Radiation hardness and charge collection in a SOI based diode array designed for medical microdosimetry.

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Abstract — **The radiation hardness of diode array devices based on silicon on insulator technology and bulk technology was investigated. The devices were exposed to 24 GeV/c protons (at CERN) up to a fluence of 4.1 10^{13} p/cm^2. Charge collection following irradiation indicated a significant reduction in minority carrier lifetime. The damage constant was calculated using alpha particle spectroscopy methods. These experiments demonstrate that such a device has sufficient radiation hardness to be used in medical radiation oncology applications as a microdosimeter.**

1. Introduction

McN ulty and Roth [1] proposed the use of arrays of silicon reverse-biased p-n junctions for characterizing complex radiation environments inside spacecraft and aircraft. The detector is connected to a spectroscopic system in which charge collection induced by radiation interactions is recorded by a multi-channel analyzer. Such a system has applications in medical microdosimetry as well as soft error upset (SEU) studies.

In this paper, we present a study of the charge collection behavior of a SOI diode array test structure. Although the device was originally designed for the study of SEU [2], it is very well suited as a prototype medical microdosimeter. The SOI structure provides a well-defined sensitive depth and the diode structure is simple and regular.

The aim of this work is to accurately define the sensitive volume and determine the effects of lateral diffusion and funneling. A comparison of broad-beam alpha particle spectroscopy and microbeam proton and alpha studies is performed. Such a comparison highlights the dangers in interpretation of broad-beam spectroscopy data. In particular, lateral diffusion effects significantly complicate charge collection especially for small diode areas.

A radiation hardness study is performed to determine the devices suitability for medical applications. Radiation induced displacement damage results in a reduction in minority carrier lifetime. The calculation of minority carrier lifetime was performed using broadbeam spectroscopy methods.

2. Device Description

The silicon microdosimeter studied in this paper consists of a SOI diode array test structure fabricated by Fujitsu Research Laboratories Ltd. The test structures were fabricated on bonded SOI wafers with thickness 2, 5, and 10 µm. In addition, a bulk device (no SOI) was fabricated. Each device was prepared with two functioning arrays designated "large"(100×100µm, 30×5=150 diodes) and "small" (10×10µm, 120×40=4800 diodes) reflecting their respective junction. Note that all diodes in a given array are connected in parallel as shown in Figure 4. The N+ and P+ silicon layers with depths 0.2 and 0.5 µm were constructed by arsenic and boron implantation's at 30keV and 5×10^{15} cm^{-2}. The impurity concentration of the P-substrate silicon was 1.5×10^{15} cm^{-3}.

3. Charge Collection Studies

3.1. *Sensitive volume definition*

The sensitive volume of the device was determined by alpha spectroscopy performed at the University of Wollongong and ion-microbeam experiments performed at the Microanalytical Research Centre, University of Melbourne. The broadbeam measurement shown in Figure 2, using a 5.3MeV Po-210 alpha source, indicates a maximum peak at an energy lower than one would expect based on TRIM calculations that consider the overlayer thickness and SOI thickness. However, using spectroscopy peak-fitting software [3] the data may be resolved into two components. The area of each component is consistent with the conclusion that the lower energy peak corresponds to charge collection via lateral diffusion whilst the higher energy peak corresponds to drift charge collection in the full 2μm SOI region. Microbeam measurements, as given in Figure 1, confirm the hypothesis of significant lateral diffusion. Clearly, microbeam measurements provide the best tool for discriminating charge collection regions and great care must be made in the interpretation of broadbeam data.

Lateral diffusion has two main effects on the dimensions of the sensitive volume:

1. The sensitive volume width and length are increased beyond the junction dimensions
2. Outside of the depletion area, charge collection occurs via diffusion and is therefore less efficient then within the junction. Therefore, the effective charge collection depth, on average, is less then the SOI thickness.

