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Ion beam induced charge collection time imaging of a silicon microdosimeter

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Abstract

The timing properties of a silicon-on-insulator microdosimeter for medical and space applications have been studied using an ion microprobe. These measurements were used with a pulse shape discrimination technique to render the microdosimeter insensitive to ion strikes outside the ideal sensitive volume.
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1. Introduction

Microdosimetry is used to study the radiobiological properties of densely ionizing radiations encountered in hadron therapy and space environments [1]. A spectrum of energy deposition events in a microscopic volume is measured and used in conjunction with a radiobiological model to estimate the probability of cell survival. The creation of a solid state microdosimeter to replace the conventional tissue equivalent proportional counter is the topic of ongoing research. The Centre for Medical Radiation Physics has been investigating a technique using microscopic arrays of reverse biased pn junctions [2].

The microdosimeter is manufactured on a bonded, silicon-on-insulator (SOI), p-type wafer of thickness 2, 5, or 10 μm. n^+ and p^+ doped regions are fabricated by arsenic and boron implantations (see Fig. 1) at 30 keV at a fluence of 5×10^{15} cm^{-2}. The impurity concentration of the p-type silicon is 1.5×10^{15} cm^{-3}. All 120×40 diodes in the array are connected in parallel and each pn junction has an area of 10×10 μm^2. A detailed description of the device and readout electronics is given in [2].

It is necessary for the microdosimeter to possess a well defined charge collection (sensitive) volume, ideally the depletion region of the pn junction. This minimises recombination losses and provides a simple gaussian response to a monoenergetic beam. This volume should be as close to cubic as possible in order to minimize the angular dependence of the device. Previous studies

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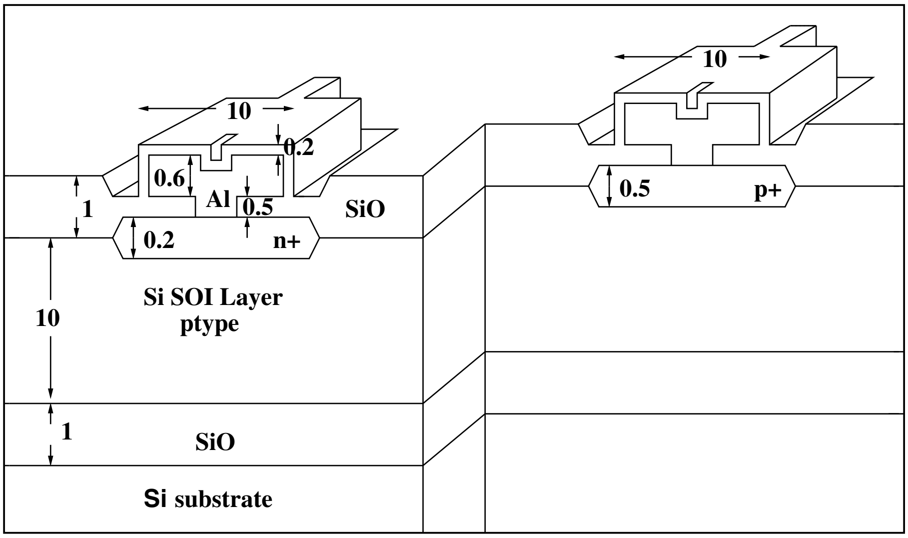

Fig. 1. Cross section of a single 10 μm diode in the silicon on insulator array. All dimensions are in microns.

were conducted using ion beam induced charge collection imaging (IBICC) with ion microprobes to measure the charge collection properties of the SOI microdosimeter [3]. These studies showed that significant charge collection occurred for ion strikes outside the junction (the ideal sensitive volume) due to the diffusion of charge carriers. Theoretical calculations of charge collection times following 5 MeV alpha strikes at various positions on the microdosimeter were made by Bradley [6]. Results showed charge collection times increased with the distance of the ion strike from the n^+ region, a result of the competing drift and diffusion mechanisms of charge collection.

The aim of this study is to investigate the charge collection time characteristics of the microdosimeter using an ion microprobe, then use this information with a pulse shape discrimination technique to ignore energy deposition events from ion strikes outside the ideal sensitive volume.

2. Heavy ion microprobe and IBIC setup

Experiments were performed with the IBICC setup at the heavy ion micro-probe at the Australian Nuclear Science and Technology Organisation (ANSTO), Lucas Heights, Australia. A detailed description of the microprobe facility is given by Siegele et al. [7].

The IBICC setup consists of a charge sensitive preamplifier (Amptek A250), mounted on a printed circuit board attached to the target holder. A 10 pin electrical feed-through conveys the preamplifier power supply, device bias, and energy deposition signal to and from the target chamber. Calibration of the system was done by connecting a fully depleted ion implanted diode to the IBICC setup and measuring the charge collection signal amplitude for a 3 MeV proton beam.

