

Charge Collection and Radiation Hardness of a SOI Microdosimeter for Medical and Space Applications

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Abstract

The first results obtained using a SOI device for microdosimetry applications are presented. Microbeam and broadbeam spectroscopy methods are used for determining minority carrier lifetime and radiation damage constants. A spectroscopy model is presented which includes the majority of effects that impact spectral resolution. Charge collection statistics were found to substantially affect spectral resolution. Lateral diffusion effects significantly complicate charge collection.

I. INTRODUCTION

The fields of radiation protection, radiobiology, and radiation effects on electronics require microdosimetry methods for measuring the pattern of energy deposition in small cell-sized volumes. The traditional tool of experimental microdosimetry for medical applications is the proportional gas counter. This device has several shortcomings including a large size, gas system and high voltage requirements, measurement in gas phase and an inability to simulate an array of cells.

McNulty, et al. [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 detector removes several of the previously mentioned problems associated with proportional gas counters. Silicon diode array microdosimetry exploits the small size, rapid development, and current manufacturing capabilities of integrated circuit technology.

A silicon diode array has applications in medical microdosimetry as well as soft error upset (SEU) studies. Fortunately, the requirements of a device designed to study SEU phenomena coincide with the requirements of a biological microdosimeter. This is a manifestation of the close correlation between SEU phenomenon, biological cell death, and microdosimetry [2]. Both applications demand

1. An accurately defined sensitive volume (region of charge collection). Minimization of charge collection complexity in particular diffusion and funneling effects.
2. An array of identical diodes to improve collection statistics.

3. Diode structure sizes of the order of a few microns.

A key problem impeding the widespread application of silicon based microdosimetry is the poor definition of the sensitive volume. The effects of diffusion and funneling may be minimized by the use of SOI structures. 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 [3], 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 charge collection characteristics of this device. Three methods were used in this study; alpha and proton microbeam spectroscopy, broadbeam alpha spectroscopy and 2D and 3D device simulation. Experiments were performed on both a SOI device and a bulk structure with an identical layout. The results quantify the spatial response of the detector for various conditions including varying bias and radiation damage levels. The dangers in interpretation of broad-beam spectroscopy data are highlighted. In particular, lateral diffusion effects significantly complicate charge collection especially for small diode areas. The extent of lateral funneling effects is also determined. A software model is presented which accurately fits both broadbeam and microbeam data and determines the components which influence the resolution of spectroscopy methods.

A radiation hardness study is performed to determine the devices suitability for medical and space applications. Radiation induced displacement damage results in a reduction in minority carrier lifetime. The calculation of minority carrier lifetime was performed using microbeam spectroscopy methods. Finally, an example clinical application of the device is given using results obtained at a Boron Neutron Capture Therapy (BNCT) facility and a proton therapy facility.

II. 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 $\times$ 100 μm , 30 $\times$ 5=150 diodes) and "small"

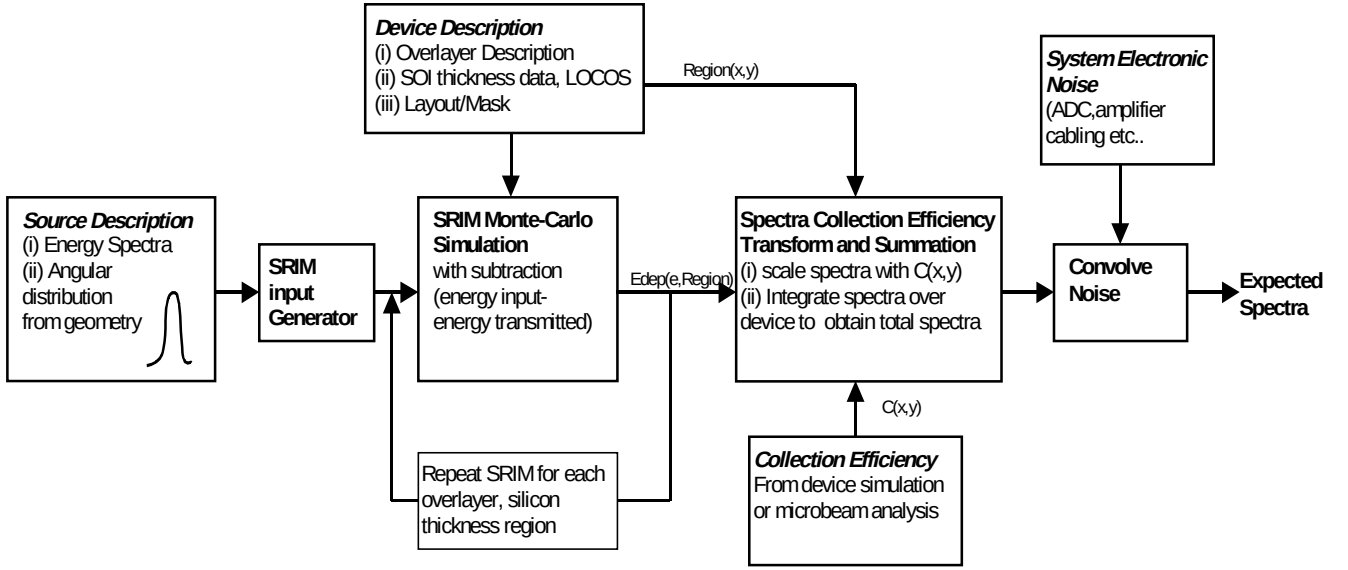


Figure 1: Flow diagram of spectroscopy modeling process.

(10×10μm, 120×40=4800 diodes) reflecting their respective junction. Note that all diodes in a given array are connected in parallel. The n+ and p+ silicon layers with depths 0.2 and 0.5 μm were constructed by arsenic and boron implantations at 30keV and 5×10¹⁵ cm⁻². The impurity concentration of the P type silicon was 1.5×10¹⁵ cm⁻³.

This work presents results for experiments on the 2μm SOI and bulk devices only. Several devices of both types were radiation damaged at CERN using 24 GeV/c protons with fluences of 4.1×10¹³ pcm⁻². The different parts are designated “unirradiated” and “irradiated” throughout the paper.

