Cylindrical silicon-on-insulator microdosimeter: charge collection characteristics

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Introduction

At present there exists a need, in both medical physics and radiation protection, for a portable microdosimeter that can be used in determining the radiobiological effectiveness (RBE) of different mixed radiation fields. The microdosimetric approach to this determination is based upon obtaining the spectrum of lineal energy events, $f(y)$, in a micron sized site produced by secondary charged particles generated during the exposure of tissue to ionizing radiation. With knowledge of $f(y)$ the RBE is calculated using $\int Q(y)y^2f(y)d\log y$, where $Q(y)$ is a quality factor obtained from radiobiological experiments [1,2]. Experimental measurements of $f(y)$ require a radiation detection instrument with a sensitive volume equivalent in size to a biological cell. Traditionally gas proportional counters have been used; however these have a number of well documented failings [2].

Recent efforts to produce a solid state microdosimeter include a semiconductor-on-insulator (SOI) based device developed at the Centre for Medical Radiation Physics at the University of Wollongong, Australia [3]. This device consisted of a 2D diode array of elongated parallelepiped shaped micron sized volumes. The device was tested for applications in radiation therapy [4-6] and in radiation protection [7]. Due to the sensitive volume geometry the device was found to have a poorly defined average chord length for isotropic radiation fields. Additionally the response of the device as a microdosimeter suffered due to the unwanted diffusion of charge from outside the defined sensitive volume [8]. Other attempts to realize a solid state microdosimeter also suffer from the limitations of the elongated parallelepiped design [9].

We present a solid state microdosimeter with a cylindrical sensitive volume fabricated as a physically and electrically isolated structure. This design allows for a reduced variance in the average chord length of the sensitive volume, with charged particles incident at varying angles to the sensitive volume, as well as a decrease in the amount of lateral charge diffusion.

In this study the electrical characteristics of the device are presented along with the results of an ion beam induced charge collection (IBICC) study.

Materials and Methods

The Device

Schematics of the detector structure are shown below in figure 1. Fabrication of the device employed planar processing techniques on a p^{-} silicon on insulator (SOI) wafer. Phosphorus and boron were diffused into the silicon wafer to produce p-n diode structures possessing coaxial geometry. The P diffusion formed an axial n^{-} region separated from the B diffused coaxial p^{+} region by an intrinsic p^{-} sensitive volume of width, w. The silicon external to the p^{+} region of each diode was removed through an etching process to create a mesa structure 2 μm in thickness (t). In production two versions of the test structure were fabricated with sensitive region widths of 2μm and 10μm respectively. Each substrate contained 10 individual diodes.

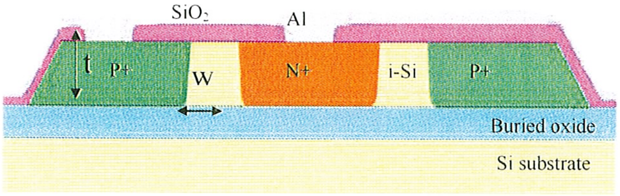

Fig. 1. A cross sectional schematic of the microdosimeter. The size of the sensitive volume is equivalent to the size of a cell nucleus. Note the cylindrical nature of the design.

Experimental Setup

The electrical properties of the diodes were determined using conventional IV and CV testing with a Keithley 6517A electrometer and a Boonton 7200 capacitance bridge. All measurements were performed under vacuum at room temperature to allow for reproducible conditions.

The charge collection characteristics of the device were experimentally measured using the Australian Nuclear Science and Technology Organisation (ANSTO) heavy ion microprobe. The microprobe was used to produce a 3 MeV beam of He^{2+} ions focused to a diameter of approximately 1.0 μm. The amount of energy deposited within the microdosimeter during each ion traversal, E, was measured with a standard charge sensitive preamplifier and shaper. The signal was fed directly into an ADC channel of the data acquisition system in coincidence with signals indicating the beam position, x and y. Data triplets (x,y,E) were saved for each event in a list mode file. Using this data IBICC imaging maps were generated to display the median charge collected, and the number of collected events within a desired energy range, as a function of beam position. The aim of using these maps was to observe the geometrical boundary of charge collection within each device, draw conclusions about the uniformity of the device thickness, and identify any other features that may produce artefacts within the subsequent microdosimetric spectra.