Sensitive volume dimensions are required in order to calculate the mean chord length needed for microdosimetric spectra. In our case, the diode sensitive volumes may be approximated by a rectangular parallelepipeds of dimensions 1.7×30×30μm and 1.7×120×120μm for the small and large diode, respectively.

3.2. *Radiation hardness*

High-energy radiation produces defect complexes in semiconductor materials which reduce minority carrier lifetime, change majority carrier density and reduce mobility. In this study, we determine the damage constant describing the change in minority carrier lifetime. The reduction of minority carrier lifetime (τ) is given by the following equation:

$$\frac{1}{\tau} = \frac{1}{\tau_i} + k\phi_n$$

where k is the damage constant and θ_n is the neutron/proton fluence. Calculating the damage constant will enable us to determine the number of patient treatment cycles (for fast hadron therapy) that the device will withstand before the charge collection behavior significantly alters. Furthermore, this study will provide a useful comparison of the relative radiation hardness of SOI versus bulk technology.

In order to calculate the damage constant we measure the minority carrier lifetime via charge collection spectroscopy methods as proposed by Edmonds [4]. In our case a Po-210 (5.3 MeV) source was placed in a vacuum with incident alpha energy varied by using thin plastic films. The diffusion length (Ld) and depletion thickness (t_{dr}) are calculated for various alpha particle input energies (E_i) using a non-linear curve fitting routine (Levenberg- Marquardt method). This routine minimizes the least squares difference between the measured and calculated energy collected as given by:

$$E_{collected} = \int_0^{t_{dr}} \frac{dE}{dx}dx + \int_{t_{dr}}^{R(E_i)} \frac{dE}{dx} e^{-\frac{x-t_{dr}}{Ld}} dx \qquad (1)$$

where, $E_1 = E_i - \int_0^{t_{ol}} \frac{dE}{dx}dx$

Note that the depletion region incident energy (E_1) is calculated by correcting for the overlayer thickness (t_{ol}=1μm). Minority carrier lifetime then follows from:

$$\tau = \frac{L^2}{D_p} \qquad (2)$$

where D_p is the diffusivity of silicon (11.6 cm^2/s).

Equation (1) assumes that the depletion region boundary is a perfect charge sink consisting of a plane of infinite extent. This assumption is best satisfied by the 100×100 μm bulk device operating at 10V bias since the depletion region covers a relatively high proportion of chip area (80%). In addition, energy collected is estimated by extracting the peak in the alpha spectrum corresponding to ion traversal through the depletion region.

Both SOI and bulk devices were irradiated at CERN using 24 GeV/c protons at fluences of 1.2×10^{13} p/cm^2 and 4.1×10^{13} p/cm^2. Table 1 and figure 2 summarize the results with the final 1 MeV equivalent damage constant calculated as K=1.4×10^{-6}cm^2/n-sec. This result is in good agreement with damage constants estimated by Messenger (p218 [Messenger, 1992 #54]) assuming high injection ratios. The displacement cross-sections required to correct the damage constant to 1MeV neutron equivalent are 65.15 MeVmb for 24 GeV/c protons and 95 MeVmb for 1MeV neutrons [5]. Given that 1 cGy is approximately equivalent to $4.1\times10^8 n/cm^2$ (1MeV neutrons) [Measurements, 1992 #53] and there is 300cGy per patient treatment, then we may expect a 10% change in diffusion length after 8 treatments. This is a reasonable result given the low cost of each device.

Table 1. Effect of irradiation on diffusion length

Parameter	Drift (μm)	Ld (μm)
Before	3.9	14.3
After (4.1×10^{13} p/cm^2)	6.5	5.2

Trapping levels introduced by displacement damage may reduce the majority carrier density. Such a reduction will increase the depletion width as seen in Table 1 and verified by capacitance voltage measurements. Note that the drift component is higher than one might expect from estimates of the depletion width. The additional charge collection is due to funneling.