III. SPECTROSCOPY MODELING SOFTWARE

To characterize the performance of a microdosimeter it is important to accurately model the statistical processes of energy deposition and measurement that lead to the spread in spectrum obtained by spectroscopy measurements. A software model was developed which incorporates source energy distribution, source angular distribution, ion energy and range straggling, overlayer variation, sensitive depth variation, system electronic noise, and the variation of collection efficiency with ion strike position. Successful comparison between the model and spectroscopy measurements implies that the collection efficiency function is well defined. Conversely, the model may also be used to extract the collection efficiency function from spectroscopy data, which is particularly useful when only broadbeam data is available.

A flow diagram of the modeling process is shown in Figure 1. The source is described by its energy spectrum and angular distribution. The angular distribution is derived from source/device geometrical considerations. The Monte-Carlo ion transport program SRIM [4] can use as input a file specifying individual ion energy and direction. This file is

constructed by randomly sampling the energy and angular distributions of 10000 ions.

Inspection of the device fabrication masks for the small (10×10μm) diode array identifies 5 regions of differing overlayer construction and SOI thickness. Figures 2 and 3 show the cross-section associated with the various regions and the location of each region on the device. Figure 3 is a representation of the discrete function $Region(x,y)$ which assumes values from 1 to 5 corresponding to each region. Note that the SOI thickness is only 2μm in the n+ and p+ regions and around 1.8μm in other areas due to consumption of silicon in the local oxidation (LOCOS) process. SRIM is run for each region to produce the SOI energy deposition spectra, $Edep(E, region)$.

The spectrum for the energy collected by the device assuming a normally incident particle at a point (x,y) is given by

$$Ecol(E, x, y) = \frac{1}{C(x, y)} Edep\left(\frac{E}{C(x, y)}, Region(x, y)\right) \quad (1)$$

where $C(x,y)$ is the spatially dependent collection efficiency defined as the proportion of energy collected to energy deposited for a normally incident ion traversing through the point (x,y). Previously we mentioned that the SRIM input may consider the angular distribution of the incident ions. For simplicity, we apply equation 1 even for these ions. This approximation assumes a slowly varying collection efficiency and relatively small angular deviations. The collection efficiency may be estimated from microbeam experiments or device simulation.

The final energy spectrum excluding electronic noise is given by integrating equation (1) over the device area:

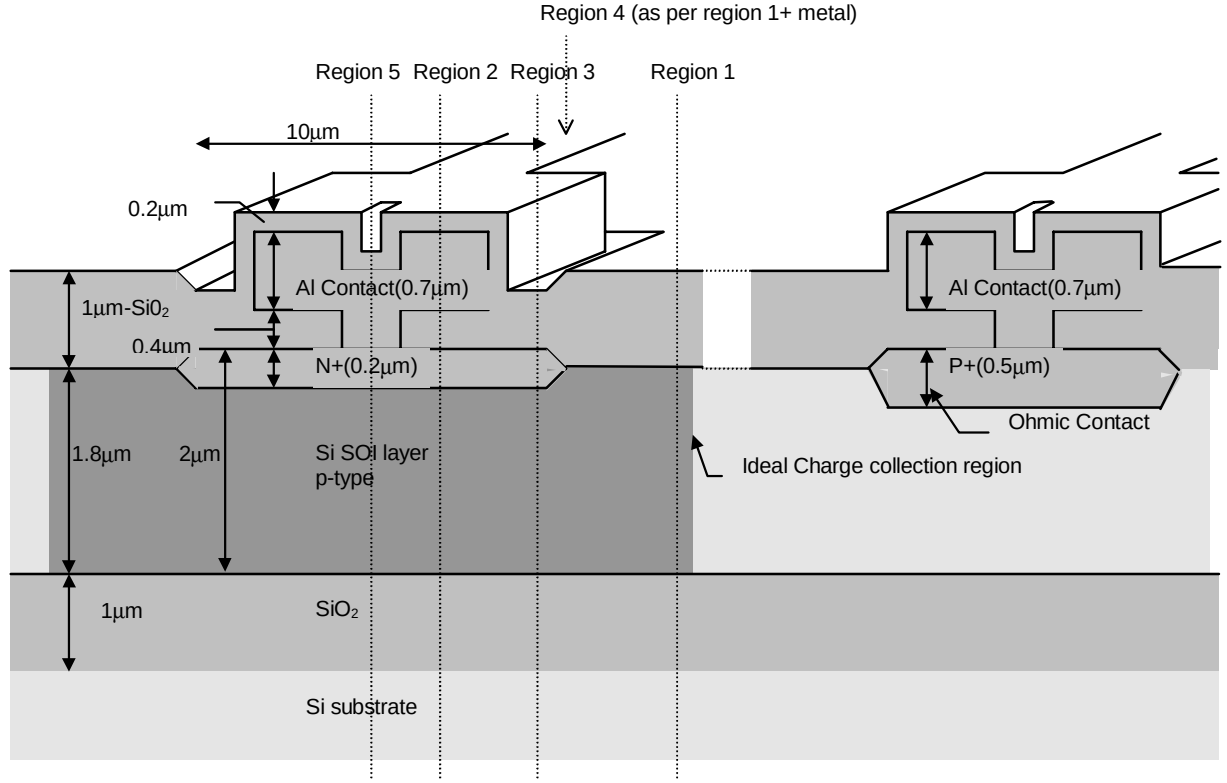


Figure 2: Detailed cross-section of diode array p+ and n+ contacts with approximate dimensions. Overlayer and SOI thickness dimensions are identified for each region shown in the plan figure below.

