

6. Charge Collection Modeling: Sensitive Volume and Radiation Hardness Characterization

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 chapter, we present a study of the charge collection behavior of the prototype microdosimeter.

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. Broadbeam alpha spectroscopy refers to the use of a standard alpha spectroscopy source with a beam area larger than the microdosimeter area. Conversely, microbeam spectroscopy uses a submicron diameter beam scanned across the device under test. It has the important advantage of directly providing information on charge collection as a function of position on the device.

Experiments were performed on 2 and 10 μm SOI devices and the bulk structure. 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 may 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. The radiation hardness study used 2 μm SOI and bulk devices only. Several devices of both types were radiation damaged at CERN using 24 GeV/c protons with fluences of $4.1 \times 10^{13} \text{pcm}^{-2}$. The different parts are designated “unirradiated” and “irradiated” throughout this chapter. Initial phases of this

work were originally presented by the author at the Nuclear Space and Radiation Effects Conference 1998 [194].

The basics of charge collection are described in section 6.1, section 6.2 describes the various sensitive volume characterization methods whilst section 6.3 applies such methods to the analysis of radiation hardness.

6.1 Charge Collection Physics

This section describes the basic physics of ion interactions with a reverse biased diode [44]. The simple case of a p-type bulk diode (n⁺-p) is generally used along with appropriate observations on behavior in SOI devices. The necessary background for subsequent detailed analysis of the microdosimeter charge collection volume is provided.

6.1.1 Motion of Carriers

The interaction of an ion with silicon produces electron-hole pairs. Such charge carriers are influenced by three main effects: drift due to an electric field, diffusion due to a concentration gradient and recombination of carriers through mid-gap recombination centers.

6.1.1.1 Carrier Drift

Under zero bias conditions at room temperature, charge carriers (holes in the valence band and electrons in the conduction band) are essentially free particles, which move rapidly due to thermal energy. The random thermal motion may be visualized as a succession of scattering collisions with lattice atoms, impurity atoms and other scattering centers. The random motion leads to zero net displacement over a sufficiently long time period. The thermal velocity of electrons is about 10^7 cm/s at 300 K with a mean free time between collisions of about 1 ps.

Application of an electric field, results in the net movement of carriers in a direction governed by the electric field and the carrier polarity. This process is called carrier drift. Mobility m is the proportionality factor that describes how strongly carrier motion is affected by the electric field strength $\vec{E}$. Thus, the drift velocities for holes $\vec{u}_p$ and electrons $\vec{u}_n$ are given by:

$$\vec{u}_p = m_p \vec{E} \quad (6.1)$$

$$\vec{u}_n = -m_n \vec{E} \quad (6.2)$$

The carrier mobility is determined by various scattering mechanisms including lattice scattering and impurity scattering. Lattice scattering results from thermal vibrations disturbing the lattice periodic potential thus allowing energy to be transferred between carriers and the lattice. Impurity scattering results when a charge carrier is deflected by Coulomb interaction with an ionized dopant impurity. Scattering processes and hence mobility are carrier type, temperature, doping and electric field dependent. At 300 K, intrinsic silicon has an electron mobility of 1350 cm²/Vs and a hole mobility of 480 cm²/Vs. The mobility of the *p*-substrate of the prototype microdosimeter is reduced somewhat although still dominated by lattice scattering whilst the *n*+ and *p*+ junction regions have much lower mobility due to high impurity scattering as shown in Table 6.1. Note that the electron mobility is approximately 3 times the hole mobility due to the lower effective rest mass of the electron.

Table 6.1. Electron and Hole Mobility

Doping Concentration	Electron Mobility (cm ² /Vs)	Hole Mobility (cm ² /Vs)
Intrinsic	1350	480
Na = 1.5 × 10 ¹⁵ (<i>p</i> substrate)	1337	458
Na = 2 × 10 ²⁰ (<i>p</i> +, <i>n</i> + contacts)	49	46

The linear relationship between drift velocity and electric field assumes that the time between collisions is independent of the applied field. At high electric field strengths (> 5 × 10⁴ V/cm) the drift velocity becomes comparable to the thermal velocity of carriers and the linear relationship no longer holds. Thus, at sufficiently high electric fields the drift velocity approaches a saturation value v_{sat} . Experimental results are well approximated by the Caughey-Thomas [44, 195] empirical expression:

$$m(E) = \frac{m_{low}}{\left[1 + \left(\frac{m_{low} E}{v_{sat}}\right)^b\right]^{1/b}} \quad (6.3)$$

where E is the electric field in the direction of current, m_{low} is the low field mobility given in Table 6.1, v_{sat} is the saturation velocity (1.07 × 10⁷ cm²/s for electrons and 8.37 × 10⁶ cm²/s for holes) and b is a constant (0.87 for electrons and 0.52 for holes) (from DESSIS manual [196]).

From equations (6.1) and (6.2) the drift current densities for holes and electrons are given by

$$\vec{J}_{p,drift} = qm_p p \vec{E} \quad (6.4)$$

$$\vec{J}_{n,drift} = qm_n n \vec{E} \quad (6.5)$$

where p is the hole density and n is the electron density.

6.1.1.2 Carrier Diffusion

Diffusion current results from the random thermal motion of carriers in a concentration gradient. The governing equations for hole and electron diffusion current densities are [44]:

$$\vec{J}_{p,diff} = -qD_p \nabla p \quad (6.6)$$

$$\vec{J}_{n,diff} = qD_n \nabla n \quad (6.7)$$

For an electron density that increases with a distance x , the gradient is positive and electrons will diffuse in the negative direction. Current flow is positive and flows in the direction opposite to the electrons. The holes also diffuse in a direction opposite to their concentration gradient. However, the current flow is negative in this case since positive charge is moving in the negative direction.

6.1.1.3 Recombination

At thermal equilibrium, the mass action law $np = n_i^2$ is valid. Recombination is the process of electron-hole pair cancellation that works towards restoring equilibrium under conditions where an excess of carriers exists, i.e. $np > n_i^2$. The recombination lifetime t_r is the average time it takes for an electron-hole pair to recombine when excess carriers exist.

The equilibrium electron and holes densities are denoted by n_0 and p_0 and by the mass action law [44]:

$$n_0 p_0 = n_i^2 \quad (6.8)$$

If we inject excess carriers Δn and Δp then the electron and hole densities are given by:

$$n = n_0 + \Delta n ; \quad p = p_0 + \Delta p \quad (6.9)$$

The injection of carriers is categorized into two conditions; low level and high level injection. Low level injection occurs when the excess carrier density is much less than the majority carrier density. Conversely, high level injection occurs when the excess carrier density is much greater than the majority carrier density. For a p-type semiconductor with a doping N_a we have

Low level injection: $\Delta p = \Delta n \ll p = N_a$

High level injection: $\Delta p = \Delta n \gg p = N_a$

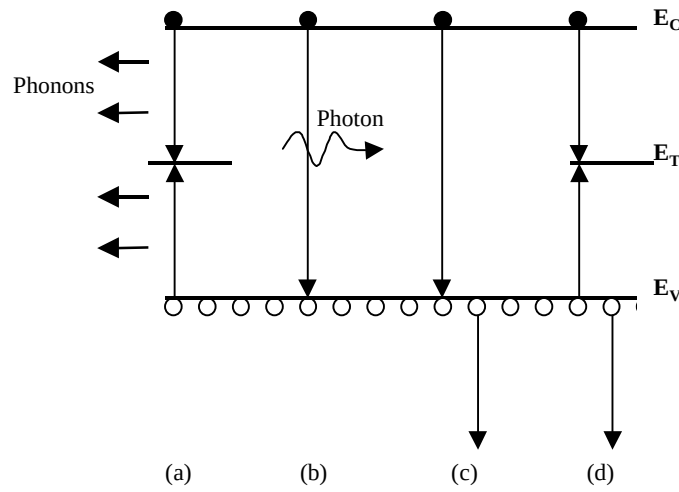


Figure 6.1. Recombination mechanisms:
(a) Shockley-Read-Hall, (b) Direct Radiative, (c) Direct Auger (d) Trap-Assisted Auger

There are four main mechanisms for recombination in semiconductors as summarized in Figure 6.1 and discussed below:

(a) *Shockley-Read-Hall:*

The basic theory of electron-hole pair recombination was initially developed in 1952 by Hall [197] and Shockley and Read [198]. During SRH recombination, electron hole pairs recombine through deep level impurities characterized by the impurity density N_T , energy level E_T in the bandgap and capture cross sections s_n and s_p and for electrons and holes, respectively. The energy liberated by the recombination event is dissipated by phonons or lattice vibrations. Shockley calculated the SRH lifetime t_{SRH} as:

$$t_{SRH} = \frac{t_p(n_0 + \Delta n + n_1) + t_n(p_0 + \Delta p + p_1)}{p_0 + n_0 + \Delta n} \quad (6.10)$$

where p_0 and n_0 are the equilibrium hole and electron densities, Δn and Δp are the excess carrier densities taken to be equal in the absence of trapping and n_1 , p_1 , t_n , t_p are defined as:

$$n_1 = n_i e^{(E_T - E_i)/kT}; \quad p_1 = n_i e^{(E_i - E_T)/kT} \quad (6.11)$$

$$t_p = \frac{1}{s_p v_{th} N_T}; \quad t_n = \frac{1}{s_n v_{th} N_T} \quad (6.12)$$

The corresponding recombination rate R_{SRH} per unit volume is given as [44]

$$R_{SRH} = \frac{pn - n_i^2}{t_p(n + n_1) + t_n(p + p_1)} \quad (6.13)$$

Note that we have used the relationships $p = p_0 + \Delta p$ and $n = n_0 + \Delta n$ along with the fact that the recombination rate is equal to the ratio of excess carriers to lifetime. If the centers are near the midgap such that $p \gg p_1$ and if $n \gg p$ then the recombination rate is

$$R \cong \frac{\Delta n}{t_n} \quad (6.14)$$

Thus, the recombination is only dependent on the minority carrier lifetime and excess carrier concentration. The rate-limiting step in the recombination process is the capture of the minority carrier since there are an abundance of majority carriers available for recombination at a center.

(b) *Direct Radiative:*

In direct radiative recombination, the electron-hole pairs recombine directly from band to band with the energy carried away by photons. Radiative recombination is highly unlikely in indirect band-gap semiconductors such as silicon but it is important in direct bandgap semiconductors such as GaAs [44]. For completeness the radiative lifetime t_{rad} is given by :

$$t_{rad} = \frac{1}{B_{rad}(p_0 + n_0 + \Delta n)} \quad (6.15)$$

where $B_{rad} = 2 \times 10^{-15} \text{ cm}^3/\text{s}$ for silicon.

(c) *Direct Auger:*

During Auger recombination, the recombination energy is absorbed by a third carrier. For a p-type semiconductor, the lifetime is given by [199]:

$$\begin{aligned} t_{Auger} &= \frac{1}{C_p(p_0^2 + 2p_0\Delta n + \Delta n^2)} \\ &= \frac{1}{C_p p^2} \quad \text{assuming } \Delta n = \Delta p \end{aligned} \quad (6.16)$$

where C_p is the Auger recombination coefficient. The general recombination rate for any doping and injection levels is given by:

$$R_{Auger} = (pn - n_i^2)(C_n n + C_p p) \quad (6.17)$$

where $C_n = 6.7 \times 10^{-32} \text{ cm}^6/\text{s}$ and $C_p = 7.2 \times 10^{-32} \text{ cm}^6/\text{s}$ [199].

Auger recombination is important in high injection conditions or regions of high doping (carrier concentrations $> 10^{19} \text{ cm}^{-3}$). The following approximation applies at high injection levels and assuming $Dp = Dn$.

$$R \cong C_p \Delta p^3 \quad (6.18)$$

Note that since three carriers are now involved the recombination rate is proportional to the cube of the excess carrier density

(d) *Trap-Assisted Auger:*

The trap assisted Auger lifetime t_{trap} is given by [199]:

$$t_{trap} = \frac{1}{B_{trap}(p_0 + n_0 + \Delta n)} \quad (6.19)$$

where $B_{trap} \sim 1 \times 10^{-15}$ to $9 \times 10^{-15} \text{ cm}^3/\text{s}$ for silicon. Note the similarity with equation (6.15). This process is relatively unimportant except when many traps are present in which case B_{trap} may be much higher.

These mechanisms combine to determine the average recombination lifetime according to the relationship [200]:

$$\frac{1}{t_r} = \frac{1}{t_{SRH}} + \frac{1}{t_{rad}} + \frac{1}{t_{auger}} + \frac{1}{t_{trap}} \quad (6.20)$$

Of course, the recombination rates simply add to give the total recombination rate R .

$$R = R_{SRH} + R_{rad} + R_{auger} + R_{trap} \quad (6.21)$$

At high carrier densities (either injection or doping), the dominant recombination process is Auger recombination whilst at low densities SRH multi-phonon recombination is dominant.

All of the above mechanisms may operate in the silicon bulk. In addition, SRH recombination may occur at surfaces due to interface states that span the bandgap. These states are introduced by the discontinuity in the lattice structure, at the interface between surfaces. The primary interface in the silicon microdosimeter is the Si/SiO₂ interface, which bounds the top and bottom of the silicon SOI layer. Analogous to the SRH bulk lifetime of equation (6.13), the SRH surface recombination velocity is given by:

$$s_r = \frac{p_{0s} + n_{0s} + \Delta n_s}{(1/s_p)(n_{0s} + \Delta n_s + n_{1s}) + (1/s_n)(p_{0s} + \Delta p_s + p_{1s})} \quad (6.22)$$

where

$$s_n = s_{ns} v_{th} N_{it}; \quad s_p = s_{ps} v_{th} N_{it} \quad (6.23)$$

At low injection levels, s_r may vary from about 5000 cm/s to as low as 20 cm/s [199]. The subscript "s" refers to the appropriate quantity at the surface. Carrier densities are in units of cm⁻³ and interface trap density N_{it} is in units of cm⁻². The number of carriers recombining at the surface per unit area and unit time is the surface recombination rate R_s , given by an expression analogous to equation (6.13):

$$R_s = \frac{p_s n_s - n_i^2}{(1/s_p)(n_s + n_1) + (1/s_n)(p_s + p_1)} \quad (6.24)$$

Surface recombination is more complex than bulk recombination because it depends not only on the density of traps but also on the state of the surface. For example, positively charged surface states in p-type silicon may induce a depleted surface that presents an attractive potential for minority carriers. The enhancement of surface recombination via this mechanism will depend on the injection level since the surface potential may be reduced as injection levels rise.

The main features of recombination have been discussed. For a more detailed discussion of lifetime refer to Schroder [199, 200] and Bullis [201].

6.1.1.4 Combined Model (Continuity and Poisson Equation)

The overall effect of drift, diffusion and recombination on the semiconductor is encapsulated in the continuity equations. The spatial and temporal distribution of carrier density and electrostatic potential may be obtained by solving the continuity equations and Poisson's equation for the device. Classical electrodynamics relates the electric field $\vec{E}$ to the charge density r by Poisson's equation:

$$\nabla \cdot \epsilon \vec{E} = r \quad (6.25)$$

where ϵ is the dielectric permittivity of silicon = 1.05 pF/cm and the net charge density r is given by

$$r = q(p - n + N_d^+ - N_a^-) \quad (6.26)$$

where n and p denote the concentrations of electrons and holes, respectively, and N_d^+ and N_a^- are the concentrations of ionized acceptors and donors.