Results and Discussion

IV and CV

The typical reverse current for diodes on both the 2μm and 10μm device were not greater than 3.0pA at an applied reverse voltage of 9V. The capacitance per unit area was found to be $\approx 0.5\ \mathrm{pF \cdot um^{-2}}$ under the same conditions, a high value due to the 2 μm depletion width.

IBICC Results: 2 μm Device

An energy spectrum of the 2 μm wide microdosimeter device in response to the 3 MeV He^{2+} ions is shown in figure 2. A peak can be seen at an energy of approximately 500 keV. The expected energy loss of a 3 MeV He^{2+} ion in 2 μm of silicon is 400 keV (196 keV/μm). The origin of events at energies below the peak can be understood in terms of the spatial location of the ion strike as discussed below.

Figure 3 shows a median energy map of the charge collected during a scan of the 2 μm device. The location of events with high median energy collection are shown in red forming an annulus. These events correspond to the charge collection under the drift of the applied electric field. The uniform nature of the energy implies a uniform thickness of the microdosimeter throughout this region. The small central region of low median energy events shown as blue corresponds to the presence of the axial n^+ region of the device.

At the outer perimeters of the diode another region of low median energy events can be seen. These low energy events correspond to ion strikes incident upon the coaxial

p^+ region external to the intrinsic silicon. These events are thought to result from the diffusion of charge from the p^+ region into the radial electric field region of the diode. No events were observed from outside of the diode mesa structure external to the intrinsic silicon. These events are thought to result from the diffusion of charge from the p^+ region into the radial electric field region of the diode. No events were observed from outside of the diode mesa structure.

Conclusion

A new design for a solid state based microdosimeter with micron sized sites typical in size to a cell nucleus was presented. Charge collection mapping of the individual diodes demonstrated a well defined region of complete charge collection corresponding to a true micron sized sensitive volume. The mesa structure design was successful in eliminating unwanted diffusion of charge from outside of the sensitive volume.

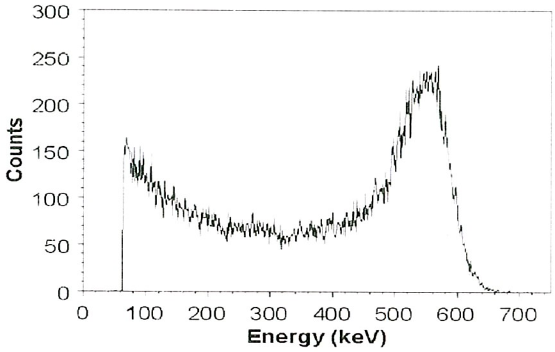

Fig. 2. Energy spectrum of the 2 μm microdosimeter device in response to 3 MeV He^{2+} ions.

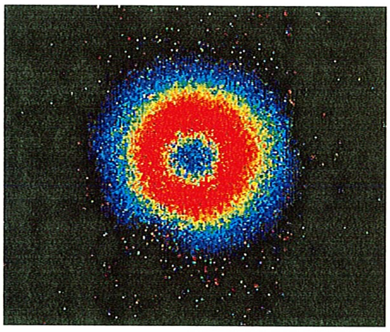

Fig. 3. The median energy map of the charge collected (calibrated in terms of energy) during a scan of the 2 μm device.

In the full paper additional results of IBICC testing with 3 MeV and 5.5 MeV He^{2+} ion beams will be presented for both the 2 μm and 10 μm wide diodes along with IBICC results for proton and carbon ion beams. Device simulations using GEANT4 will also complement the presented experimental results.

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