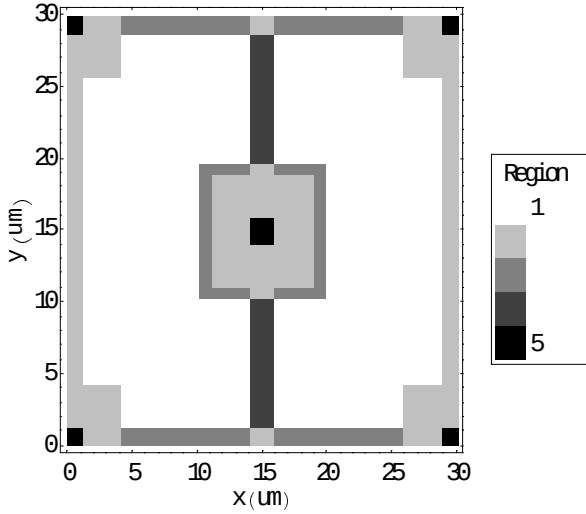


Figure 3: Layout showing location of regions whose overlayer and SOI construction is identified in Figure 2.

$$E_{total}(E) = \int_0^{y_{max}} \int_0^{x_{max}} E_{col}(E, x, y) dx dy \quad (2)$$

In practice equation (2) is calculated numerically with a spatial resolution of $0.3\mu m$ and y_{max} and $x_{max} = 15\mu m$. The final energy spectrum including electronic noise is given by convolving E_{total} with a Gaussian noise spectrum having a standard deviation σ_n .

$$E_{totaln}(E) = \int_{E-3\sigma_n}^{E+3\sigma_n} E_{total}(u) \frac{\exp(-(E-u)^2/2\sigma_n^2)}{\sqrt{2\pi}\sigma_n} du \quad (3)$$

Microbeam spectroscopy will produce an image which is defined by taking the median energy of equation (1) for each pixel. Both microbeam and broadbeam spectroscopy may produce a spectrum given by equation (3).

Note that the model presented thus far does not consider the statistics of the charge collection process which would increase the spread of the final spectrum. Ideally $C(x,y)$ should be defined as a distribution to incorporate charge collection variability. It also does not consider diode to diode variation and non-discrete transitions between the defined regions (e.g. LOCOS “birds-beak”). Later sections will further discuss the application and limitations of the model.

IV. NUMERICAL DEVICE SIMULATION

Two and three dimensional numerical device simulations have been performed on the $2\mu m$ SOI, $10 \times 10\mu m$ array using the DESSIS code [5]. The objective of the simulations was to determine the characteristics of the collection efficiency function, in particular the variation with bias and minority carrier lifetime.

A. Simulation Setup and Parameters

2D simulations have been predominantly used due to the lengthy computation time required for 3D simulations. For both simulation types the device simulated was constructed using a process simulator (LIGAMENT, PROSIT(3D) and TE2DIOS(2D) [5]) with manufacturer mask information and process specifications directly used. The 2D simulation considered a cross-section, referring to Figure 3, along the line (0,15) to (15,15) whilst the 3D simulation considered the area with minimum coordinates (0,0) and maximum (15,15). In both cases we exploit device symmetry to minimize the eventual simulation grid size.

The DESSIS code incorporates drift-diffusion, hydrodynamic and thermodynamic models. In our case we neglect self-heating effects and use the drift-diffusion model. This model solves the transient semiconductor equations comprising the Poisson equation and the current continuity equations. Current density is expressed by the conventional drift-diffusion constitutive relations.

The physics included in the simulation setup included doping dependent Shockley-Read-Hall (SRH) recombination, Auger recombination, and trap-assisted Auger recombination. Surface recombination at oxide interfaces above and below the SOI layer were included in the model. Surface recombination velocity was set to a typical value of 5000 cm²/s, from Schroder [6]. The field dependence model for recombination was not employed since the maximum electric field was less than 3×10⁵ V/cm. The intrinsic density model used was the Bennett-Wilson model with bandgap narrowing [7]. A doping and field dependent mobility model was used. Carrier-carrier scattering models were not included in the simulations to save simulation time. The ramifications of this exclusion are discussed in later sections.

The ion modeled was a 5.3MeV alpha particle corresponding to a Polonium-210 alpha spectroscopy source. We used a varying LET along the length of the path based on an accurate fit to SRIM calculations over the 2 μm SOI region. The radial distribution of charge generation used a Gaussian model with a standard deviation radius of 0.1μm. The ion strike was modeled as Gaussian in time with a characteristic decay time of 20 fs. These ion track parameters are consistent with previous simulations in the literature [8].

Of critical importance in numerical device simulation is the use of correct spatial and transient discretization. The grid resolution was refined in the depletion, doping, and alpha particle track regions. Typically, 1500 and 20000 points were used for 2D and 3D simulations, respectively. To confirm that sufficient resolution was achieved all simulations have been run without recombination to ensure charge conservation is observed. In all cases, the total charge collected is within 2% of charge deposited for 2D and 5% for 3D simulations.

B. Simulation Results

2D simulations were performed for alpha particle strikes every 0.75 μm from the p+ to the n+ regions. Two different minority carrier lifetimes and two sets of voltages were simulated. The longer lifetime corresponds to a lifetime calculated from proton microbeam measurements as discussed in section VII.A. The shorter lifetime is a coarse estimate for a radiation-damaged device. The substrate doping density for the undamaged device is 1.5×10¹⁵ cm⁻³ whilst the radiation damaged device has a lower doping density of 1×10¹⁵ cm⁻³.

The collection efficiency was calculated for each point with the results shown in Figure 4. Charge collection efficiency approaches 100% in the depletion region since drift collection is strong for an unirradiated device. As we move away from the depletion region a transition region occurs in which a combination of funneling and diffusion takes place. In this region, the charge carriers diffuse into the depletion region with a sufficient carrier density to cause depletion region collapse. The lateral funnel effect, confirmed by simulation voltage distribution plots, has been reported previously by Edmonds [9, 10]. Eventually we reach a point at which only diffusion occurs and the efficiency decays exponentially with a constant that is related to the effective recombination time, which depends on both surface and bulk recombination. The point at which funneling disappears is easily identified by observing the simulation current transients. This point always corresponds to the beginning of the exponential phase. For example, x=4.9 μm in Figure 9 for the 10V unirradiated device.

Following these results, the collection efficiency is modeled by a 3-parameter function. As shown in the equation below, three regions are defined: a constant region corresponding to the depletion region, an exponential region characterized by a parameter L, and a transition region between these two regions, which is defined by a quadratic.