Conservation of charge conditions and the spatial and time continuity of carrier concentrations is expressed by the continuity equations for each carrier type [44]:

$$\nabla \cdot \vec{J}_n = q \left(R - G + \frac{\partial n}{\partial t} \right) \quad (6.27)$$

$$\nabla \cdot \vec{J}_p = -q \left(R - G + \frac{\partial p}{\partial t} \right) \quad (6.28)$$

where R is the total recombination rate given by the sum of bulk and surface recombination components (equations (6.21) and (6.24)) and G is the carrier generation rate.

These equations must be solved together with the constitutive relationships for current density (the actual drift-diffusion equations obtained by combining equations (6.4) to (6.7)) are:

$$\vec{J}_n = qm_n n \vec{E} + qD_n \nabla n \quad (6.29)$$

$$\vec{J}_p = qm_p p \vec{E} - qD_p \nabla p \quad (6.30)$$

One should also note the important relationship between mobility and diffusivity provided by the Einstein relationship:

$$D_n = \frac{kT}{q} m_n \quad (6.31)$$

where kT/q is 0.026 V. This relationship also applies between D_p and m_p . In addition to the conduction currents, there is the displacement current given by:

$$\vec{J}_d = e \frac{\partial \vec{E}}{\partial t} \quad (6.32)$$

These currents add up to give the total current at a point in the semiconductor:

$$\vec{J}_T = \vec{J}_d + \vec{J}_n + \vec{J}_p \quad (6.33)$$

6.1.2 Ion Interaction: Generation of Carriers

An energetic ion passing through a material predominantly deposits energy via coulomb collisions with the material's atomic electrons. The energy loss per unit path length or Linear Energy Transfer (LET) may be approximated by the Bethe equation provided in section 5.2. The numerous collisions slow down the ion until it eventually stops and has only the thermal energy of the surrounding material. Importantly, the energy deposition is not entirely along the trajectory of the incident ion but has a finite radial extension around the incident track trajectory. Liberated electrons, called delta rays (δ -rays), have sufficient energy to follow trajectories away from the incident track. Delta rays travel in a zigzag pattern and similarly lose energy from coulomb collisions until they are thermalized. The δ -rays account for roughly half of the collisional energy [202]. The rest are accounted for in soft collisions, between the ion and atomic electrons, which produce essentially thermal electrons that mainly contribute to the electron-hole pairs in the plasma core.

For a semiconductor material, the deposited energy is converted directly into a dense population of electron-hole pairs. The familiar conversion rate in silicon is 3.62 eV/e-h pair. Thus, if the initial energy distribution is known then the initial electron-hole pair distribution may be calculated. In microdosimetry, it is important to understand the extent of the electron-hole pair plasma that remains following the thermalization of

delta electrons. Many calculations assume that the track width is negligibly small in comparison with microdosimeter dimensions. Furthermore, semiconductor device simulations require as input the initial electron-hole pair distribution.

Several researchers [203-211] have investigated the track structure of ions traversing silicon and other materials. Monte Carlo calculations [204] have provided quite accurate information on track structure but are time consuming and largely incompatible with other semiconductor simulation codes. Much of the effort has focussed on obtaining an accurate semi-empirical analytical expression for the energy density deposited in a cylindrical shell about the ion track trajectory.

The current approach, which most accurately corresponds with Monte Carlo results and experiment, is based on a method initially proposed by Kobetich and Katz [203] and frequently called Katz theory. They utilized two empirical relations for electron range in aluminium and electron transmission through thin foils, to determine the energy deposition of δ -rays traveling in straight lines perpendicular to the incident track. Also required is a relationship for the delta ray energy distribution (i.e. spectrum; the number of delta rays per cm per energy). Note that electron range, expressed in gm/cm^2 , is approximately the same for materials of similar atomic number. Hence the use of aluminium data to approximate other materials.

Many improvements have been made to the initial model, including work by Waligorski [205] who introduced a correction factor to the dose that provides better agreement with experiment and Monte-Carlo and Katz [209] who extended the work to mediums other than water. For silicon, the most recent and accurate Katz model is attributable to Fageeha [211]. The equations given by Fageeha were implemented in a relatively simple Mathematica program (Note that Fageeha wrote a program called REDCHP).

The electron hole pair density formed in silicon from a 5 MeV alpha particle and 2 MeV proton is shown in Figure 6.2. For these ions, high injection conditions occur in a cylindrical region less than about 0.1 μm radius. Auger recombination will be dominant in the region of radius less than about 5-10 nm. An alternative form of presentation is to plot the radial profile of the cumulative fraction of total dose as shown in Figure 6.3. (calculated as the cylindrical integral of Figure 6.2 divided by the total dose). From this figure, we see that the two ions have similar radial dose profiles except for almost an order of magnitude lower total dose for the 2 MeV proton. The lower total dose is

simply due to the lower LET. In both cases, fifty percent of the dose is within 2.5 nm of the center track and almost the entire dose is within 150 nm.

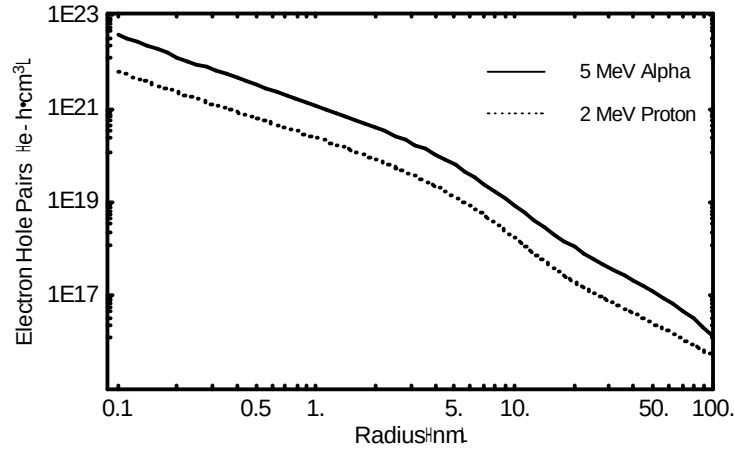


Figure 6.2. Plot of energy density profile as a function of radial distance from the center of an alpha and proton ion track based on Fageeha's implementation of Katz's model [211].

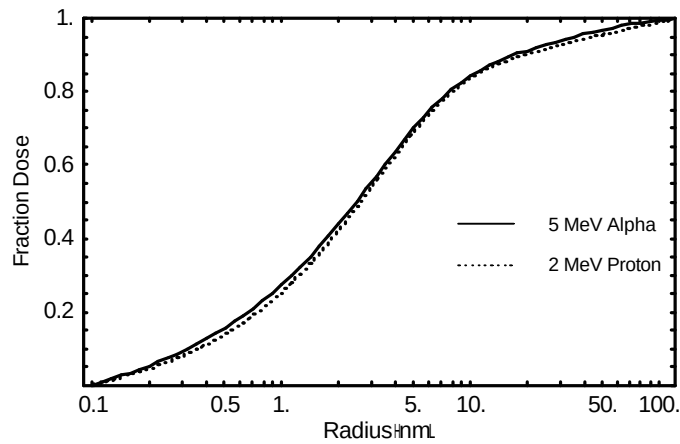


Figure 6.3. Cumulative fraction of dose deposited from the center of the track to the given radius. Fifty percent of the dose is within 2.5 nm of the center track.

6.1.3 Ion Interaction: Motion of Carriers

Having determined the initial carrier density following an ion strike, the evolution of the plasma column and the collection of carriers will now be described. We will consider an ion strike normally incident from above the device and intercepting the depletion region (DR, a strong space charge region) of a n⁺/p diode as shown in Figure 6.4. Three separate processes transpire, denoted by DR collapse, DR recovery and then stable DR operation. Charge collection may occur during each of these processes but to varying degrees depending on the time of the process. DR collapse and DR recovery are characterized by high injection conditions with a dynamic depletion region boundary

(DRB) whilst stable DR operation occurs in low level injection conditions and maintains a stationary DRB.

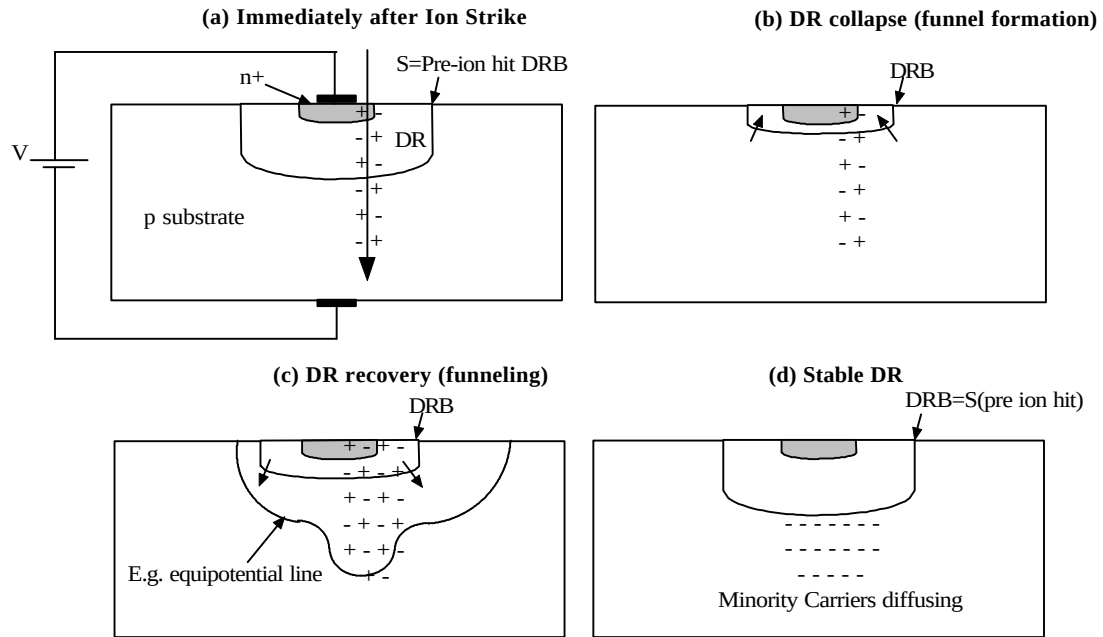


Figure 6.4. Charge collection stages for an ion strike on a n^+/p bulk diode. Most of the charge collection occurs during DR recovery (c) and the following stable DR (d).

The **DR collapse** is caused by a rearrangement of charge carriers located above the initial DRB. The strong electric field in the depletion region very quickly produces a redistribution of carriers liberated by the ion track until many of the previously unshielded impurity ions become shielded by carriers. Thus, the DR shrinks and the quasi-neutral region of the track extends upwards. A quasi-neutral region is defined by the property that the charge imbalance is small compared to the majority carrier density. Below the DRB, under high injection conditions, the track is quasi-neutral because the electron and hole densities are equal and much larger than the substrate doping defining the majority carrier density.

An implication of a collapsed or partially collapsed DR, first discovered by Hsieh [212], is that it supports much less voltage than prior to the hit. Voltage formally across the depletion region now occurs across the quasi-neutral region and substrate. The substrate voltage drops enhances minority carrier (electron) flow from the substrate to the DR, a phenomenon called funneling. A simulation of a 5.3 MeV alpha particle incident on a p^+/n bulk diode is shown in Figure 6.24 (and described in more detail in section 6.2.2.3). Even as short as 1 ps following the ion strike one can see the funnel shaped

voltage distribution. The end of the first stage is characterized by the DR at a minimum, the beginning of funneling, but with very little charge collected due to the very short time frame.

It has been assumed thus far that the DR collapse is caused by an ion strike intercepting the depletion region. However, if the track misses the junction there can still be a DR collapse producing a voltage across the quasi-neutral region. In this case, the collapse is more gradual since carriers must first diffuse to the DR to generate the collapse. Furthermore, the distinction between collapse and recovery is not as clear as for the direct strike since the DRB is quite well defined at all times and both collapse and recovery are gradual.

Throughout the collapse and subsequent recovery, the cylindrical electron-hole pair plasma expands radially outward by ambipolar diffusion. The diffusion is ambipolar as the plasma attempts to remain charge neutral [213]. Since the electron diffusion constant is higher than the hole diffusion constant the charge will attempt to separate. However, any charge imbalance is quickly rectified by strong electrostatic restoring fields. The common ambipolar diffusion constant is given by McKelvey [214, 215] as:

$$\begin{aligned}
 D &= \frac{(n+p)D_n D_p}{nD_n + pD_p} \\
 &\approx \frac{2D_n D_p}{D_n + D_p} \quad \text{High injection: if } n = p \gg N_a \\
 &\approx D_n \quad \text{Low injection}
 \end{aligned} \tag{6.34}$$

Note that mobility is reduced at higher carrier concentrations. This further decreases diffusivity at early times in the plasma track evolution via Einstein's relationship between mobility and diffusivity (equation (6.31)). The diffusivity constant will typically vary from 1.5 cm²/s under high injection conditions to 35 cm²/s under low injection conditions. Ambipolar diffusion requires high level injection. Once the carrier density approaches the substrate doping level then electron and hole diffusion may occur at separate rates since the restoring electrostatic fields are no longer supported.

Assuming ambipolar diffusion is the dominant process, high level injection conditions with a constant diffusivity and including only SRH recombination then equation (6.14), (6.27) and (6.29) reduce to:

$$D\nabla^2 n - \frac{n}{t} = \frac{\partial n}{\partial t} \quad (6.35)$$

which has the solution for a Dirac delta function initial condition, $n(r, t=0) = N$ e-h/unit length [215, 216]:

$$n = \frac{N}{4pDt} \exp\left(\frac{-r^2}{4Dt} - \frac{t}{t}\right) \quad (6.36)$$

As an example, the above equation was calculated for a 5 MeV alpha particle (LET=150 keV/ μm , $N = 4.2 \times 10^8$ e-h/cm) at 1, 10 and 100 ps with $t = 1 \mu\text{s}$. The diffusivity constant was approximated to 1.5, 3 and 20 cm^2/s for the plots at 1, 10 and 100 ps respectively. We note that this equation is very much an approximation since the diffusivity constant will vary spatially and temporally with carrier density. However, it still provides some rough insight into the time scale of various processes. For the time periods considered, SRH recombination is not significant although Auger recombination may contribute for time periods less than about 5 ps when carrier densities exceed 10^{19}cm^{-3} . Ambipolar diffusion may occur for the first 500 ps after which the carrier density returns to low level injection conditions.

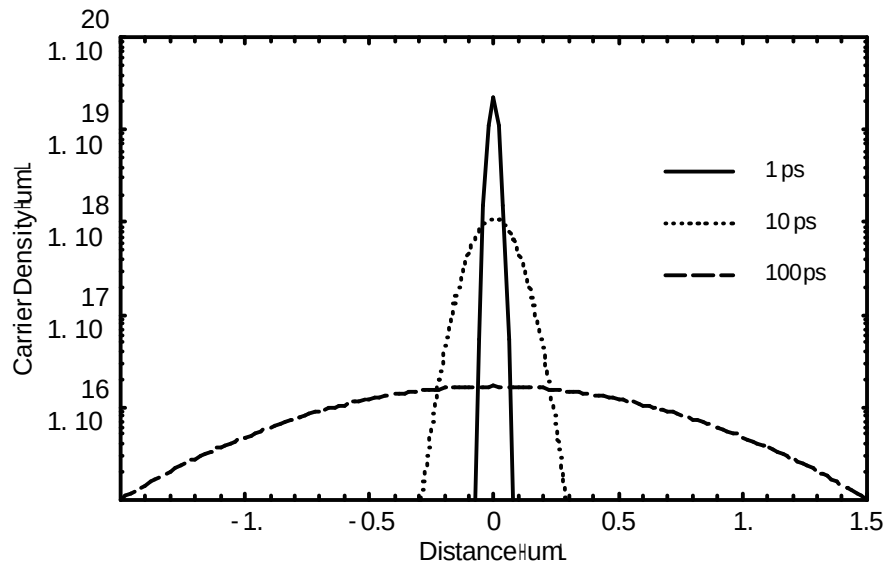


Figure 6.5. Approximate minority carrier density (electron) during ambipolar diffusion around a 5 MeV alpha strike. The diffusivity constant was approximated to 1.5, 3 and 20 cm^2/s for the plots at 1, 10 and 100 ps respectively.