For these experiments a 20 MeV C^{+3} beam was focussed to a diameter of 1 μm using the quadrupole triplet and scanned over an area of 100×100 μm^2 with magnetic scanning coils. The 10 μm SOI device was reverse biased to 10 V and placed in the scan area, incorporating approximately nine diodes.

3. Timing measurements

3.1. Experimental method

The rise time of the charge sensitive preamplifier signal is known to be related to the collection time of electron hole pairs in silicon detectors [4]. We measure this rise-time with a technique based on that used by Pausch et al. [5]. As shown in Fig. 2 (circuit A) the preamplifier signal is passed through timing filter amplifiers to produce a bipolar signal. The zero-crossing time (referred to herein as T_{zc}) of the resulting bipolar signal is a monotonic increasing function of the rise-time of the preamplifier signal [5]. The bipolar signal is split and fed into two constant fraction discriminators (CFDs). One of these is configured to trigger a logic pulse as the leading edge of the bipolar signal rises above the background noise. The second CFD is configured to produce a logic pulse when the bipolar signal crosses zero (see Fig. 2). The CFD outputs are used as start and stop signals for a time-to-amplitude converter. This produces a signal of amplitude proportional to T_{zc} which is fed into channel 1 (see Fig. 2) of the microprobe data acquisition system along with the beam coordinates. During the measurement a list of data triplet (T_{zc}, x, y) events are accrued for analysis.

4. Results and discussion

Fig. 3 shows the spectrum of T_{zc} events is composed of two peaks. Fig. 4 shows the number of events registered at each pixel of the scan within a window of the T_{zc} spectrum shown in Fig. 3, $N(T + \Delta T_{zc}, x, y)$. The results clearly show the zero-crossing time T_{zc} and hence preamplifier signal rise-time increases as the distance of the ion strike from the n^+ region increases. This in turn is a direct result of the corresponding increase in charge

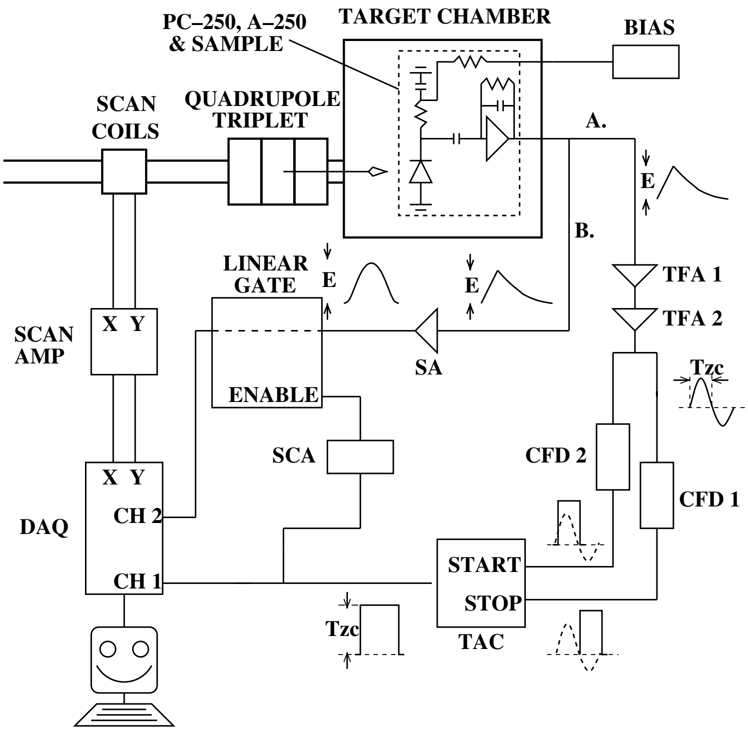

Fig. 2. Illustration of microprobe components, IBICC setup and circuit diagrams. Circuit A is used for timing measurements; TFA: Timing filter amplifier, CFD: constant fraction discriminator, TAC: Time-to-amplitude converter, DAQ: Data Acquisition System. Circuit B is used for pulse shape discrimination measurements and is not connected during timing measurements; SCA: single channel analyzer, SA: Spectroscopy amplifier. Voltage signals at various stages of the circuits are illustrated.

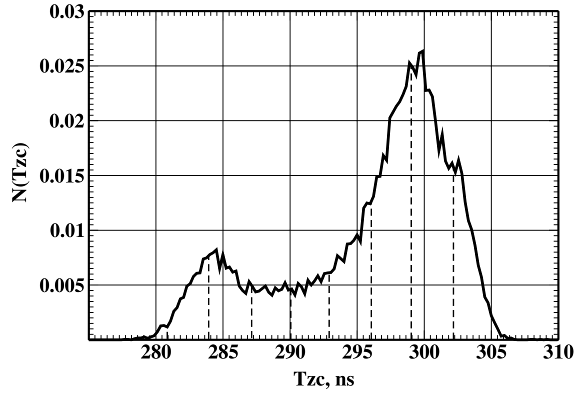

Fig. 3. Total zero-crossing time spectrum obtained with 20 MeV carbon-12 ions incident on the 10 μm SOI device.