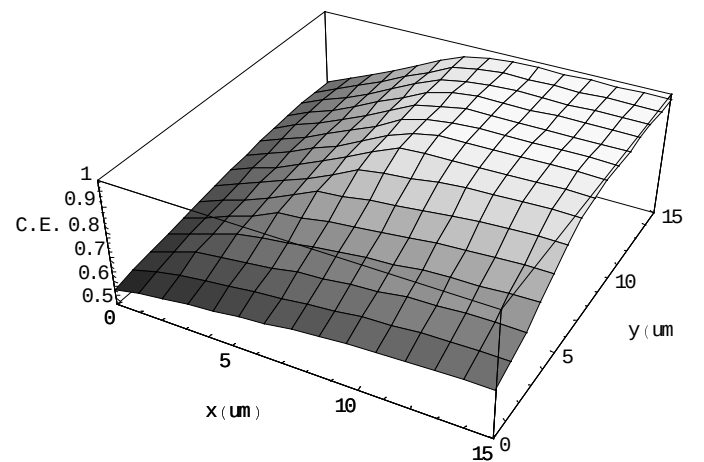


Figure 4: Collection efficiency function derived from 2MeV alpha microbeam measurements. One quarter of the diode is shown with coordinates corresponding to the layout of figure 3.

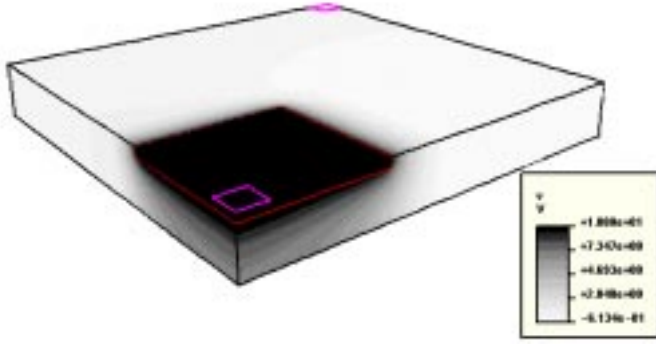


Figure 5: Voltage distribution for 2μm SOI device, 100ps after 5.3MeV strike at x=3.5,y=15μm. (1/4 of device is shown, dimensions 15×15×2μm, center of diode is nearest to viewpoint).

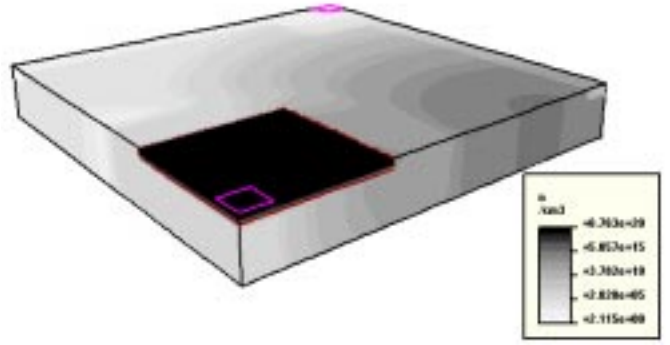


Figure 6: Electron density for 2μm SOI device, 100ps after 5.3MeV strike at x=3.5,y=15μm. (1/4 of device is shown, dimensions 15×15×2μm, center of diode is nearest to viewpoint).

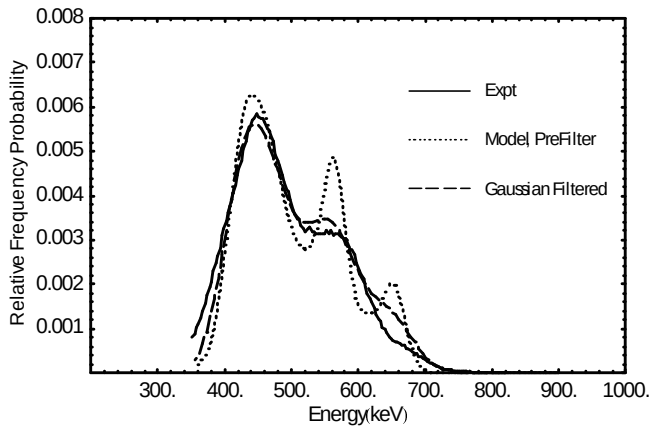


Figure 7: Comparison of 2MeV alpha microbeam spectrum with spectroscopy model. The model is shown without Gaussian filtering and following 20keV Gaussian filtering. The filtering is intended to imitate the statistics of charge collection.

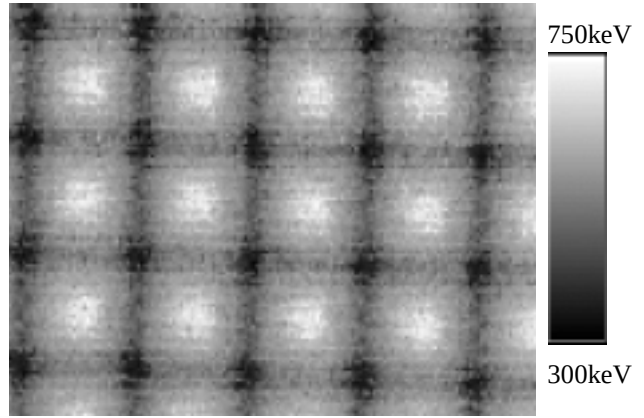


Figure 8: Microbeam image (2MeV alpha) of 10×10μm 2μm SOI array. Black corresponds to lowest charge collection amplitude and white is highest amplitude.

The parameters defining the boundaries of the transition region are (x_f, c_f) and (x_d, c_d) . The derivative of the transition function is zero at the depletion region boundary x_d .

$$C_{2D}(x) = \begin{cases} c_f e^{(x-x_f)/L} & 0 \leq x < x_f \\ a_2 x^2 + a_1 x + a_0 & x_f \leq x < x_d \\ c_d & x_d \leq x < 15 \end{cases} \quad (4)$$

where $a_2 = \frac{c_f - c_d}{(x_d - x_f)^2}$, $a_1 = -2x_d a_2$,
 $a_0 = \frac{c_f x_d^2 + c_d x_f^2 - 2x_d x_f c_d}{(x_d - x_f)^2}$

$$C_{3D}(x, y) = \begin{cases} C_{2D}(10) = c_d & 10 \leq x \leq 15 \\ & 10 \leq y \leq 15 \\ C_{2D}(10 - d1) & \text{else where} \end{cases} \quad (5)$$

$c_d > 10$

where d1= the distance from (x,y) to (x1,y1) with (x1,y1) defined as the intercept of a line drawn from (x,y) to the center of the n+ region (15,15). The 2D function is used to

approximate the 3D function by effectively rotating the 2D function around the center of the diode (15,15) whilst observing a constant value of c_d within the n+ region. Note that the parameter L is not the diffusion length (L_d) although it may be closely related. An example 3D collection efficiency function is shown in Figure 4.