An important concept highlighted by Edmonds [217] is that a strong current may flow longitudinally through a quasi-neutral region radially expanding via diffusion. The current does not require a charge separation because carriers leaving a volume element

can be replaced by others moving in. Thus, the ambipolar diffusion equation may describe the carrier density but says very little about carrier flow. A full description incorporating current flow requires complete solution of the continuity and Poisson equations over the entire device, a problem usually solved using device simulators as described in section 6.2.2.

A qualitative discussion of carrier flow is provided by considering the second stage of **DR recovery** in some detail. The collapsed DR begins to expand because the electric field continues to push holes down so that they move below the negative acceptor ions that they were previously screening. There are essentially no replacement holes coming from the n^+ region since high recombination in the heavily doped n^+ region eliminates virtually all holes. Thus, the downward flow of holes produces an expanding space charge region. However, the region is not depleted of electrons because the large electron supply in the quasi-neutral region and particularly the lightly doped p region are capable of replacing electrons that are moving up and out of the DR to the upper electrode. Much of the DR is characterized by a high electron density with virtually no holes.

Recovery time is much longer than collapse time, but this time may range from tens of picoseconds to nanoseconds depending on substrate doping and ion track characteristics. The recovery concludes when all the holes have been pushed out of the pre-ion hit DRB. This time corresponds with the drop in plasma column carrier density to values close to the substrate doping density at which stage there is no opposing hole diffusion current. Therefore, a strong diffusion current slows down the process because the upward hole diffusion at points below the DRB opposes the downward flow. For example, a thick substrate with an ion track long enough to produce a strong and long-lasting diffusion will result in a long recovery time.

Charge collection during recovery consists of the longitudinal funnel assisted drift collection of electrons at the n^+ junction. The funnel is essentially a weak field ambipolar region with moderate longitudinal drift. The pre-ion hit electric potential is gradually restored as the carrier density approaches the substrate density. The potential restoration proceeds from the outer surface of the plasma column into the center. From the above discussion, we can see that current flow is the cause and the voltage across the quasi-neutral region (i.e. the funnel) is an effect.

The extent of funnel assisted charge collection is heavily dependent on whether the substrate is p or n type doping. For long tracks, the n -type substrate retains a significant portion of its voltage whilst the p -type readily exhibits funnel behavior [217]. The difference in mobility of electrons and holes is the fundamental reason. Edmonds [218, 219] has investigated this effect theoretically extending the earlier work of Hu [220] and McLean and Oldham [221] whilst Dodd has also investigated funneling using device simulation [222, 223].

Following the DR recovery, charge collection will still occur under a condition of **stable DR operation**. The predominant current at this time is minority carrier diffusion from the substrate. Note that for a low LET ion strike, such as a proton, the DR collapse and recovery is very fast and almost all of the charge collection occurs under the condition of a stationary DR.

Edmonds [224] presented a simple model for calculating the total charge collected under the condition of funneling. The model assumes high injection conditions with the electron density n very nearly equal to the hole density h . In addition, the ratio of electron and hole diffusion constants is equal to ratio of electron and hole mobilities as given by equation (6.31). Combining these observations with equations (6.4) to (6.7) gives the following relationships:

$$\vec{J}_{n,drift} = (m_n / m_p) \vec{J}_{p,drift} \quad (6.37)$$

$$\vec{J}_{n,diff} = -(m_n / m_p) \vec{J}_{p,diff} \quad (6.38)$$

Combining equations (6.29), (6.30), (6.37), (6.38) and (6.33) gives the total current density:

$$\vec{J}_T = (1 + m_n / m_p) \vec{J}_p + 2 \vec{J}_{n,diff} \quad (6.39)$$

This is conveniently integrated over the stationary surface S representing the pre-ion hit DRB to obtain the current. As mentioned earlier, because of the lack of replacement holes from the $n+$ region, the time integrated hole current passing through S corresponds to the initial number of holes created. Using this fact and integrating equation (6.39) with respect to time gives Edmond's final model for charge collected $Q_T(t)$ at a time t .

$$Q_T(t) = (1 + m_n / m_p)Q_D + 2Q_{diff}(t), \quad t > t_r \quad \text{High level injection} \quad (6.40)$$

where $Q_{diff}(t)$ is the total collected diffusion charge at time t . The equation is valid for times greater than the DR recovery time t_r . The physical explanation for why Q_T exceeds Q_D is that both kinds of carriers contribute to the collected charge. The contribution from holes moving from the DR to the substrate is Q_D and the remainder of (4.20) is the contribution of electrons moving from the substrate to the DR. The factor of two for the diffusion component arises fundamentally from the high injection level assumption, which gives rise to an electron drift current (equal to $(m_n / m_p)Q_D + Q_{diff}(t)$) and due to the plasma column high conductivity), as well as a diffusion current. Both the electron drift and diffusion currents are in the same direction and hence add together.

The opposite assumption of low level injection conditions predicts a total current given by the sum of the hole drift current Q_D and an electron diffusion current Q_{diff} .

$$Q_T(t) = Q_D(t) + Q_{diff}(t), \quad \text{Low level injection} \quad (6.41)$$

Low injection conditions occur during the post DR recovery stage. In addition, a low injection strike may occur for a low LET particle, such as a proton, where equation (6.41) is always applicable.

When an ion strike misses the DR the hole drift current Q_D is zero for both low and high injection conditions. For an indirect strike, under high injection, holes diffuse into the DR to create the collapse but the same number flow back out during recovery to give a net hole flow of zero. The electron drift and diffusion currents are equal and in the same direction hence the total charge collected is simply twice the minority carrier diffusion current.

A summary of Edmonds approximate charge collection equations for a direct strike to the DR and a non-direct strike to the substrate are given in Figure 6.6. In practice, if the charge collection process begins with high injection conditions then the total charge collected is not determined strictly by equation (6.40) since low level injection conditions eventually occur in which case equation (6.41) applies. If most of the collected charge occurs when the DR is still recovering, implying high injection conditions, then equation (6.40) is a good approximation. A useful area of research would be to obtain a simple expression that merges the two regions of operation.

Charge collection simulations and device behavior specific to the microdosimeter devices will be discussed further in the device simulation section 6.2.2.

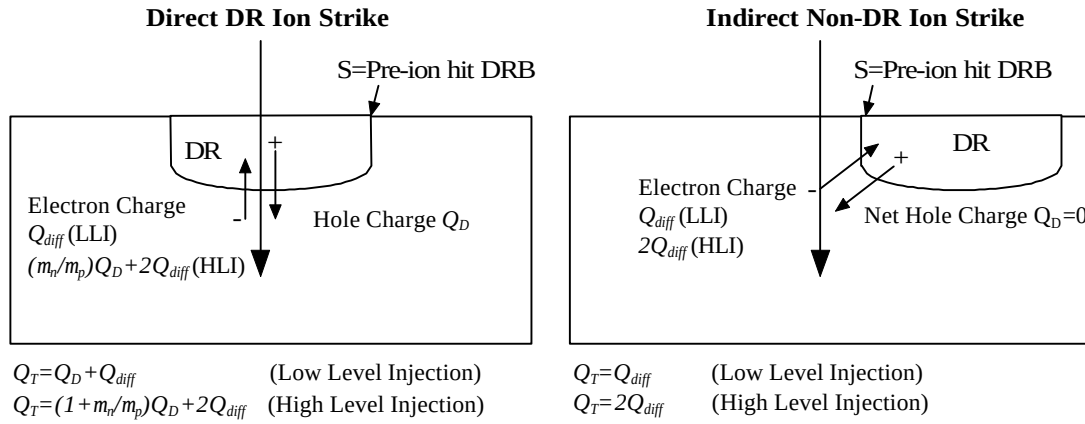


Figure 6.6. Summary of Edmonds approximate charge collection equations for a direct strike to the DR and a non-direct strike to the substrate. The equations for low (LLI) and high level injection (HLI) conditions are shown.

6.1.4 Induced Currents by Carrier Motion (Ramos theorem)

An important theorem relating to charge carrier motion in an electric field is due to Ramo [225]. Currents may be induced in electrodes prior to the arrival of any electrons and holes due to the instantaneous change in electrostatic flux lines which end on the electrode. The instantaneous current induced by a single carriers motion I is given by

$$I = qvE_v \quad (6.42)$$

where q is the carrier charge, v is the carrier velocity and E_v is the electric field component in the direction of v which would exist at the carriers position under the following circumstances: electron removed, given electrode raised to unit potential, all other conductors grounded. For the case of parallel infinite electrodes, frequently assumed in semiconductor detectors this equation becomes

$$I = qmE / d \quad (6.43)$$

where d is the electrode spacing, E is the electric field strength at the carriers position and m is the carrier mobility. Equation (6.43) may be integrated over time and over each carrier contribution to obtain the final total collected charge. For n electron hole pairs generated a distance x from the anode, the total collected charge will be nqx/d from the electron and $nq(d-x)/d$ from the holes giving a total charge collected of nq as expected assuming drift collection and no recombination.

This theorem proves useful for analyzing current profiles where charge collection occurs purely by drift. Hence it is particularly relevant for fully depleted semiconductor detectors [226] and ionization chambers (p 153 Knoll, [23]). Knoll derives a similar result based on energy conservation across a capacitor. A good example of the application of drift-diffusion equations to calculate electron density and Ramo's theorem to calculate the induced charge on an electrode is given by Toney [227].

The theorem is provided here for completeness. The complex microdosimeter charge collection includes drift and diffusion components and is more easily analyzed using semiconductor simulation methods.

6.2 Sensitive Volume Characterization

Sensitive volume characterization involves determining the proportion of generated charge which is collected (i.e. the charge collection efficiency (CE)) as a function of deposited position within the sensitive volume. To characterize the sensitive volume, three methods are employed including semiconductor device simulation, microbeam spectroscopy and broadbeam spectroscopy. These methods provide information for a spectroscopy model which is implemented in software and determines the charge collection efficiency.

6.2.1 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 spatial 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 software uses the SRIM [126] Monte-Carlo program to transport ions through the device. The entire process is encapsulated in a flexible Mathematica [141] framework coded to automatically run the SRIM program, generate input conditions and process output

results. 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 [126] 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 a user selectable number of ions (typically > 10000 ions).

Inspection of the device fabrication masks for the small diode array as provided in Appendix A identifies 5 regions of differing overlayer construction and SOI thickness. Figure 6.8 shows the cross-section associated with the various regions and the location of each region on the device. Figure 6.9, for the $10 \times 10 \mu\text{m}^2$, diode and Figure 6.10, for the $100 \times 100 \mu\text{m}^2$, diode are representations 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 $2 \mu\text{m}$ in the n^+ and p^+ regions and around $1.8 \mu\text{m}$ 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 scaling down the deposition spectrum by the collection efficiency and

$$Ecol(E, x, y) = \frac{1}{C(x, y)} Edep\left(\frac{E}{C(x, y)}, Region(x, y)\right) \quad (6.44)$$

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) . That is, the energy deposition spectrum is scaled down by the CE function with appropriate normalization ($Ecol$ is a probability distribution function). Previously we mentioned that the SRIM input may consider the angular distribution of the incident ions. For simplicity, we apply equation (6.44) even for these ions. This approximation assumes a slowly varying CE and relatively small angular deviations. The CE is also assumed to be independent of depth (z). This is a reasonable assumption provided the diffusion length is much larger than the device depth dimensions. The CE may be estimated from microbeam experiments or device simulation.

The final energy spectrum excluding electronic noise is given by integrating equation (6.44) over the device area:

$$E_{total}(E) = \int_0^{y_{max}} \int_0^{x_{max}} E_{col}(E, x, y) dx dy \quad (6.45)$$

In practice equation (6.45) is calculated numerically with a spatial resolution of $0.3 \mu\text{m}$ and y_{max} and $x_{max} = 15 \mu\text{m}$. The final energy spectrum including electronic noise is given by convolving E_{total} with a Gaussian noise spectrum having a standard deviation s_n .

$$E_{totaln}(E) = \int_{E-3s_n}^{E+3s_n} E_{total}(u) \frac{\text{Exp}((E-u)^2 / 2s_n^2)}{\sqrt{2\pi} s_n} du \quad (6.46)$$

Microbeam spectroscopy will produce an image which is defined by taking the median energy of equation (6.44) for each pixel. Both microbeam and broadbeam spectroscopy may produce a spectrum given by equation (6.46).

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.

