microsensor) of the microdosimeter with a volume equal to the average size of the cellular tissue to be irradiated.

Each microdosimeter consists of 121 independent microsensors. Figure 4 shows two SEM images of a processed wafer which contains some microsensors. Microdosimeters are connected to an appropriate readout electronics system to carry out the experimental tests.

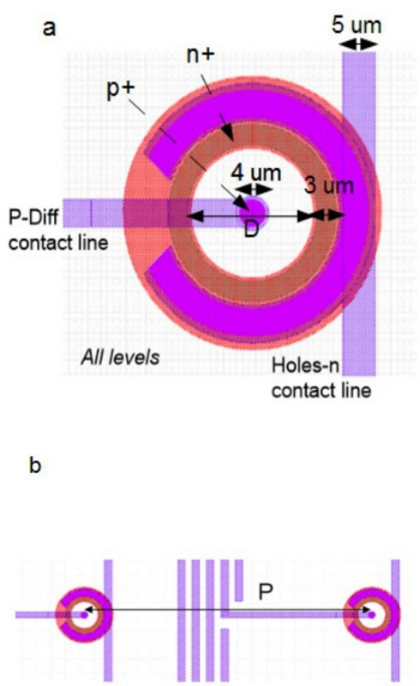

Figure 3. (a) Sketch of the one microsensor layout (not to scale). The n-type and p-type holes are connected with metal lines. (b) sketch of two microsensors at a distance P.

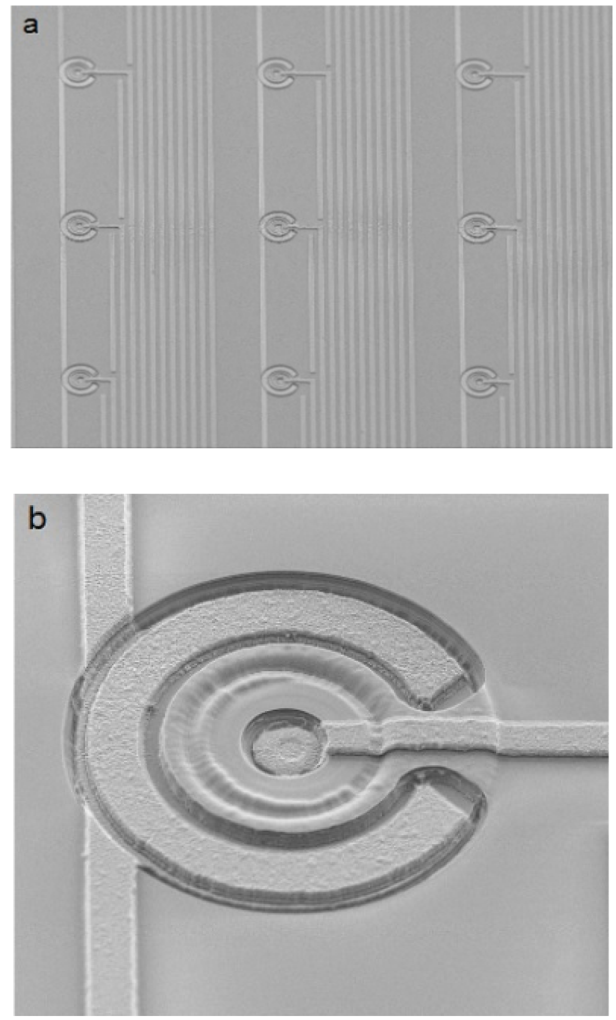

Figure 4. (a) SEM image of the top-view of a microdosimeter with 9 µm diameter, 100 µm pitch and 2 µm thick. (b) SEM image of the top-view of one manufactured microsensor equal to that designed in the Fig.4a.

3 CONCLUSIONS

Innovative microdosimeters based on 3D-cylindrical structures with 2 µm, 5, 10 and 20 thick, and 9, 10, 15, 20 and 25 µm of internal diameter (and 25, 50, 100 and 200 µm pitches), have been successfully fabricated. These first generation of microdosimeters based on an optimized 3D-cylidrical structure to create microsensors show the feasibility for down to the level of the average cell size, and thus providing a closest measurement of silicon ΔE.

Future studies will be soon carried out at the Perelman Center for Advanced Medicine (University of

Pennsylvania), which provides proton beam for clinical research proposals. The use of these 3D microdosimeters could enhance the accuracy of RBE calculations normally affected by the inherent uncertainty of Monte Carlo simulations due to the approximation of material composition and energy dependent physical laws involved in such calculations. The effect of such approximations will be quatified by comparison with absolute measurement of radiation quality parameters.

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