It is important to point out that the 3D collection efficiency may decay faster than an exponential and that the function presented above is a first order approximation. In order to determine the extent of this geometrical error a 3D simulation was performed at the point (3.5,15) for the unirradiated device at 10V bias. At this point, the ratio of 3D to 2D collection efficiency was only 0.93 indicating that the above equation may be a reasonable first order approximation. The voltage distribution and electron density at 100 ps following this strike are shown in Figures 5 and 6. Note that the SOI is fully depleted at this bias level and funneling is not evident. Further 3D simulations are in progress in order to calculate an improved collection efficiency function.

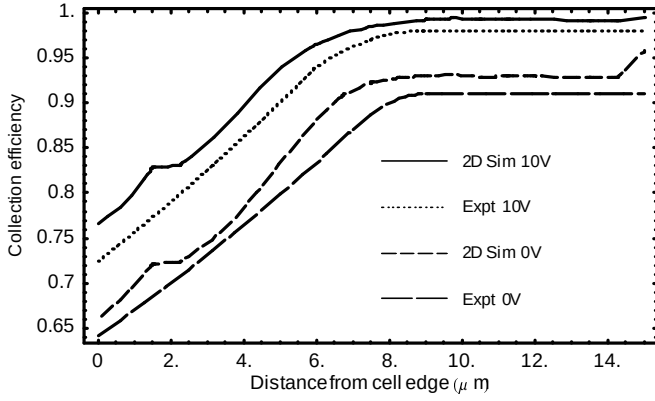


Figure 9: Unirradiated $2\mu\text{m}$ SOI device: collection efficiency function derived from 5.3MeV broadbeam alpha spectroscopy (figure 10) and a comparison with 2D simulation results.

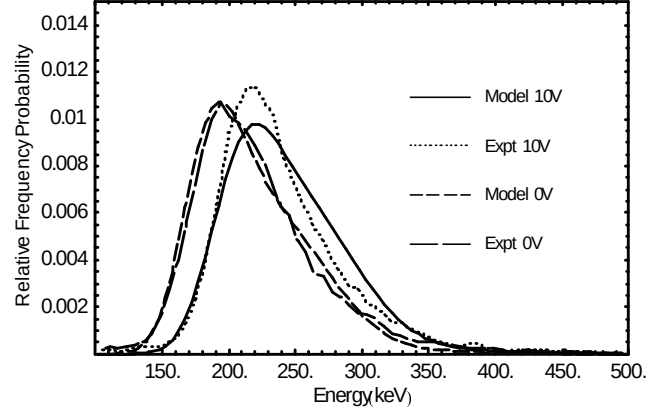


Figure 10: Unirradiated $2\mu\text{m}$ SOI device: 5.3MeV broadbeam alpha spectroscopy and a comparison with spectroscopy model.

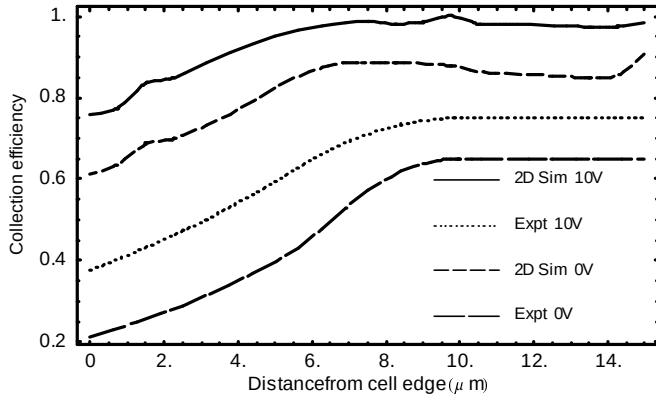


Figure 11: Irradiated $2\mu\text{m}$ SOI device: collection efficiency function derived from 5.3MeV broadbeam alpha spectroscopy (figure 12) and a comparison with 2D simulation results.

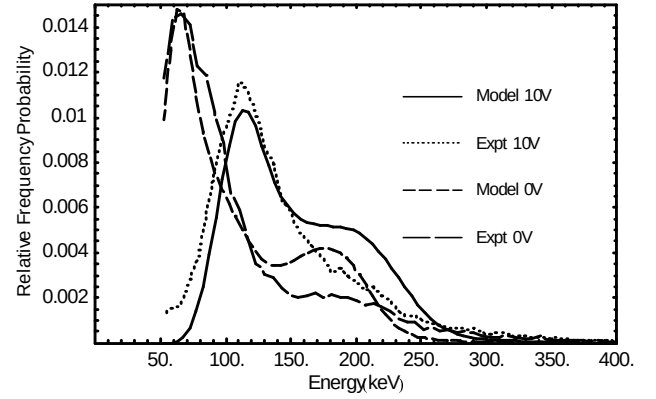


Figure 12: Irradiated $2\mu\text{m}$ SOI device: 5.3MeV broadbeam alpha spectroscopy and a comparison with spectroscopy model.

V. MICROBEAM SPECTROSCOPY

Microbeam spectroscopy (or Ion Beam Induced Charge (IBIC)) experiments were carried out using the NEC 5U Pelletron accelerator at the Microanalytical Research Centre, University of Melbourne, Australia. IBIC was performed on the unirradiated diodes with H, H_2 and He ion beams. The beam was initially focussed to a micron spot size on the target and was further reduced to submicron by reducing the diameter of both the object and collimator diaphragms. The adjustment and beam alignment process was carried out on a reflective region neighboring the diode array to avoid radiation damage to the device. The focussed beam was rastered across the array and the IBIC signals were individually amplified, digitized, and stored along with beam coordinate data.