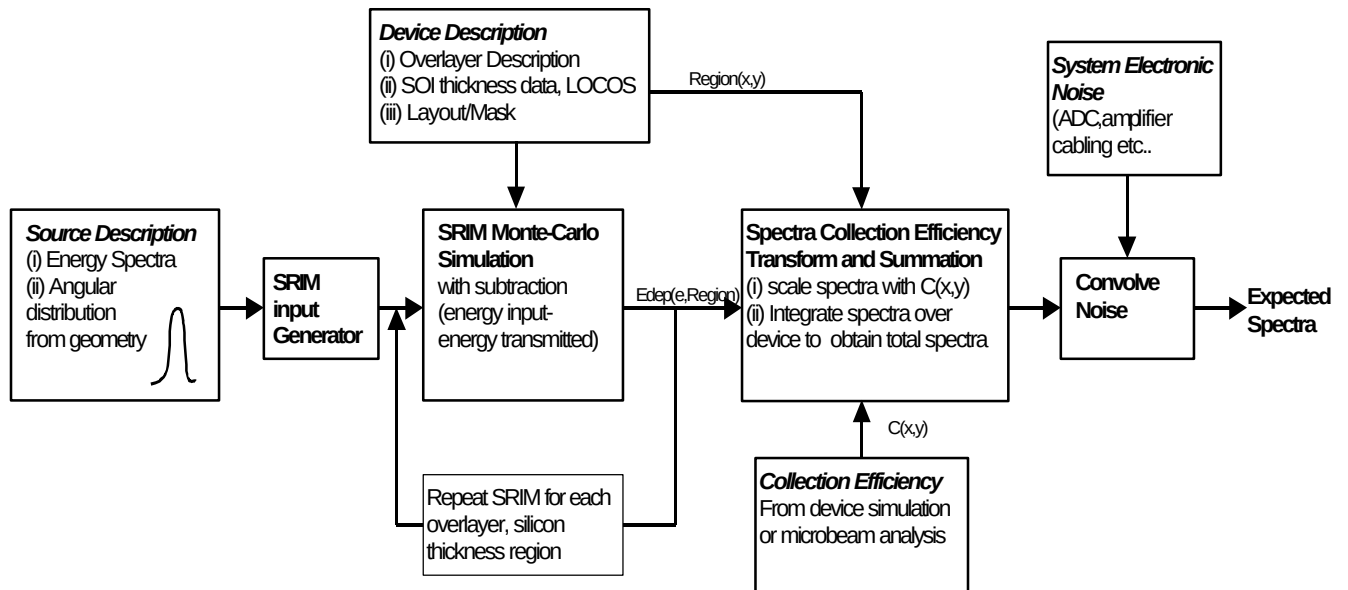


Figure 6.7. Flow diagram of spectroscopy modeling process

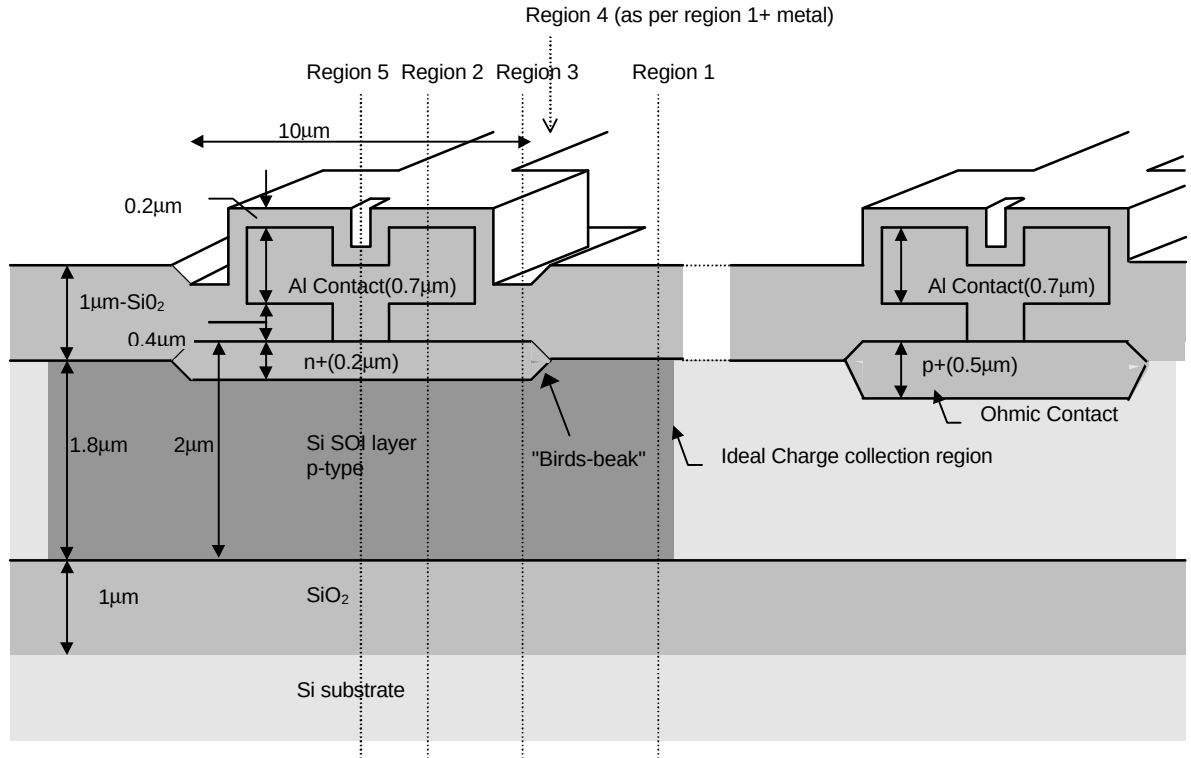


Figure 6.8. Detailed cross-section of diode array p^+ -ohmic and n^+ -junction contacts with approximate dimensions. Overlayer and SOI thickness dimensions are identified for each region shown in the plan figure below.

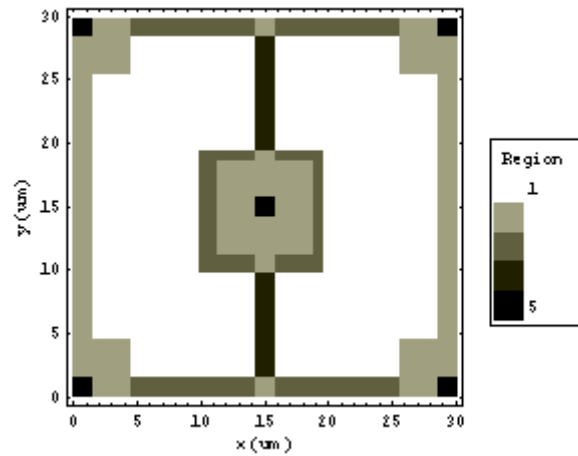


Figure 6.9. Layout of $10 \times 10 \mu\text{m}^2$ (junction area) diode cell showing location of regions whose overlayer and SOI construction is identified in Figure 6.8.

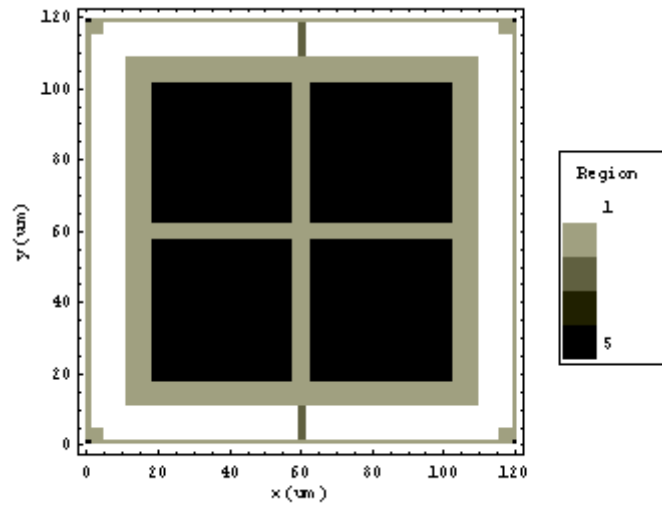


Figure 6.10. Layout of $100 \times 100 \mu\text{m}^2$ (junction area) diode cell showing location of regions whose overlayer and SOI construction is identified in Figure 6.8.

6.2.2 Numerical device simulation

Two and three dimensional numerical device simulations have been performed on the $2\mu\text{m}$ SOI, $10 \times 10 \mu\text{m}$ array using the DESSIS code [196]. The objective of the simulations was to determine the characteristics of the CE function, in particular the variation with bias and minority carrier lifetime and the effect of funneling.

6.2.2.1 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) [196]) with manufacturer mask information and process specifications directly used as provided in Appendix A. The 2D simulation considered a cross-section, referring to Figure 6.9, 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 cross-section of the $2 \times 10 \times 10 \mu\text{m}$ SOI device, constructed by the process simulator, is shown in Figure 6.11. Note the accurate formation of the LOCOS region including the characteristic "birds-beak" at each end. The top portion of the upper oxide layer was trimmed following the process simulation to reduce the simulation size.

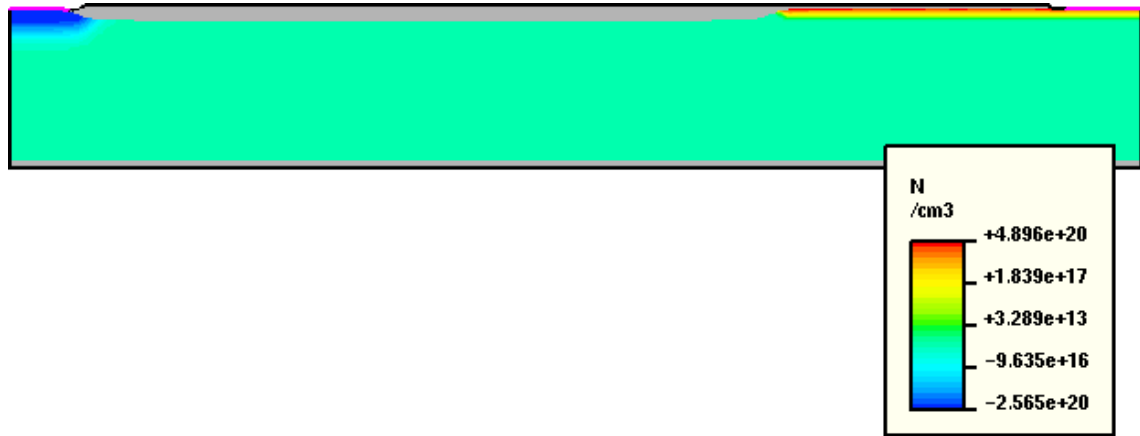


Figure 6.11. Process simulator derived 2D geometry showing doping distribution. On the scale, positive is n type and negative is p type doping. Oxide region is colored gray.

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 as described in section 6.1.1.4. Current density is expressed by the conventional drift-diffusion constitutive relations again provided in section 6.1.1.4. The numerical method employed to solve the boundary value problem involves a spatial discretization of the partial differential equations using the box method [228]. The discretized non-linear equations are solved using a fully coupled Newton method developed by Bank and Rose [196, 228].

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 $5000 \text{ cm}^2/\text{s}$, from Schroder [199]. The field dependence model for recombination was not employed since the maximum electric field was less than $3 \times 10^5 \text{ V/cm}$. The intrinsic density model used was the Bennett-Wilson model with bandgap narrowing [229]. Deviations from Boltzmann statistics due to degeneracies at high doping concentrations are treated by replacing the intrinsic concentration by an effective intrinsic concentration determined by the Bennett-Wilson bandgap narrowing model. A doping and field dependent (Caughey Thomas, equation (6.3)) 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 ions modeled were a 5.3 MeV alpha particle corresponding to a Polonium-210 alpha spectroscopy source and a 2 MeV proton typical of microbeam sources. A varying LET along the length of the path was used based on an accurate fit to SRIM [126] calculations over the 2 μm SOI region. The radial distribution of charge generation used a Gaussian model with a standard deviation radius of $r_o = 100$ nm. As seen from Figure 6.2 and Figure 6.3, the same radial profile exists for the 2 MeV proton as for the 5 MeV alpha and thus the standard deviation radius remains unchanged between these ions types. The ion strike was modeled as Gaussian in time with a characteristic decay time of 20 fs. The decay time of 20 fs is reasonable given that the maximum delta electron energy is 2.6 keV with a typical range of 135 μm for a 5 MeV alpha strike. If we assume the delta electron travels twice this distance due to scattering and that a linear range-energy relationship applies then the electron travel time is close to 20 fs.

These ion track parameters are consistent with previous simulations in the literature [222]. Note that literature estimates of track radius may sometimes quote the effective radius (radius at which carrier density corresponds to doping density) rather than a model parameter. It is important to consider the radial distribution in some detail, since the initial charge density may affect recombination rates. The gaussian radial distribution model is the only one available in DESSIS.

$$Q(r) = Q_0 e^{-\frac{r^2}{2r_o^2}} \quad (6.47)$$

Unfortunately, the gaussian profile is a poor fit to the Katz model described in section 6.1.2. The best gaussian fit to the Katz model occurs for $r_o = 2.25$ nm compared with the typical simulation value of 100 nm. The various track structure models are compared in Figure 6.12. A significantly better fit is a power-law relationship such as:

$$Q(r) = Q_0 \left[1 + \frac{r}{r_0} \right]^{-n} \quad r < 135 \text{ nm (max delta)} \quad (6.48)$$

where $n = 2.6$, $r_o = 0.35$ nm, $Q_o = 5 \times 10^{22}$ eh/cm³ for a 5 MeV alpha particle. Dussault [230] has studied the effect of track structure variations on simulation results and found a less than 8% difference in collected charge and current transient between the gaussian model and the power law model. A 100 MeV Fe ion was used with 100 nm standard

deviation radius track incident on a $p+/n$ bulk diode. This ion has a similar profile to the alpha and proton under consideration but with a much higher LET. In terms of funneling behavior, the $p+/n$ diode with a high LET ion will behave like a $n+/p$ diode with a lower LET, so we may expect Dussault's results to be broadly applicable to our case.

Note that the large gaussian radius of $r_o = 100$ nm used in the simulations severely underestimates the center track density and simulations may then underestimate Auger recombination. However, the time scale for ambipolar diffusion to attain the densities given by the 100 nm gaussian model ($5.9 \times 10^{17} \text{ cm}^{-3}$) is only about 20 ps as given by equation (6.36) and Figure 6.5 so the recombination error is not expected to be significant. Moreover, the process of ambipolar diffusion will tend to reshape the track towards a gaussian profile within this time frame.

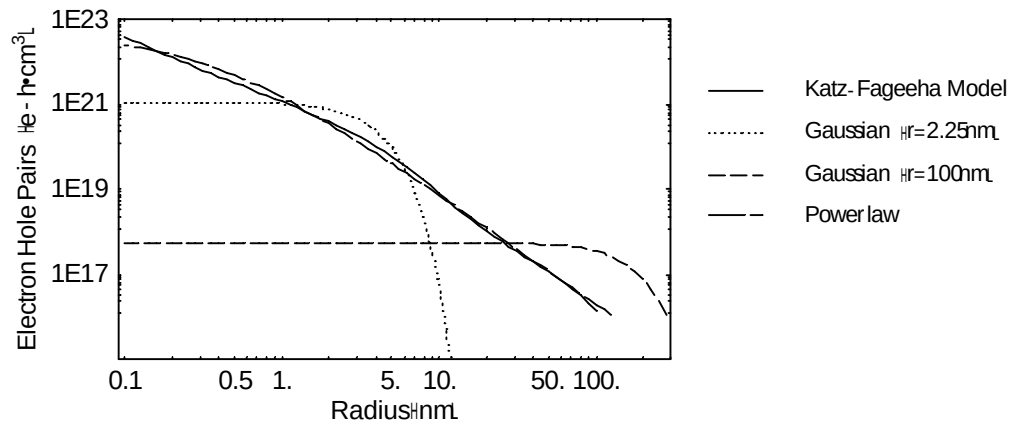


Figure 6.12. The Katz-Fageeha model for 5 MeV alpha track density compared to the Gaussian model used by DESSIS (with $r=2.25\text{nm}$ (best fit), $r=100\text{nm}$ (typical simulation)) and also compared to a power law relationship (with $n=2.6$, $r_o=0.35$ nm, $Q_o=5 \times 10^{22}$ eh/cm³). The gaussian is a poor fit whilst the power law is a good approximation to the Katz model.

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, 2000 and 20000 nodes (or vertices) were used for 2D and 3D simulations, respectively. An example 3D grid is shown in Figure 6.21. Time discretization is equally important and the time step was controlled so that at early periods in the simulation the maximum allowable step was very small, 5 fs at 100 fs, which progressively increased exponentially to 1ns at 10ns. 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. If the charge conservation conditions are not met then insufficient discretization is almost always the reason.

Note however, that one should avoid excessive discretization if possible because the simulation time varies according to $O(n^a)$ where n is the number of nodes and a is between 1.5 and 2 [223]. The 2D simulations with 2000 nodes typically take less than 30 minutes whilst the 3D simulations with 20000 nodes take over 24 hrs running on a DEC alpha processor with 1 GByte memory. Currently, a reasonable limit for such a system is 50000 nodes.

6.2.2.2 Collection Efficiency Simulations

2D simulations were performed every $0.75\ \mu\text{m}$ along the line (0,15) to (15,15) (referring to Figure 6.9), from the p^+ to the n^+ region. A 5.3 MeV alpha particle strike was modeled for each of the 21 simulations. Two different minority carrier lifetimes, corresponding to a normal device and a radiation damaged device, were simulated along with two sets of voltages (0 and 10 V). The lifetimes were calculated from proton microbeam measurements, described later in section 6.3.2. The substrate doping density for the undamaged device is $1.5 \times 10^{15}\ \text{cm}^{-3}$ whilst the radiation damaged device has a lower doping density of $1 \times 10^{15}\ \text{cm}^{-3}$. In addition, the maximum mobility was adjusted to account for radiation damage effects as discussed in section 6.3.2.