We are currently extending Edmonds' method to enable the calculation of diffusion length in the SOI devices. In addition, post irradiation alpha and proton microbeam measurements are currently being performed that will enable a comparison of broadbeam and microbeam methods. The microbeam has several important advantages including the use of a proton beam to minimize funneling, a mono-energetic source and localization of charge collection.

4. Conclusion

This paper indicates that future SOI microdosimeter designs should introduce methods to minimize lateral diffusion such as guard rings or other isolation boundaries. Such a device would provide an excellent test structure for experimental microdosimetry both in the realm of radiobiology and for SEU studies. In the later category, an important application is the verification of neutron burst generation rate models central to SEU prediction software. Applications in radiobiology include the study of dosimetry in space and avionics and radiation oncology modalities such as BNCT, heavy ion, fast neutron and proton therapy in which dosimetry has been traditionally quite difficult.

Unambiguous characterization of the sensitive volume and charge collection regimes requires the testing of such devices with a microbeam. Charge collection spectroscopy has been used to determine minority carrier lifetime in SOI and bulk devices. Furthermore, a comparison of microbeam and broadbeam spectroscopy methods for determining minority carrier lifetime and radiation damage constants is provided. Radiation damage studies have demonstrated the usefulness of this device over repeated clinical exposures.

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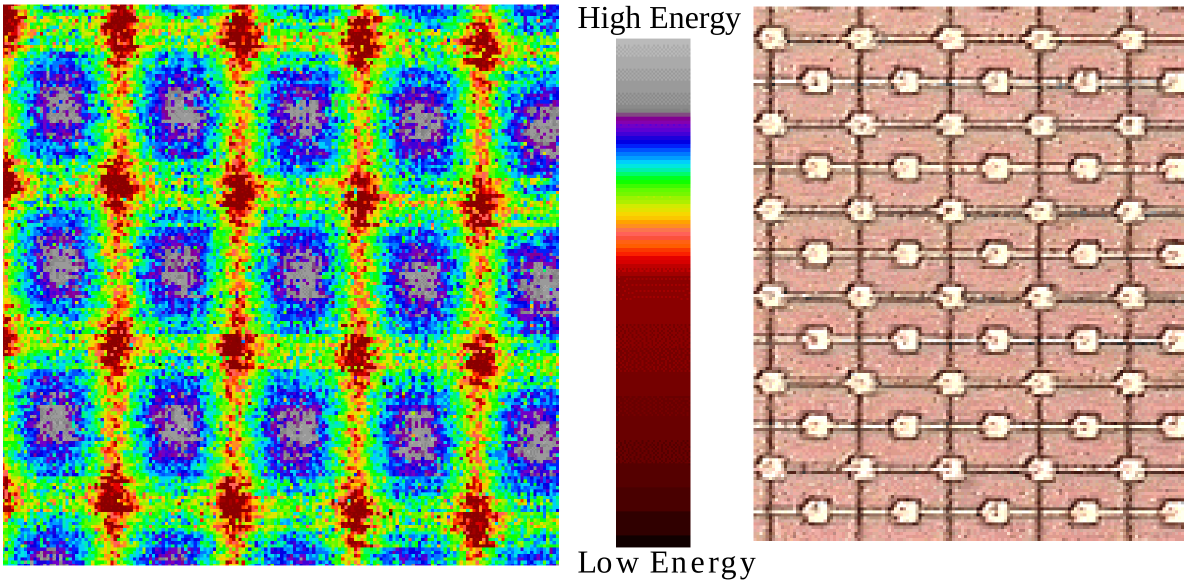

Figure 2: 2MeV Microbeam Measurement of 10x10x2um SOI diode array(Left) with optical image on the right for comparison