In order to test the spectroscopy modeling software and determine the device collection efficiency function, we compare a 2MeV alpha microbeam spectrum with the spectroscopy model. The parameters for the collection efficiency function were calculated by iterative adjustment of the model to the measured data using 2D simulation results as a starting point. Figure 7 compares the experimental spectrum

with the model spectrum whilst Figure 4 shows the collection efficiency function used in the model.

The model predicts a spectrum with three peaks with the lowest energy peak originating by diffusion from region 1 and the highest from drift collection in region 2 which has a thicker SOI and overlayer. The middle peak results from drift dominated charge collection in both regions 1 and 3, close to and including the border of the depletion region. These peaks are smoothed out in the experimental spectrum due to effects that are not initially included in the model. In particular, the statistical process of charge collection creates a variation in collection efficiency for a given point. Inadequacies also exist in the modeling of the device between regions. For example, the “birds-beak” associated with the edge of the LOCOS region, which accounts for about 10% of device area, is not modeled. Finally, actual overlayer and device thickness may differ. In particular the SOI thickness across the wafer may vary from 1.8 to $2.5\mu\text{m}$. Note that the microbeam measurement has the advantage of minimizing any cell-to-cell variation in charge collection that may exist under broadbeam conditions.

To account for these effects the input charge deposition spectrum was Gaussian filtered with the filter standard

deviation progressively increased to obtain the best match between the model and experimental data. The charge collection statistics and device modeling inadequacies required a Gaussian standard deviation of 20keV with the resultant spectrum shown in Figure 7. The final spectrum was also filtered (Gaussian, $\sigma=5\text{keV}$ from pulser measurements) to simulate electronic noise. Clearly, such a result highlights the inadequacy of finite-element type device simulators versus Monte-Carlo device modeling methods [11]. However, Monte-Carlo methods are very computationally intensive and not as widely available. The remainder of the paper uses the Gaussian filter as calculated above.

A microbeam image for the 2MeV alpha is shown in Figure 8. This figure confirms the significant lateral diffusion of the SOI device.

VI. BROADBEAM SPECTROSCOPY

The aim of this section is to further test the spectroscopy modeling software and again determine the device collection efficiency function that provides the best comparison between experimental results and the model.

Alpha spectroscopy was performed using a Po-210 (5.3MeV) alpha source in a vacuum and a 7401 Canberra alpha spectroscopy amplifier connected to a PC-based multi-channel analyzer. The source was placed 5mm from the diode array. Since the diode array dimensions are $3.63 \times 1.21\text{mm}$, the alpha particle may strike at an angle of up to 20° assuming a point alpha source. This geometrical consideration is accounted for in the spectroscopy modeling as described earlier.

Both the damaged and undamaged devices were tested at two voltages 0 and 10V bias. Figures 10 and 12 compare the experimental spectra with the model spectra whilst Figures 9 and 11 show the collection efficiency functions used in the model spectra. The parameters for the collection efficiency function were calculated by iterative adjustment of the model to the measured data.

For the 10V unirradiated device the 3 collection efficiency parameters (see equation 3, and 4, $L=23\mu\text{m}$, transition points (6,0.94),(9,0.98)) are quite close to those determined for the 2MeV alpha microbeam ($L=20\mu\text{m}$, identical transition points). This is to be expected although some differences, such as a slight increase in lateral funneling, will occur due to the higher LET of the 2MeV alpha. As discussed previously, due to geometrical effects the 2D simulation results will overestimate the charge collection by lateral diffusion even if recombination parameters (lifetime and surface recombination velocity) are correctly defined. For the unirradiated device, the amount of overestimation is consistent with 2D/3D simulation comparisons indicating that the recombination parameters are reasonable.

These parameters are less certain for the irradiated device as discussed in section VII and the difference in 2D simulation results from the experimentally derived collection efficiency is

more than one would expect from geometrical effects. The difference even extends to the depletion region where charge collection is drift dominated and rapid. If we increase recombination in the simulation we may obtain a drop in collection efficiency, even in the depletion region: however, the decrease in collection from lateral diffusion becomes much too large (i.e. the parameter L in equation 3 is too large). So the observed difference in Figure 11 cannot be largely attributed to uncertainty in lifetime parameters. This result implies that the 2D simulation poorly models recombination within the plasma column for the irradiated device.

For 2D simulations, due to geometrical effects, either the correct total charge or the correct charge density can be simulated but not both [12, 13]. DESSIS ensures total charge conservation and so the initial ion track charge density is underestimated. This will affect correct simulation of high injection effects such as Auger recombination and carrier-carrier scattering (CCS). The underestimation is further compounded by the use of a Gaussian ion-track profile which has a much reduced peak ion track density in comparison to more accurate ion track models [14-16]. A 2D simulation of a 5.3MeV alpha particle was performed which accounted for CCS via the unified mobility model and included self heating effects by using a thermodynamic model. The simulation indicated negligible self-heating and only a 2% drop in total charge collected versus a model without CCS. 3D simulations of the irradiated device with an improved ion track model are planned in order to accurately investigate the effect of CCS, auger recombination, and trap-assisted Auger recombination.

Despite the absolute errors, the 2D simulation results appear to correctly estimate the relative voltage variation. With 0V bias, drift collection is relatively weak and recombination is dramatically increased. Generally, the comparison between calculated spectra and experimental results shown in Figures 10 and 12 are reasonable. The poorest fit occurs for the 0V irradiated device spectrum.

VII. 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:

$$\frac{1}{\tau} = \frac{1}{\tau_i} + k\theta_n \quad (6)$$

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.

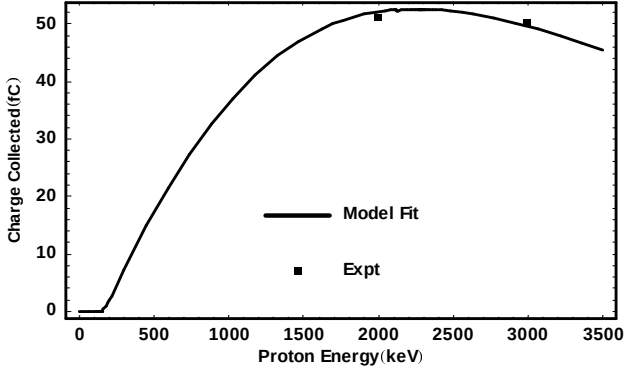


Figure 13: Fit of diffusion model to proton microbeam peak charge collection data.