The CE was calculated for each point with the results shown in Figure 6.32. 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 [218, 219]. 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 diffusion length is long relative to the device dimensions so the exponential decay is approximately linear as shown in Figure 6.32. However, simulations were performed with shorter lifetimes that confirmed the exponential drop in CE. The onset of funneling corresponds to the transition point between the exponential decay and the constant high CE as we move

toward the junction. For example, $x = 6 \mu\text{m}$ in Figure 6.32 for the 10V unirradiated device.

The point at which funneling disappears is easily identified by observing the simulation current transients as plotted in Figure 6.13 for the undamaged device. As the strike moves closer to the depletion region (increasing x) from the p^+ contact, the collection time decreases since the diffusion distance is less. A larger current provides for a larger collected charge despite the shorter collection time. For $x \geq 6 \mu\text{m}$, the trailing edge of the current transient exhibits a "kink" corresponding to the reformation of a collapsed depletion region. Funneling begins much more rapidly for strikes ($x \geq 8 \mu\text{m}$) to the depletion region since no preceding diffusion process is required. All of these strikes have high currents at times early in the transient ($<1\text{-}10 \text{ ps}$) due to fast drift collection.

Interestingly, the fastest collection time occurs for an ion strike, $x = 9 \mu\text{m}$, through the depletion region at a point where the pre-strike electric field is orientated radially to the ion strike. Both drift and diffusion currents flow radially towards the junction; a direction that minimizes recombination, decreases collection time and enhances the reformation of the collapsed DR. In contrast, the drift flow is longitudinal and the diffusion flow radial for an ion strike at the center of the junction $x = 15 \mu\text{m}$. Thus, designing the detector with the electric field orientated perpendicular to the most typical ion direction will maximize CE.

A more detailed examination of the lateral funneling behavior was performed by considering an ion strike at $x = 7.5 \mu\text{m}$. Hole and electron density distributions along with potential distributions were generated for various simulation times as shown in Figure 6.15, Figure 6.16 and Figure 6.17, respectively. The times selected were $t = 0, 1 \text{ ps}, 100 \text{ ps}, 500 \text{ ps}, 1 \text{ ns}$ and 2 ns as identified for reference on the corresponding current transient plot shown in Figure 6.14. The DR collapse associated with funneling is most clearly recognized by consideration of the hole density distribution. The pre-strike DRB denoted by S is distinctly demarcated by the sharp transition in hole density from the substrate doping concentration to the extremely low values of the DR. For the first picosecond, little charge collection occurs as ambipolar diffusion spreads the high injection plasma track. However, after a period of tens of picoseconds, sufficient carriers have diffused into the pre-strike DR to shield previously uncompensated acceptor impurities and generate DR collapse as described in 6.1.3. (Note that the

surface S is only about $0.8\ \mu\text{m}$ from the ion strike and one may use equation (6.36) to determine the approximate diffusion time). The quasineutral region electric field, characteristic of funneling, is clearly evident in the voltage distribution plots for times greater than 100 ps (but less than 2 ns). The maximum collapse of the DRB ($1.2\ \mu\text{m}$) occurs at 500 ps as given by the hole density distributions. Shortly after 1 ns the reformation of the DRB begins when the opposing hole diffusion current from the quasi-neutral region has dropped, electric fields are restored and low level injection conditions begin to apply. Almost all of the charge collection occurs during the funneling process. The CE plot ($= Q(t)/Q_{\text{deposited}}$) of Figure 6.14 indicates that only 10% of charge is collected after 1 ns so post funneling diffusion is minimal.

Finally, one should mention an interesting effect not previously seen in the literature that appears in the voltage distribution plots. The potential drops to $-4.8\ \text{V}$ in the potential distribution at 1 ps. During ambipolar diffusion quasineutrality is not perfect which means that the electron density may still deviate from the hole density by small amounts [217]. At high carrier concentrations, this is sufficient to generate electrostatic fields and the unusual potential effect seen in this simulation. The effect disappears as the plasma density drops.

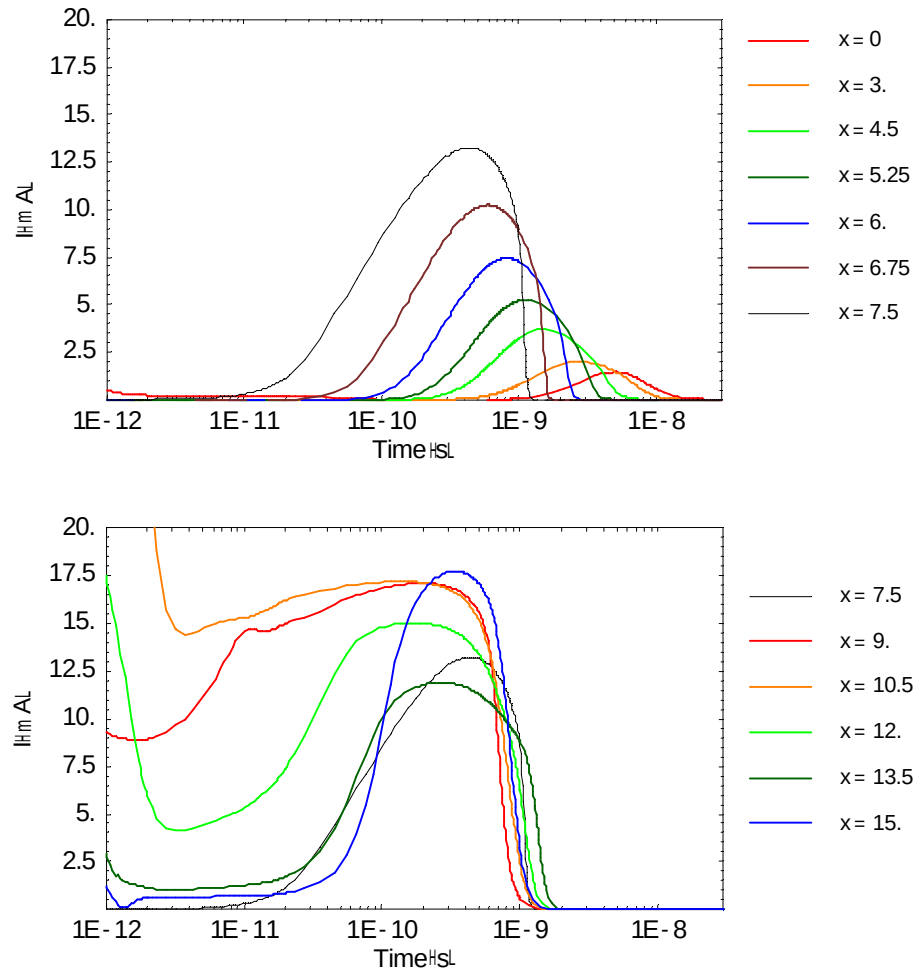


Figure 6.13. 2D simulation: Current Transient generated by a 5.3 MeV alpha particle traversing the 2D geometry given by Figure 6.11 at various distances x from the p+ contact edge of the simulation. Diffusion dominates from $x=0$ to 6-6.75 μm . For $x>6.75$ -15 funneling charge collection is present.

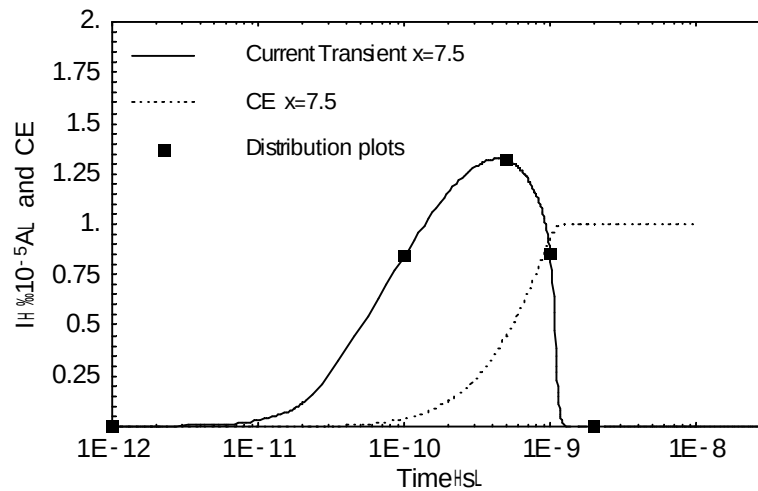


Figure 6.14. Current Transient at $x=7.5$ μm (conditions as for Figure 6.13) showing the points at which distribution plots have been made as shown in Figure 6.15, Figure 6.16 and Figure 6.17. Also shown is the collection efficiency CE as a function of time.

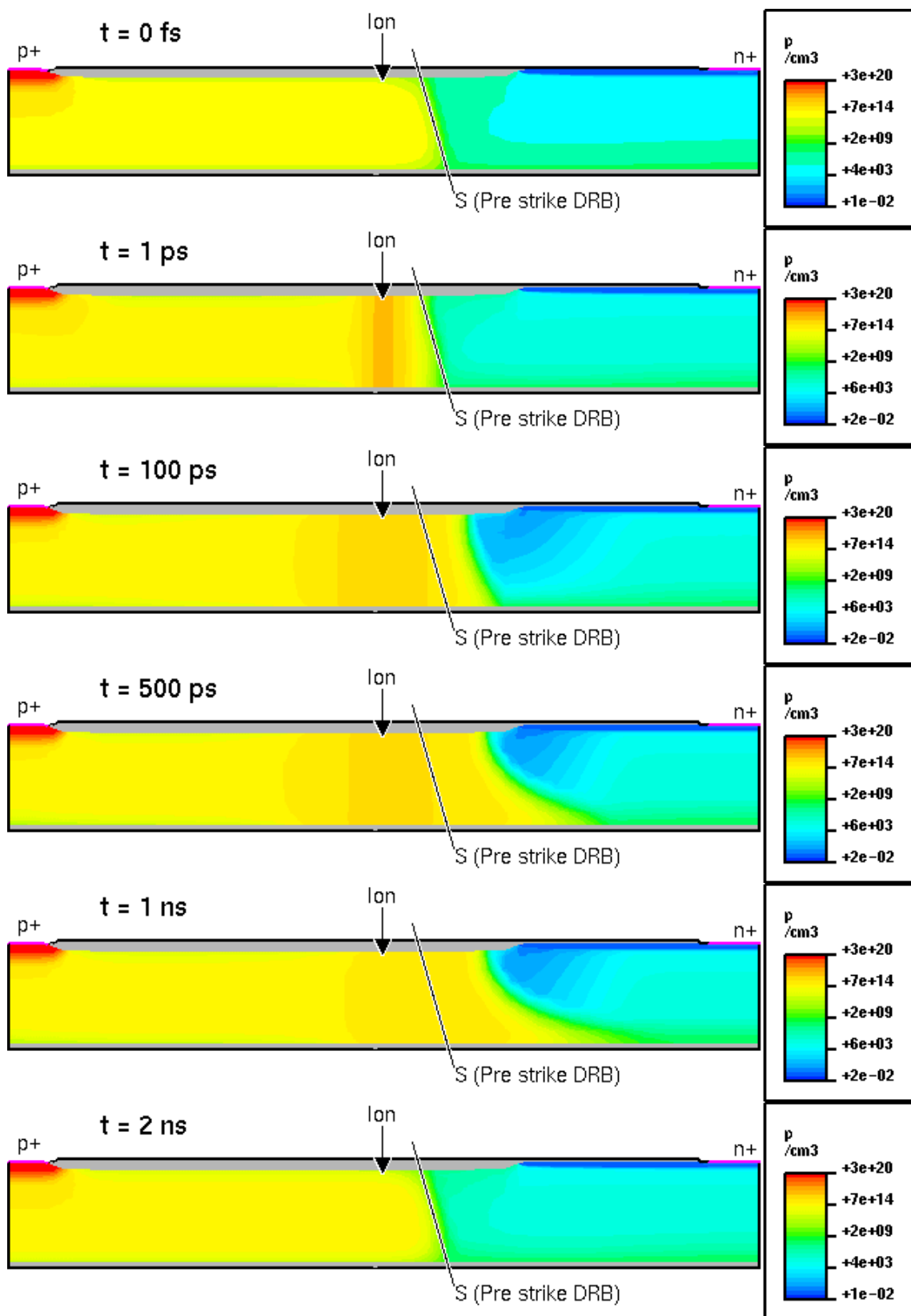


Figure 6.15. Hole density distribution for a 2D 5.3 MeV alpha particle transient simulation. Diode is the $10 \times 10 \mu\text{m}$ junction size on $2 \mu\text{m}$ SOI substrate. The boundary denoted by S is the pre-ion strike (0 fs) depletion region boundary defined by the sharp transition in hole density.

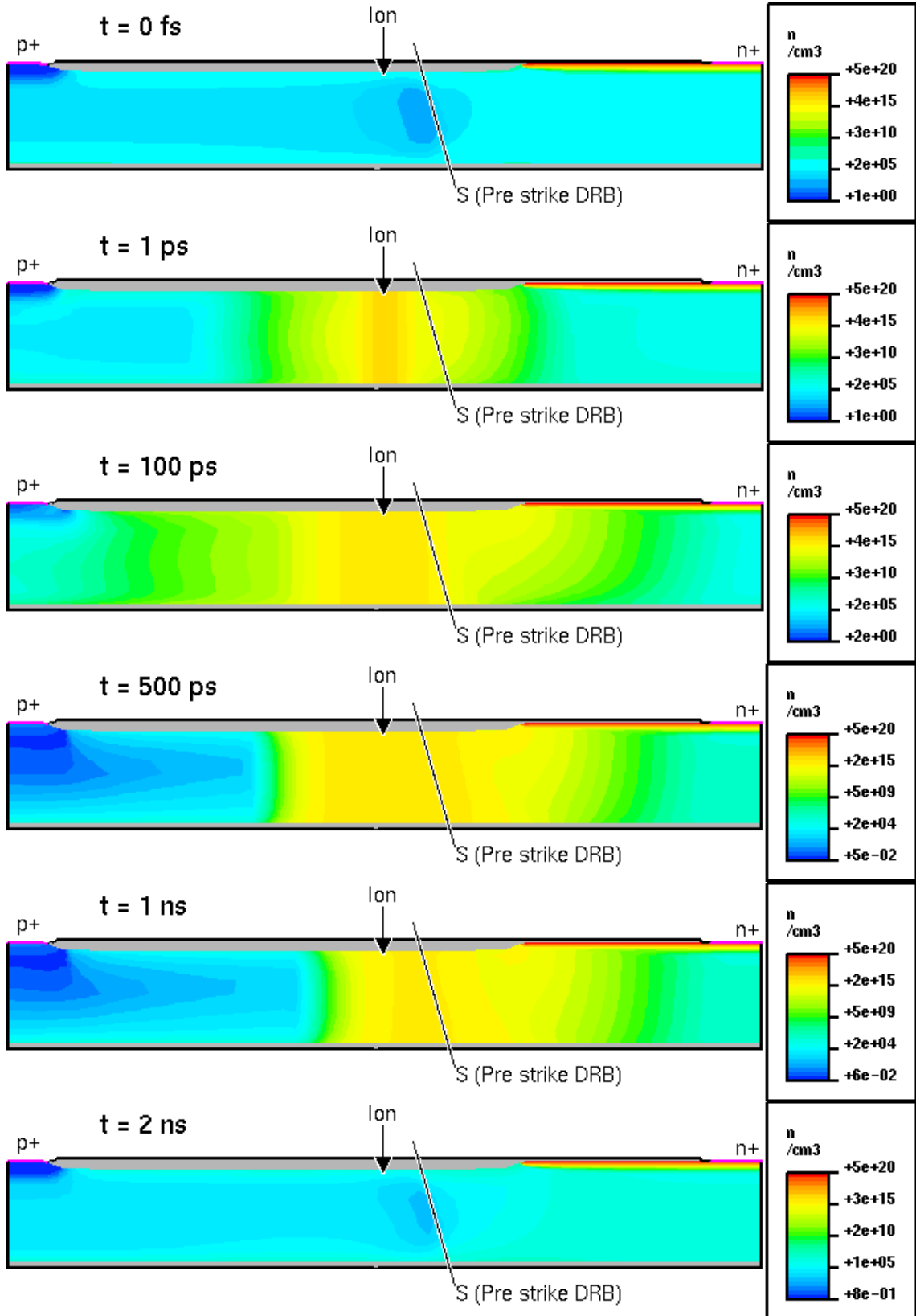


Figure 6.16. Electron distribution for a 2D 5.3 MeV alpha particle transient simulation. Diode is the $10 \times 10 \mu\text{m}$ junction size on $2 \mu\text{m}$ SOI substrate. The boundary denoted by S is the pre-ion strike depletion region boundary defined by the hole density distribution (see Figure 6.15).