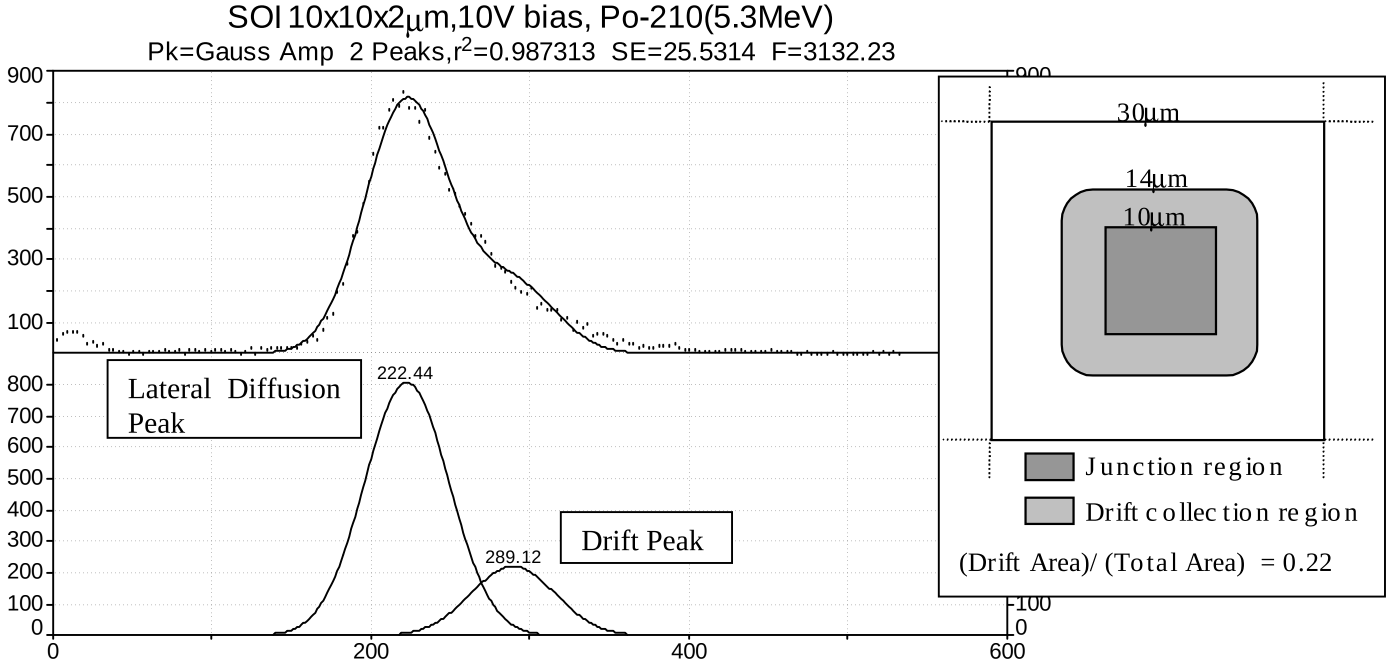

Figure 3: 5.3MeV (Po-210) Broadbeam Measurement of 10x10x2µm SOI diode array(showing the relative contributions of drift and lateral diffusion. Drift collection at 289 keV corresponds very closely to TRIM based calculations (291 keV) with an overlayer thickness of 1.3µm and 2µm sensitive depth.

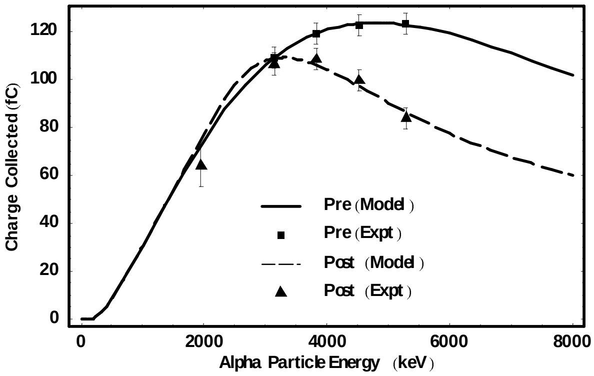

Figure 1: Experimental determination of diffusion length before and after irradiation with 4.1×10^{13} 24 GeV/c protons.