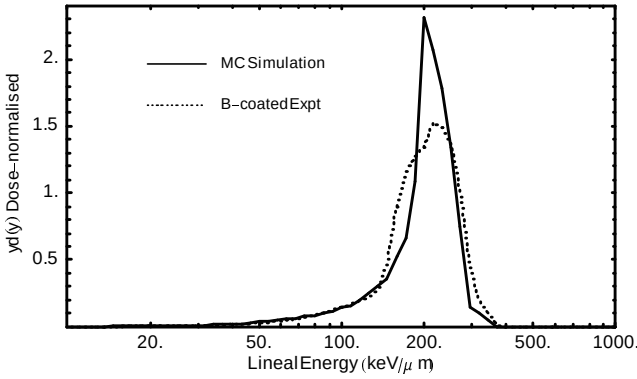


Figure 14: Microdosimetric spectra in BNCT: 1%B coated diode array. Monte-Carlo simulation is shown for comparison. Microdosimetric spectra are presented in the standard $yd(y) \propto y^2 f(y)$ versus $\text{Log}(y)$ format, where $f(y)$ is the lineal energy probability density distribution calculated from the number of events in the lineal energy range interval dy and $d(y)$ is the dose probability density distribution. Presented in this way, equal areas under different regions of the function $yd(y)$ correspond to equal doses.

A. Minority Carrier Lifetime Estimation

In order to calculate the damage constant we measure the minority carrier lifetime via charge collection spectroscopy methods as proposed by Edmonds, et al. [17]. The diffusion length (L_d) and depletion thickness (t_{dr}) are calculated for various input ion 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:

$$E_{\text{collected}} = \int_0^{t_{dr}} \frac{dE}{dx} dx + \int_{t_{dr}}^{R(E_1)} \frac{dE}{dx} e^{-\frac{x-t_{dr}}{L_d}} dx \quad (7)$$

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}). The

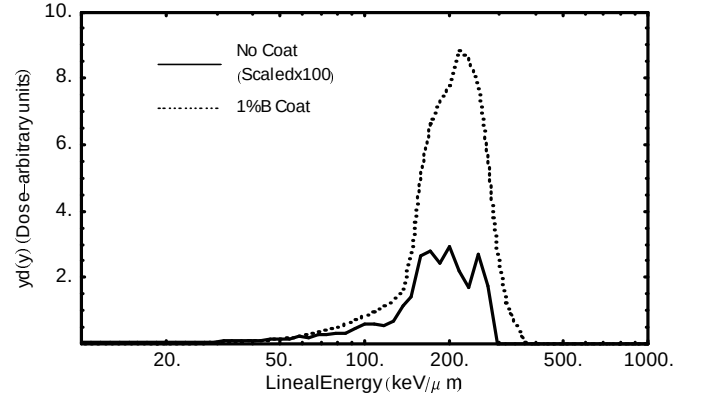


Figure 15: Microdosimetric spectra for non-boron coated device compared with boron coating. The spectra were obtained at a depth of 6.5cm in the Lucite phantom with a reactor power of 300kW and an acquisition time of 5 minutes. Note that the no coat spectrum is scaled up by a factor of 100 and the spectra are unnormalized. The peak at 200 keV/μm in the no coat spectrum arises from boron p+-dopant in the device.

range of a particle with energy E_1 is given by the function $R(E_1)$. Minority carrier lifetime then follows from:

$$\tau = L_d^2 / D_n \quad (8)$$

where D_n is the diffusivity of electrons in silicon ($37.6 \text{ cm}^2/\text{s}$).

Equation 7 assumes that the depletion region boundary is a perfect charge sink consisting of a plane of infinite extent. This assumption is not completely satisfied by our devices with deviations from complete charge collection at the upper surface resulting in an underestimation of diffusion length.

Both SOI and bulk devices were irradiated at CERN using 24 GeV/c protons at a fluence of $4.1 \times 10^{13} \text{ p/cm}^2$. For the unirradiated bulk device, we apply the above method to 2 and 3 MeV proton beam data. Imaging measurements were performed on a bulk device using the $10 \times 10 \text{ μm}$ diode array. The energy collected was taken as the energy of a particle traversing the middle of the diode. Figure 13 shows the fit to the data and Table 1 gives the extracted diffusion length and minority carrier lifetime. Proton microbeam measurements have significant advantages over alpha broadband experiments since the lower LET protons are much less susceptible to funneling and the imaging method allows us to select the ion position which best satisfies the model assumptions.

For the irradiated device, only broadband spectroscopy measurements are currently available. We cautiously apply the lifetime estimation method using broadband alpha spectroscopy with the knowledge that funneling will significantly affect results. However, for this prototype device we require only a first order estimate of radiation hardness. A Po-210 (5.3 MeV) source was placed in a vacuum with incident alpha energy varied by using thin plastic films. A $100 \times 100 \text{ μm}$ bulk device at 10V bias was used. The results shown in Table 1 indicate a large difference between proton microbeam and alpha broadband methods due to alpha

funneling effects. Note that the drift component for the alpha experiment is higher than one might expect from estimates of the depletion width. The additional charge collection is due to funneling.

Trapping levels introduced by displacement damage may reduce the majority carrier density. Capacitance-voltage measurements indicate a drop in substrate doping density from 1.5 to $1 \times 10^{15} \text{cm}^{-3}$. Such a reduction will increase the depletion width as seen in Table 1. 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.