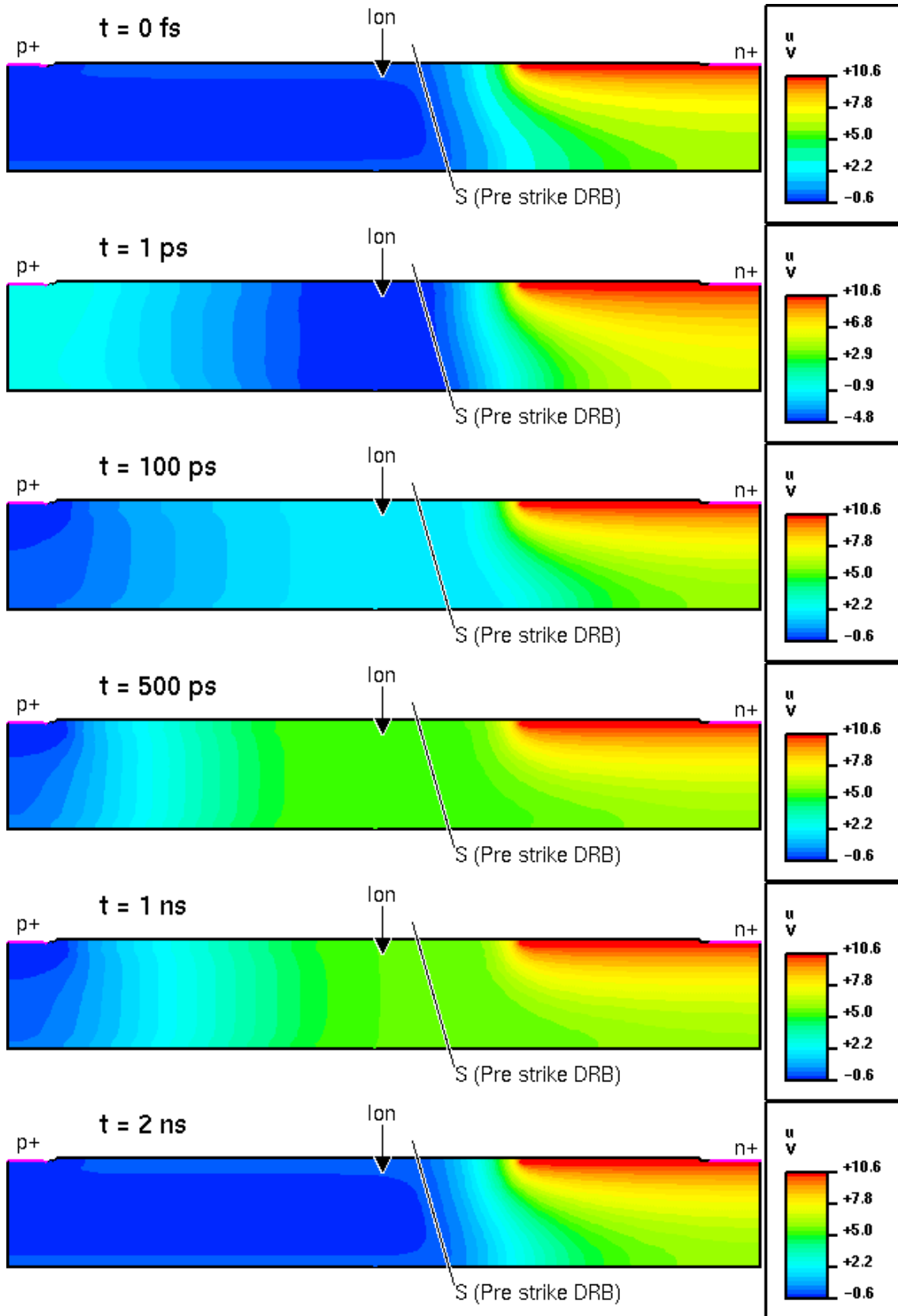


Figure 6.17. Potential distribution for a 2D 5.3 MeV alpha particle transient simulation. Diode is the $10 \times 10 \mu\text{m}$ junction size on $2 \mu\text{m}$ SOI substrate. The boundary denoted by S is the pre-ion strike depletion region boundary defined by the hole density distribution (see Figure 6.15). Note that the potential includes built in voltage and contact potentials, hence a range >10 V.

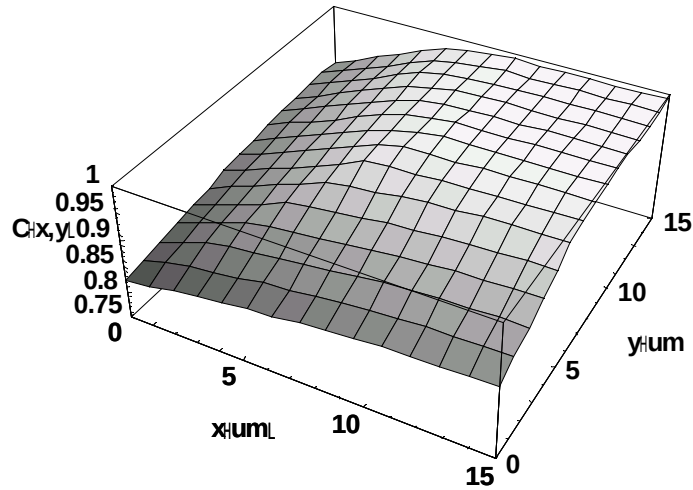


Figure 6.18. An example collection efficiency function with the parameters ($L=55$, $(x_f, c_f) = (5, 0.97)$ and $(x_d, c_d) = (9, 0.99)$) derived from 5.3 MeV alpha broadbeam measurements of section 6.2.4.1. One quarter of the diode is shown with coordinates corresponding to the layout of Figure 6.9.

Following these results, the CE 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. 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 .

$$\begin{aligned}
 C_{2D}(x) &= c_f e^{(x-x_f)/L} & 0 \leq x < x_f \\
 & a_2 x^2 + a_1 x + a_0 & x_f \leq x < x_d \\
 & c_d & x_d \leq x < 15
 \end{aligned} \tag{6.49}$$

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

$$\begin{aligned}
 C_{3D}(x, y) &= C_{2D}(10) = c_d & 10 \leq x \leq 15 \\
 & & 10 \leq y \leq 15 \\
 & c_d & c_d > 10 \\
 & C_{2D}(10 - d1) & \text{else where}
 \end{aligned} \tag{6.50}$$

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 CE function is shown in Figure 6.18.

It is important to point out that the 3D CE 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 CE 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 Figure 6.19 and Figure 6.20. Note that the SOI is fully depleted at this bias level and funneling is not evident. Additional 3D simulations would be useful in order to calculate an improved CE function, although these are extremely time consuming. The comparison of simulation results with experimental results is discussed further in sections 6.2.3 and 6.2.4.

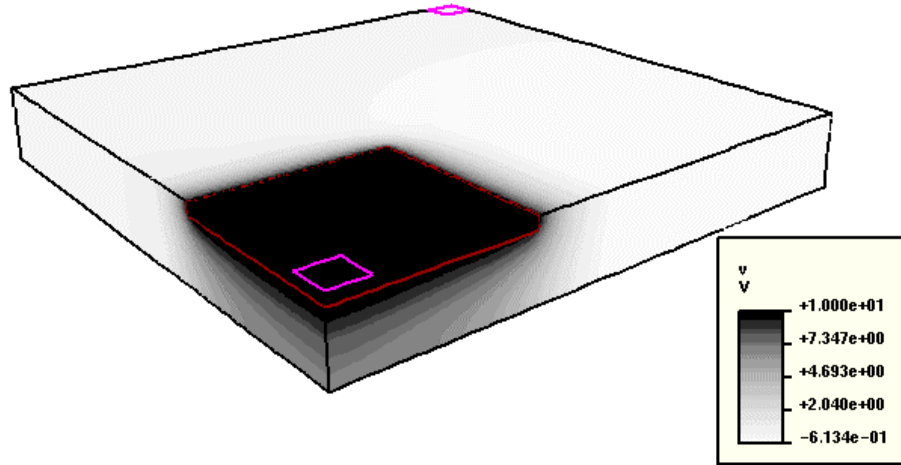


Figure 6.19. Voltage distribution for 2μm SOI device, 100ps after 5.3MeV alpha strike at $x=3.5, y=15\mu\text{m}$. (1/4 of device is shown, $15\times 15\times 2\mu\text{m}$, center of diode is nearest to viewpoint).

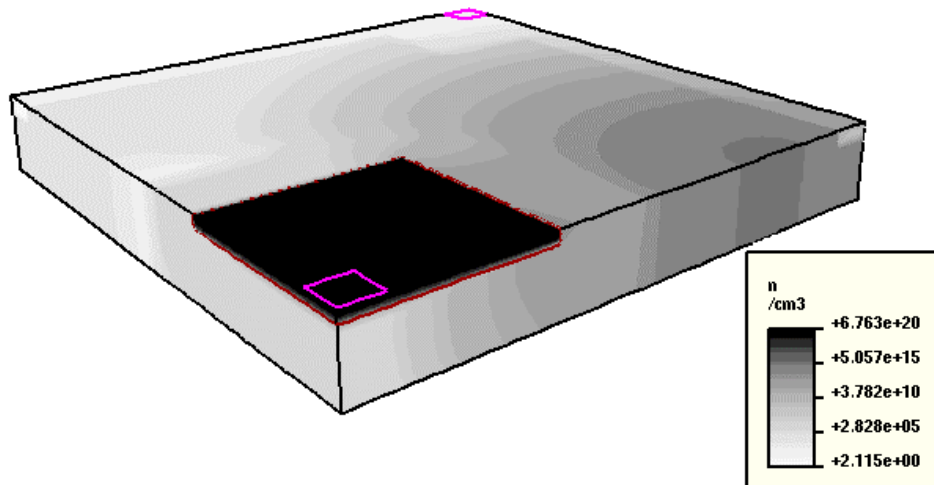


Figure 6.20. Electron density for 2μm SOI device, 100ps after 5.3MeV alpha strike at $x=3.5, y=15\mu\text{m}$. (1/4 of device is shown, $15\times 15\times 2\mu\text{m}$, center of diode is nearest to viewpoint).

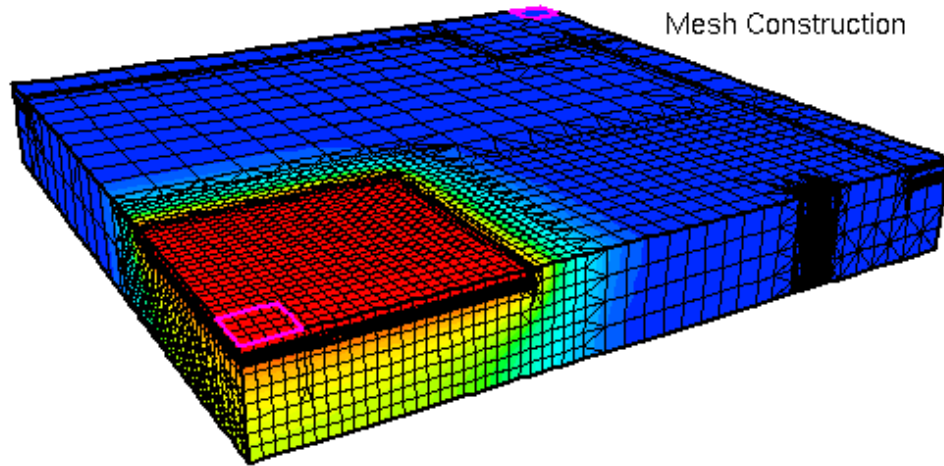


Figure 6.21. Mesh construction used for the 3D simulation of a 5.3MeV alpha strike at $x=3.5, y=15\mu\text{m}$. with voltage distribution also shown. 20000 vertices are required with refinement in high doping, depletion region and alpha strike region.

6.2.2.3 Comparison of alpha and proton funneling in the $100 \times 100 \mu\text{m}^2$ bulk diode.

Later calculations of minority carrier lifetime given in section 6.3.2 use a model that assumes negligible funneling and charge collection dominated by diffusion. The model uses data from experiments performed on the $100 \times 100 \mu\text{m}^2$ bulk diode using a 1-3 MeV proton microbeam. Protons have a lower LET and are expected to produce smaller degrees of funneling than the higher LET alpha. The aim of this section is to check the assumption that funneling is negligible for a proton strike to the junction center of the $100 \times 100 \mu\text{m}^2$ bulk diode. A comparison with a 5.3 MeV alpha strike is also provided.

The 2D simulation considered a cross-section of the $100 \times 100 \mu\text{m}^2$, referring to Figure 6.10, along the line (0,60) to (60,60). The thickness of the bulk device was taken to be $300 \mu\text{m}$. The ion strike was along the right edge of the simulation region. The current transients associated with the ion strikes are compared in Figure 6.22. The voltage potential and electron density distributions at 1 ps and 1 ns are shown in Figure 6.23 and Figure 6.24 for the proton and alpha, respectively. The electron distributions are useful for indicating the track size and injection levels. The injection levels at the center of the alpha track are an order of magnitude higher than the proton and the total charged deposited is 2.65 times higher. The proton voltage distribution shows a small funnel formation at 1 ps which is quickly restored and not evident at 1 ns. This contrasts markedly with the alpha voltage distributions that show classical funnel shaped equipotentials at 1 ps and significant depletion voltage collapse across the entire substrate by 1 ns.

The current transient response of Figure 6.22 shows an early peak at around 3 ps. This behavior has been previously noted by Dussault [230]. During the first few picoseconds the funnel collapse process is occurring; holes are beginning to screen negative acceptor ions in the depletion region and electrons are moving upwards predominantly via drift. The depletion region electric field still exists to some extent to assist charge collection. The depletion region collapse, formation of funnel-like equipotentials and movement of the potential distribution into the substrate occur in the first few picoseconds (see Figure 6.24 at $t = 1$ ps). Once the depletion region is completely collapsed then the collection current drops since drift is temporarily suspended. This accounts for the drop in current after 3 ps for the alpha transient of Figure 6.22.

