First Silicon Microdosimetry Based on Cylindrical Diodes

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Abstract: Silicon detectors are used in many medical applications for particle tracking, X-ray medical imaging, gamma or X-ray spectrometry, among others. The development of new silicon detectors for specific physics areas leads to overcome technological challenges that means not only optimize the design, but also improve the micro-fabrication processes. A new design of a solid-state-detector based on silicon microfabrication is described 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 background radiations present in nuclear medicine, aerospace exploration, nuclear facilities, particle accelerator and aviation.

Keywords: Microdosimetry, Radiation silicon detectors, Hadrontherapy.

1. Introduction

Microdosimetry deals with the study of the distribution of energy deposition in microscopic volumes, and establishes relationship between these depositions and their physico-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, such as cellular or subcellular structures. These instruments are called ‘microdosimeters’ and special considerations have to be taken into account when designing them. For example, firstly, the microsensor should have a cross-section size in the range of the nucleus of mammalian cells (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 radiation therapy. Radiotherapy (RT) is a type of cancer treatment where the tumors are irradiated with ionizing radiation while keeping the organs at risk (near the tumor) within a tolerable dose. 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 very radio-resistant tumors that may be treated more effectively using radiotherapeutic modalities based on the use of particles with 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 a higher radiobiological effectiveness (measured in terms of the relative biological effectiveness, RBE [3]) and provides more conformal dose distribution to the target allowing a greater preservation of the health tissue immediately surrounding 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) [4]. In radiotherapy, the treatment planning system (TPS) is used to determine the dose distribution to be applied to a tumor volume. In the case of hadrontherapy, the TPS is hampered due to the strong influence of the structure of the trace on the therapeutic effectiveness. Treatment with non-optimized biological dose (= dose x RBE) 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. [5] 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 [7], high-energy physics [8], or neutron detection [9] among others. Most of them are based on three-dimensional diodes (3D columnar structures with PN junctions) on SOI silicon wafers fabricated with optimized micromachining techniques. These detectors [7, 9] 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 has developed a new type of three-dimensional diode with cylindrical etchings that match the sensitive volume (SV) 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.

$$\bar{I} = 4 \frac{V}{S},$$  \hspace{1cm} (1)

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

$$y = \frac{ε}{\bar{I}},$$ \hspace{1cm} (2)

which is the microdosimetric magnitude 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.

![Fig. 1. (a) SEM image of a 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.](image)

2. Microdosimeter Fabrication and Result

We have proposed and manufactured a novel microdosimeter as the base detector for this microdosimetric application [9, 10].
These devices are fabricated on three types of SOI wafers with a high resistivity n-type substrate and with active volumes of 6, 10 and 20 μm, 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-CNMC (CSIC) and fully fabricated at the Institute’s clean room facilities. Fig. 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 6, 10 and 20 μm depth (for each type of wafer) distributed in a square geometry. A wafer contains microdosimeters with 25, 50, 100 and 200 μm pitches (P, distance between p-columns) and with internal diameter (D) 9, 10, 15, 20 and 25 μm, in order to include a greater number of cell distribution and sizes. The p-type electrode is circular and an ionic implantation with boron (p+) is performed. A cylindrical 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 is metalized with aluminum and each electrode is connected with an aluminum line to provide the electrical contact.

Each microdosimeter consists of 121 independent microsensors arranged in a square matrix.

Three main types of detector structures were performed: pad (pixel-array detector), strip and pixel detectors. The simplest configuration is the pad-detector in which all n+ electrodes are connected to the n+ contact on one side of the sensor while all p+ electrodes were connected to p+ contact on the opposing side, thus collecting the whole charge in all the unit-cells or sensitive volumes. In the strip configuration, consecutive p-type electrodes are lined up, resulting in a strip of connected microsensors in a row. In the pixel configuration, although is customarily bump-bonded to the readout electronic chip in flip-chip fashion, in this design each microsensor is routed through a metal line to a connecting pad for microstrip readout electronics to make readout easier. Etching the support silicon of the SOI wafer from the back side with patterning on this side is expected to make microsensors thinner for the three configurations aforementioned. Fig. 4 shows two SEM images of a processed wafer which contains some pixel microsensors. Microdosimeters are connected to an appropriate readout electronics system to carry out the experimental tests. Results of the electrical characterization of the first pad-type prototypes are shown in Section 3.
3. Electrical Characterization

An initial functional testing was performed on wafer. The current versus reverse voltage characteristics of the diodes fabricated were obtained with a semiautomatic probe station and a HP4155 Semiconductor Parameter Analyzer. Fig. 5 shows the results for some pad-type microsensors. These pad-type microdosimeters have one readout channel, a total area of 2000 x 2625 μm² and its microsensors are distributed in a square grid of 11 x 11 pixels. The I-V curves show typical diode behaviour. The devices are fully functional as they can be biased up to reverse voltages higher than full depletion (<1V) and the leakage currents are low.

4. Conclusions

Innovative microdosimeters based on 3D-cylindrical structures with 6, 10 and 20 μm thick, and varying dimensions and pitches, i.e. 9, 10, 15, 20, 25 μm of internal diameter and 25, 50, 100 and 200 μm pitches, have been successfully fabricated.

This first generation of pad-type microdosimeters based on an optimized 3D-cylindrical 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 assessed by comparison with absolute measurement of radiation quality parameters.

Fig. 4. (a) SEM image of the top-view of a microdosimeter with 9 μm diameter, 100 μm pitch and 6 μm thick. (b) SEM image of the top-view of one manufactured microsensor equal to that designed in the Fig. 4 a.

Fig. 5. Current-voltage characteristics of some pad-type microdosimeters in one of the fabricated wafers.

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References