Table 1
Lifetime parameters for damage constant estimation

Experiment	Drift (μm)	Ld (μm)	τ (nsec)
Unirradiated, proton μbeam	3	45	540
Unirradiated, α broadbeam	3.9	14.3	-
Irradiated, α broadbeam	6.5	5.2	-
Irradiated, estimated	3	16	70

B. Damage Constant

The final 1 MeV equivalent damage constant is calculated as $K=4.4 \times 10^{-7} \text{cm}^2/\text{n-sec}$. This result is in good agreement with damage constants estimated by Messenger and Ash [18] assuming high injection ratios. The displacement cross-sections required to correct the damage constant to 1 MeV neutron equivalent are 65.15 MeVmb for 24 GeV/c protons and 95 MeVmb for 1 MeV neutrons [19]. Given that 1 cGy is approximately equivalent to $4.1 \times 10^8 \text{n/cm}^2$ (1 MeV neutrons) [20] and assuming 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.

Bulk devices were also irradiated at Australian Nuclear Science and Technology Organization (ANSTO) using 1 MeV neutrons at fluences of 10^{10} - 10^{12}n/cm^2 . The spectrum shift at the highest fluence was approximately 5% compared to an expected change in diffusion length of 10%. We can conclude that the damage constant calculated above is moderately conservative.

Future experiments intend to use the microbeam method, applied to the irradiated device, to improve lifetime and damage constant estimates.

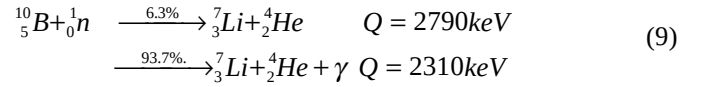
VIII. APPLICATIONS

The microdosimeter may be used for characterizing complex radiation environments in terms of the risk of SEU to electronics and the biological effect on tissue cells. Such environments include spacecraft and airplanes as well as medical environments such as high LET radiation therapy.

Roth, et al. [21] have constructed a solid state microdosimeter for radiation monitoring in spacecraft and avionics. Our device is intended for similar applications with the SOI construction the first step towards improved sensitive volume definition. Examples of the devices application in radiation oncology are now presented.

A. Boron Neutron Capture Therapy

Boron neutron capture therapy (BNCT) involves the thermal neutron irradiation of a tumor site that has been selectively sensitized to thermal neutrons via the concentration of boron-10 (B-10) within or near cancer cells. The capture of thermal neutrons by B-10 results in the following nuclear fission process:



The alpha and lithium products are high LET particles that deposit their energy in ranges comparable to typical mammalian cell dimensions. Experimental microdosimetry is an important tool in BNCT. In particular, experimental microdosimetry provides techniques for separating varying LET components and measuring boron dose, total dose, beam quality, and dose enhancement factors.

A clinical trial of BNCT is currently underway at the 3 MW Brookhaven Medical Research Reactor at BNL. The device was exposed to the epithermal neutron beam. Some example results are now presented with detailed analysis reported elsewhere [22]. In order to sensitize the microdosimeter to thermal neutrons the device was coated with 1% B^{10} Lucite. Figure 14 shows the microdosimetric spectrum along with a comparison to a Monte-Carlo simulation. The comparison is reasonable given the simplicity of the Monte-Carlo simulation, which neglects many sources of variation such as diffusion effects, overlayer thickness variations, and straggling effects. The charge collection analysis presented in this paper will enable improvements in the Monte-Carlo model.

Measurements were also made of the signal from boron deposited within the p+ regions of the chip as shown in Figure 15. These results are the first experiments that use ion implanted boron to simulate boron deposition in various regions of a cell, an idea recently proposed by Rosenfeld, et al. [23]. Such local B^{10} concentration variation is not possible with a proportional gas counter.

B. Proton Therapy

Measurements were performed using the 250 MeV proton therapy facility at the Particle Radiation Medical Center (KEK), University of Tsukuba, Japan. Microdosimetry in this beam has been extremely difficult due to the pulse structure of the beam, which delivers a high fluence of protons every 50 msec with a width of 50 ns. The silicon microdosimeter was

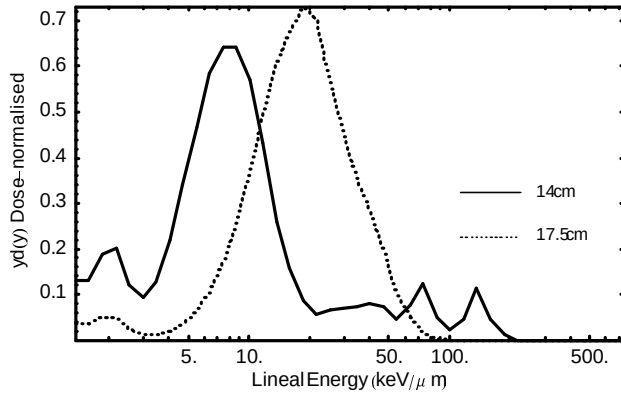


Figure 16: Microdosimetric spectra from 250MeV proton beam at KEK. 10 μ m SOI microdosimeter is placed in water phantom.

much less susceptible to pile-up than a proportional gas counter due to its small array area.

Measurements were performed in a Lucite phantom at various distances from 0-20cm encompassing the proton range. The microdosimetric spectra at two depths are shown in Figure 16. The lineal energy at 17.5 cm is higher than at 14 cm since the proton LET is closer to the Bragg peak as we near the end of the proton range. The measurement at 14 cm includes some high LET components from nuclear reaction products generated at high proton energies. This was the first successful microdosimetric measurement of this beam, highlighting the size advantage of a silicon-based microdosimeter.

IX. CONCLUSION

Tests of the prototype microdosimeter in clinical applications demonstrate the potential of SOI based silicon diode arrays. In addition to the BNCT and proton applications presented, we have also successfully tested the device in a fast neutron (Gershenson Radiation Oncology, Wayne State University) medical facility. Plans are currently underway for heavy ion therapy studies in Japan.

This paper indicates that future SOI microdosimeter designs should introduce methods to minimize lateral diffusion such as 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. 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. Care must be taken in the interpretation of broad-

beam data to avoid associating peaks in the spectrum directly with drift collection regions. The effect of significant lateral diffusion is to shift the spectrum to lower energies due to reduced collection efficiency. The spectroscopy modeling presented assists in correctly interpreting data by including, as far as practicable, all the sources of variation which contribute to the measured spectral character.

Charge collection spectroscopy has been used to determine minority carrier lifetime in SOI and bulk devices. Radiation damage studies have demonstrated the usefulness of this device over repeated clinical exposures.

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