The charge collection time for the proton is shorter than for the alpha even though the proton track is longer and minority carrier diffusion is the dominant charge collection process for the proton. Again, the earlier description of charge collection processes (6.1.3) provides an explanation for this behavior. The DR recovery is slow for the alpha strike due to the strong hole diffusion current from the long track opposing the downward flow of holes (shielding acceptor ions) necessary for depletion region recovery.

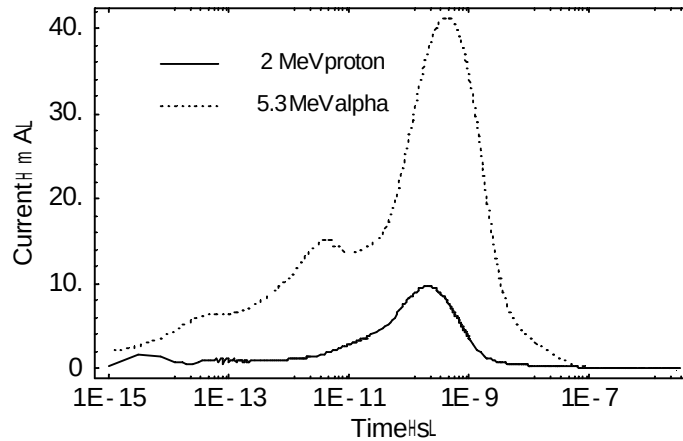


Figure 6.22. Comparison of current transient generated by 2 MeV proton and 5.3 MeV alpha particles. Device simulated was the $100 \times 100 \mu\text{m}^2$ bulk diode biased at 10 V with the ion incident on the junction center. The alpha current transient shows signs of funneling not evident in the proton response (such as the peak at 3 ps).

Proton Strike

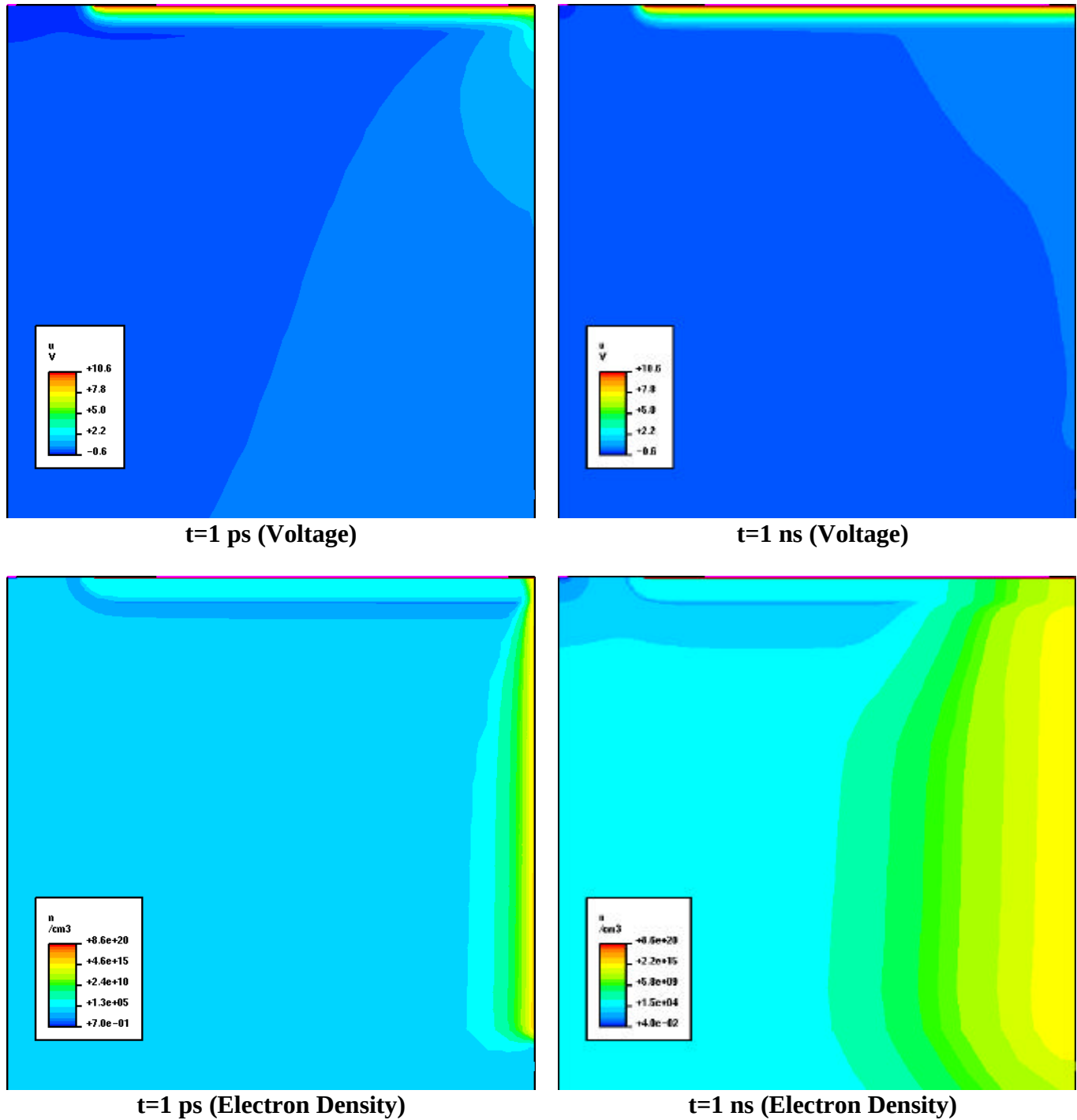


Figure 6.23. Transient 2D simulation of 2 MeV proton strike at center of $100 \times 100 \mu\text{m}^2$ (junction size) diode cell on bulk device. Strike is at $(x=60, y=60)$ referring to Figure 6.10. The reverse bias is 10V. Each image is $60 \mu\text{m}$ wide and $58 \mu\text{m}$ deep although the actual simulation was performed on a $60 \times 300 \mu\text{m}^2$ section. Use of reflective boundary conditions are used so that only half the diode cell needs to be simulated. Two different time snapshots are displayed; 1 ps (left side) and 1 ns (right side) after the proton strike. Voltage distribution is displayed in the upper images whilst electron density is displayed in the lower images.

Alpha Strike

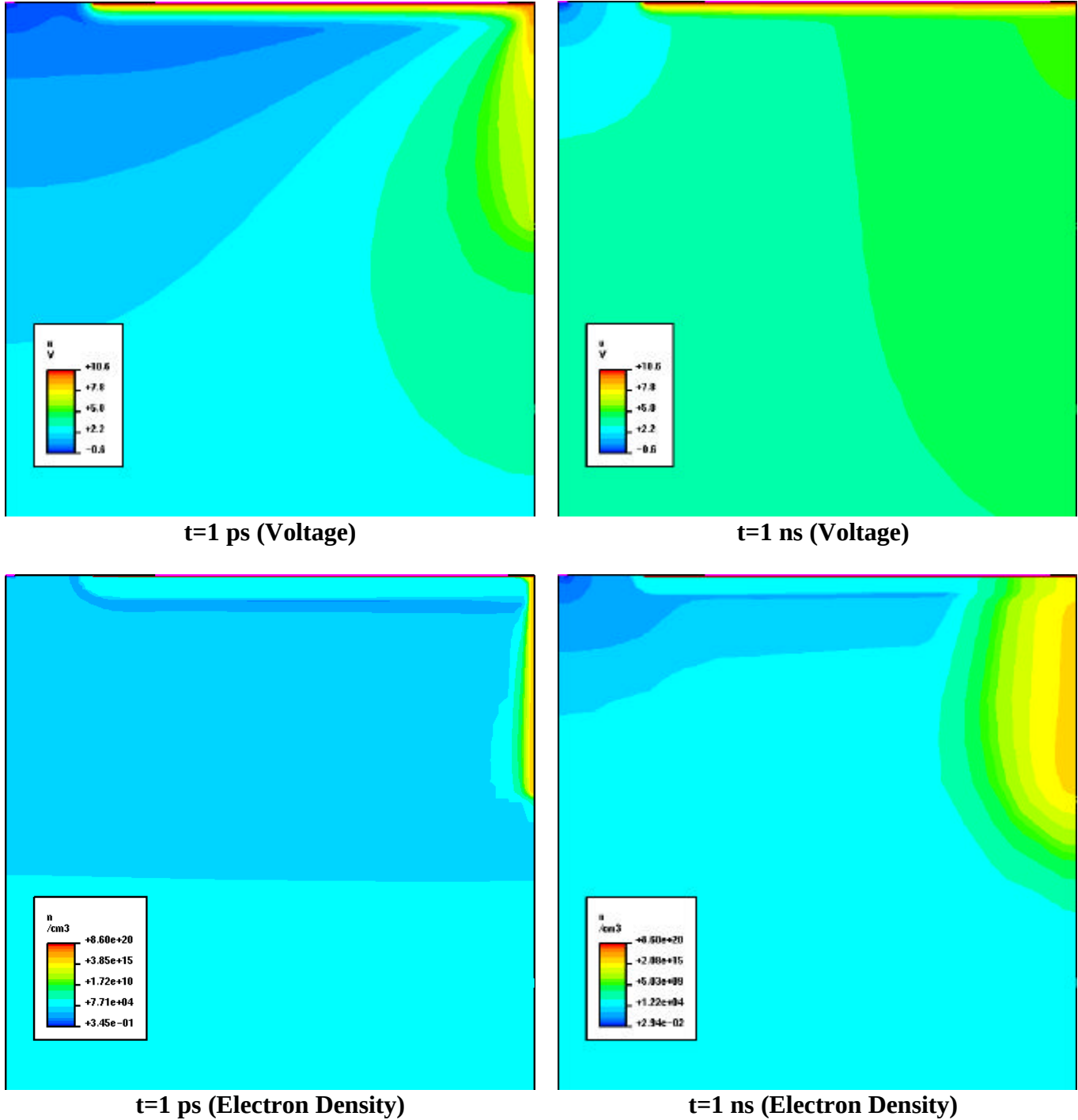


Figure 6.24. Transient 2D simulation of 5.3 MeV alpha strike at center of $100 \times 100 \mu\text{m}^2$ (junction size) diode cell on bulk device. Ion track is on the right edge. The reverse bias is 10V. Each image is $60 \mu\text{m}$ wide and $58 \mu\text{m}$ deep although the actual simulation was performed on a $60 \times 300 \mu\text{m}^2$ section. Use of reflective boundary conditions are used so that only half the diode cell needs to be simulated. Two different time snapshots are displayed; 1 ps (left side) and 1 ns (right side) after the alpha strike. Voltage distribution is displayed in the upper images whilst electron density is displayed in the lower images.

6.2.2.4 Simulation of angled BNCT alpha generated strike

The aim of this simulation is twofold; firstly to check that the CE function is independent of depth and secondly to model a typical BNCT generated alpha particle. Chapter 7 discusses in detail BNCT. A typical reaction product is a 1.75 MeV alpha particle emanating from the p+ region of the device with its high boron content. An angle of 80 degrees is assumed for this simulation although the emission is isotropic.

The CE has thus far been treated by considering normally incident ions and the CE function is assumed to be independent of depth. This assumption may be verified by simulating an angled strike. The total charge collected for the angled strike Q_{sim} is compared with the expected value Q_{est} (in fC) based on integrating the normally derived CE function over the ion range. That is calculate:

$$Q_{est} = \frac{1}{K} \left(\int_0^R \frac{dE}{dx_1} C_{2D}(x_1 \cos(q)) dx_1 \right) \quad (6.51)$$

where $C_{2D}(x)$ is the 2D simulation CE function using normally incident ions (quadratic interpolation of data from Figure 6.31 was used), x_1 is the distance along the ion track dE/dx is the ion LET as used by DESSIS, q is the ion angle and K is the conversion from keV to pC = 22.5 keV/fC.

The simulation was setup as per previous simulations discussed in section 6.2.2.1 except for the energy and angle of the alpha. The starting point for the track was 0.3 μm to minimize contact with the p+ electrode. Note that one should avoid placing ion tracks too close to electrodes in device simulations because the boundary conditions at the electrode are not good physical models for very high injection conditions (assumes local thermal equilibrium which implies quasi-Fermi potentials equal to the Fermi potential).

The estimated value from the ion strike was $Q_{est} = 69.2$ fC or 89% CE compared to the angle simulation value of $Q_{sim} = 67.8$ fC or 87%. This excellent correspondence of within 2% indicates that CE with no depth dependence is a reasonable approximation for the 2 μm SOI device. For thicker devices, with dimensions approaching the diffusion length, the approximation is not expected to be valid as CE will decrease with depth.

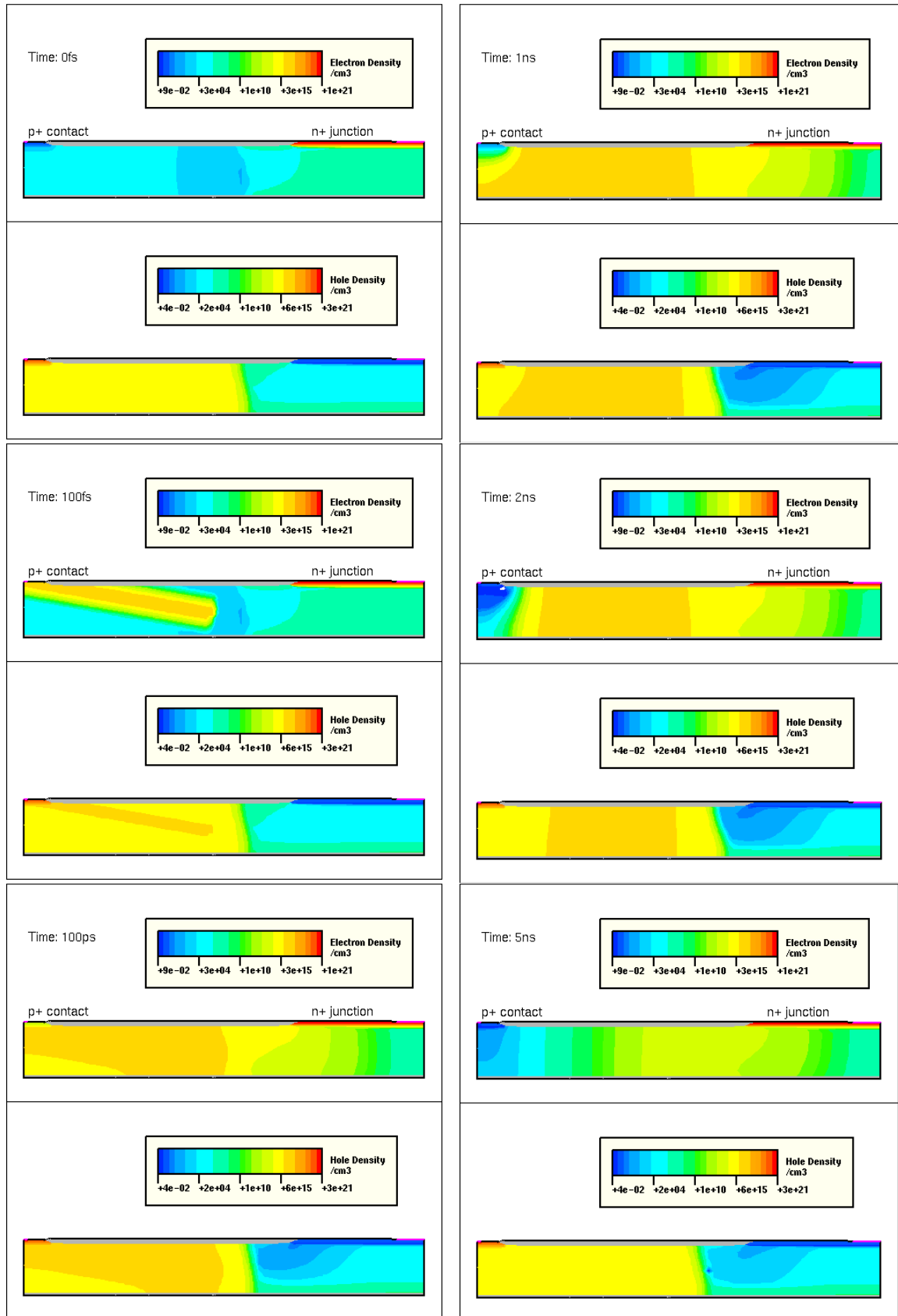


Figure 6.25. 2D simulation of an angled 1750 keV alpha particle originating from the p+ contact. Device is the $10 \times 10 \times 2 \mu\text{m}^2$ SOI diode. Electron and hole densities are shown for various. This models the recoiling alpha from a thermal neutron capture reaction with boron. See University of Wollongong web-site for dynamic GIF animation [231].