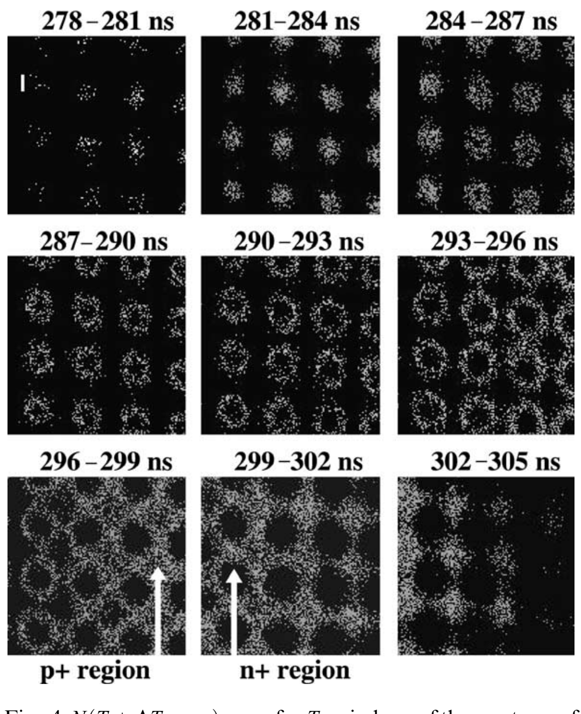

Fig. 4. $N(T + \Delta T_{zc}, x, y)$ maps for T_{zc} windows of the spectrum of Fig. 3. The white bar in the first map indicates a distance of 10 μm.

collection time, consistent with the theoretical results of [6]. These results indicate ion strikes are confined to the geometrical boundaries of the 10×10 μm n^+ region for zero-crossing times, $T_{zc} \leqslant 284$ ns.

5. Pulse shape discrimination

5.1. Experimental method

To preclude non-junction strikes, a window incorporating zero-crossing times, 0 ns $< T_{zc} \leqslant$ 284 ns was set on the single channel analyzer of the time to amplitude converter (see Fig. 2). The single channel analyzer provides a logic pulse which is used as the "enable" signal of a linear gate, through which the output of the spectroscopy amplifier is passed. The function of the spectroscopy amplifier is to shape the energy signal from the charge sensitive preamplifier to provide a pulse suitable for the multi channel analyser of the data acquisition system. This signal is fed into channel 2 of the data acquisition system along with the beam coordinates. Using this circuit, only energy deposition events corresponding to $T_{zc} < 284$ ns would pass through the linear gate and be registered by the data acquisition system. Beam conditions were identical to those for the previous experiment.

5.2. Results and discussion

Fig. 5 shows the energy deposition event spectrum before and after the pulse shape discrimination technique is implemented. The low energy component of the spectrum is drastically reduced and the energy deposition spectrum is close to

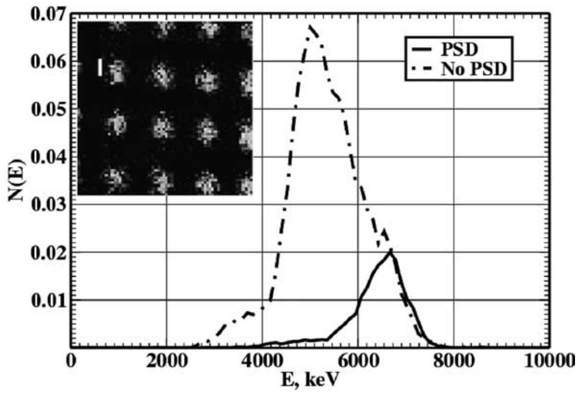

Fig. 5. Energy deposition event spectra obtained with (solid line) and with-out (broken line) pulse shape discrimination (PSD). Inset: Map of events for energy deposition events with PSD (i.e. $N(x, y)$).

gaussian. The inset in Fig. 5 confirms the position of all ion strikes to be within the geometrical boundaries of the n^+ region.

6. Conclusions

The timing properties of a SOI microdosimeter for medical and space applications have been studied using an ion microprobe. The zero-crossing time parameter, related to charge collection time, increased as a function of the distance of ion strike from the pn junction. These timing properties were used to implement a pulse shape discrimination technique to render the microdosimeter insensitive to ion strikes outside the ideal sensitive volume.

In addition to the charge transit time, the charge collection time is also influence by the plasma decay time which is believed to be dependent upon ion LET. Further studies with the ANSTO microprobe are planned to investigate the influence of ion LET on the timing properties of the microdosimeter over the LET range relevant to hadron therapy (1–1000 keV/μm).

Acknowledgements

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