Carrier density distributions resulting from the angle simulation at various times are shown in Figure 6.25. Ambipolar diffusion proceeds until sufficient carries have diffused into the junction to create DR collapse. The collapse is not as complete as for the previously described normally incident strike at $x = 7.5 \mu\text{m}$ since the carrier diffusion is not as rapid and large.

6.2.3 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 [232, 233]. IBIC was performed on the unirradiated diodes with H, H₂ and He ion beams. A schematic of the facility is shown in Figure 6.26. 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.

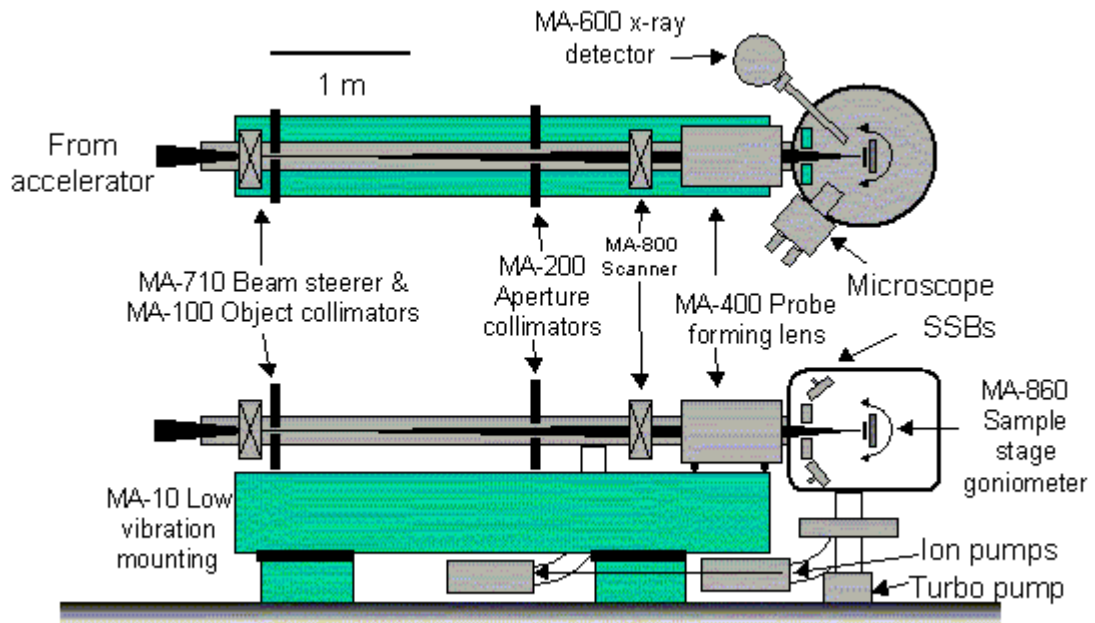


Figure 6.26. Schematic of microprobe used at the Microanalytical Research Centre, University of Melbourne, Australia.

6.2.3.1 Collection efficiency derived from complete spectroscopy model

In order to test the spectroscopy modeling software and determine the device CE function, we compare a 2 MeV alpha microbeam spectrum with the spectroscopy model for a $10 \times 10 \text{ } \mu\text{m}^2$ junction size, 2 μm SOI device. The parameters for the CE function were calculated by iterative adjustment of the model to the measured data using 2D simulation results as a starting point. Figure 6.28 compares the experimental spectrum with the model spectrum. The best fit was obtained for a constant 100% CE.

The spectra for each region, calculated using SRIM [126] and scaled according to the relative areas, are shown in Figure 6.27. Note that the spectral broadening caused by energy straggling is 30 keV. The model predicts a spectrum with two 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. 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 CE 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 (see Figure 6.8 and Figure 7.12), 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 μm . 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 13 keV with the resultant spectrum shown in Figure 6.28. The final spectrum was also filtered (Gaussian, $\sigma=5\text{keV}$ from pulsar measurements) to simulate electronic noise. Clearly, such a result highlights the inadequacy of finite-element type device simulators which do not model charge collection statistical variations versus Monte-Carlo device modeling methods [234]. However, Monte-Carlo methods are very computationally intensive and not as widely available. The remainder of this work uses the Gaussian filter as calculated above.

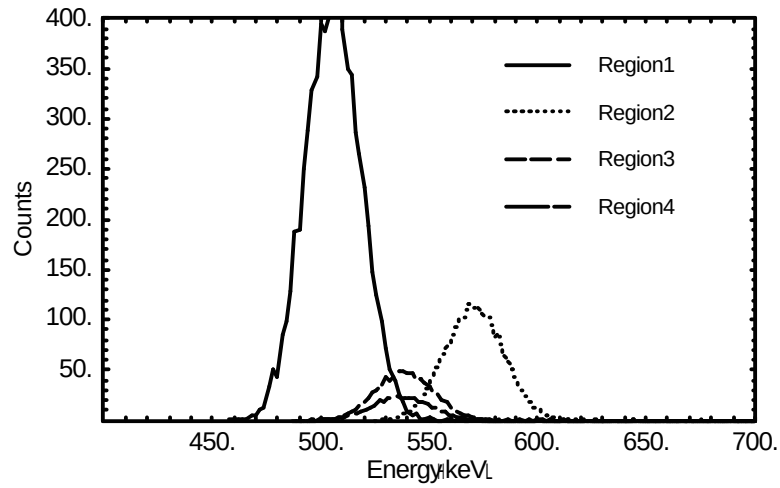


Figure 6.27. 2 MeV alpha spectra of energy deposited in the $10 \times 10 \mu\text{m}^2$ $2 \mu\text{m}$ SOI microdosimeter for the four main device regions. The spectra were calculated using the Monte Carlo transport program SRIM (10000 samples) based on the device cross-section of Figure 6.8. Scaling of the spectra counts was made according to the relative area of each region.

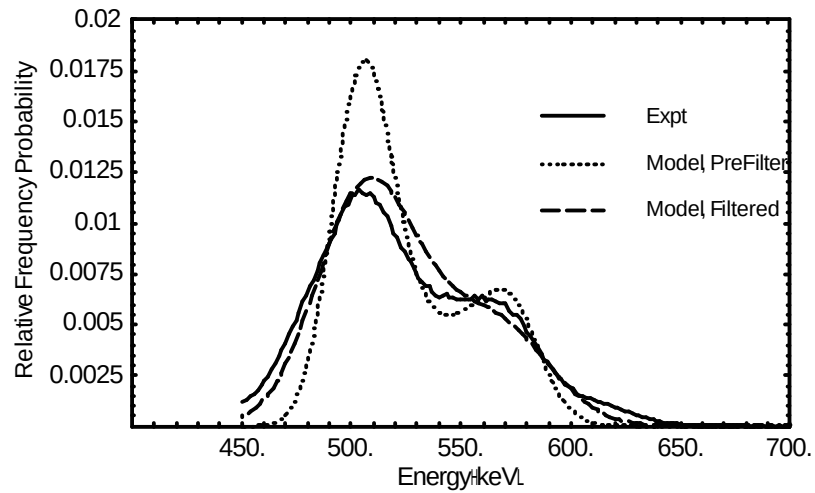


Figure 6.28. Comparison of 2 MeV alpha microbeam spectrum with spectroscopy model. The model is shown without Gaussian filtering and following 13 keV Gaussian filtering. The filtering is intended to imitate the statistics of charge collection

6.2.3.2 Collection efficiency derived from microbeam image

A microbeam image for the 2 MeV alpha is shown in Figure 6.29. The image shows the spatial charge collection information directly available from scanned microbeam methods. The CE function $CE_{mbeam}(x,y)$ may be derived directly from such data since we may calculate the energy deposited at a given position $E_{dep}(x,y)$ using knowledge of the device construction and SRIM calculations such as provided by Figure 6.27. Thus,

$$CE_{mbeam}(x,y) = E_{mbeam}(x,y) / E_{dep}(x,y) \quad (6.52)$$

where $E_{mbeam}(x,y)$ is the microbeam image data. The raw data shown by the bottom 12 cells of Figure 6.29 is obtained by taking the median average of all events traversing a given pixel location. The image data for the single diode cell may be improved further by splitting the image into 12 cells and taking the median over all the cells for each pixel. For a given cell we may use cell symmetry to produce the best possible data for a 1/4 diode by calculating the median of the four quarters with appropriate image reflections. The result calculated using Matlab software [235] has been displayed in the top 8 cells of Figure 6.29 with each cell identical. The left-hand side of Figure 6.30 shows the data E_{mbeam} for a quarter diode and the right hand side is the calculated CE_{mbeam} .

Using this method CE_{mbeam} is expected to have discontinuities at the boundaries between regions since $E_{dep}(x,y)$ is defined to have a single value in each region given by the mean of the distributions in Figure 6.27. The acquisition time was not long enough to obtain a sharper image so data at the boundaries between regions is blurred and the microbeam's effective spatial resolution is weakened. Furthermore, the calculated CE will be greater than 1 in some regions due to the image noise. Obtaining adequate image statistics was a major difficulty during experiments since great care had to be taken to avoid radiation damage of the device given the relatively large minimum beam currents at the time. Ideally, we would have preferred a system with single ion control of the beam synchronized to beam position on the device.

Nevertheless, the data is valuable qualitatively for investigating the CE within a given region. In particular the dominant region 1 shows a gradual drop in CE as we move away from the central n+ junction. This result is consistent with later broadbeam spectroscopy analysis and device simulation with the gradual drop indicating a large diffusion length in comparison with device dimensions. Given the relatively small drop it is not unreasonable that the previous section analysis derived a constant CE of 100%.

In general, the CE method proposed in this section is preferred over others due to the direct spatial information derived and well defined ion energy. However, to fully utilize the benefits of microbeam IBIC, reasonable data statistics are needed. A further improvement in this approach would be to use data from a minimum of two other alpha energies and simultaneously extract the CE, overlayer thickness and SOI thickness without any a-priori information regarding device structure. Assisting this approach is

that lower alpha energies are particularly sensitive to overlayer structures due to the sharply changing LET as a function of range (a reason the higher 2 MeV energy was used here). In addition, the range-energy and LET functions for the different overlayer materials are similar so one could assume an overlayer constructed purely of the one material (SiO_2). Equation (6.52) may be written as:

$$CE_{mbeam}(x, y) = E_{mbeam_i}(x, y, a_i) / E_{dep}(x, y, a_i, t_{ol}, t_d) \quad (6.53)$$

where a_i is the i -th alpha energy. A minimum of 3 equations (or alpha energies) is required to solve for the 3 unknowns, CE , t_{ol} the overlayer thickness and t_d the SOI thickness at each point (x, y) . E_{dep} may be calculated using range-energy or LET relationships as described later in equation (6.56) (with diffusion term removed).

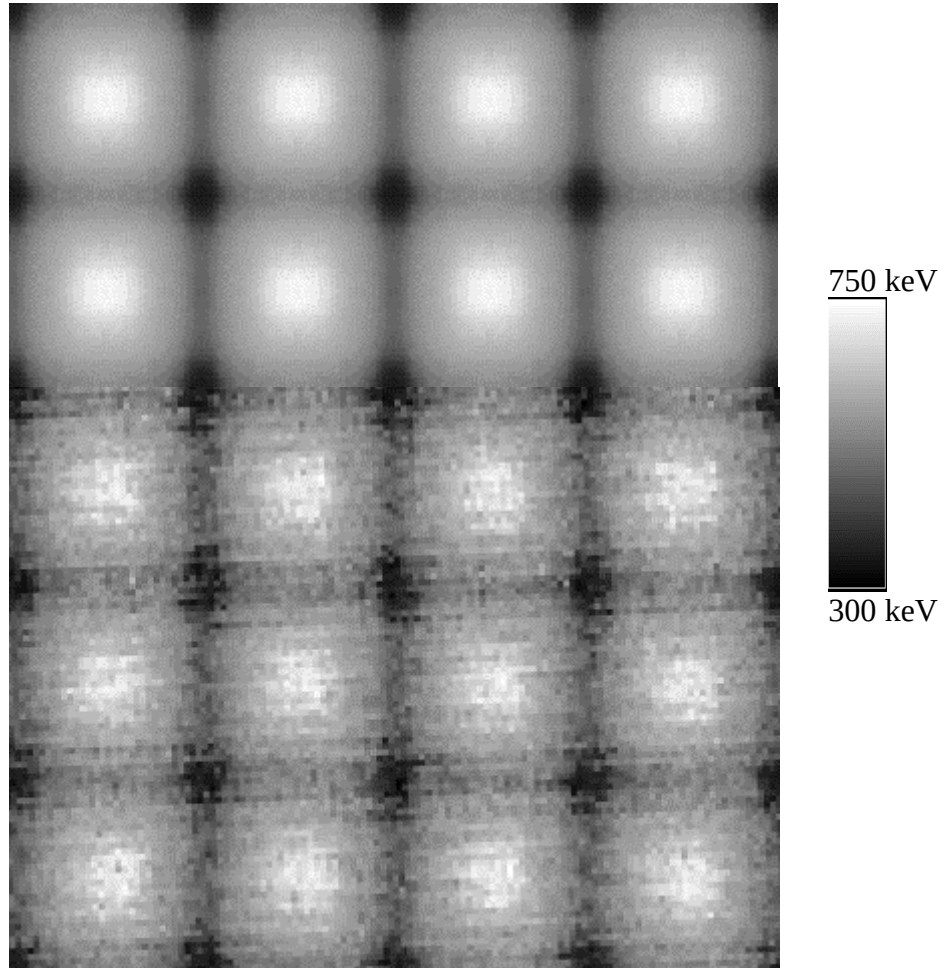


Figure 6.29. Microbeam image (2MeV alpha) of 10×10μm 2μm SOI array. Black corresponds to lowest charge collection amplitude and white is highest amplitude. The top two rows show the image following median filtering of the bottom 12 cells. The bottom image was split into 12 cells and the median over all the cells was calculated for each cell pixel.

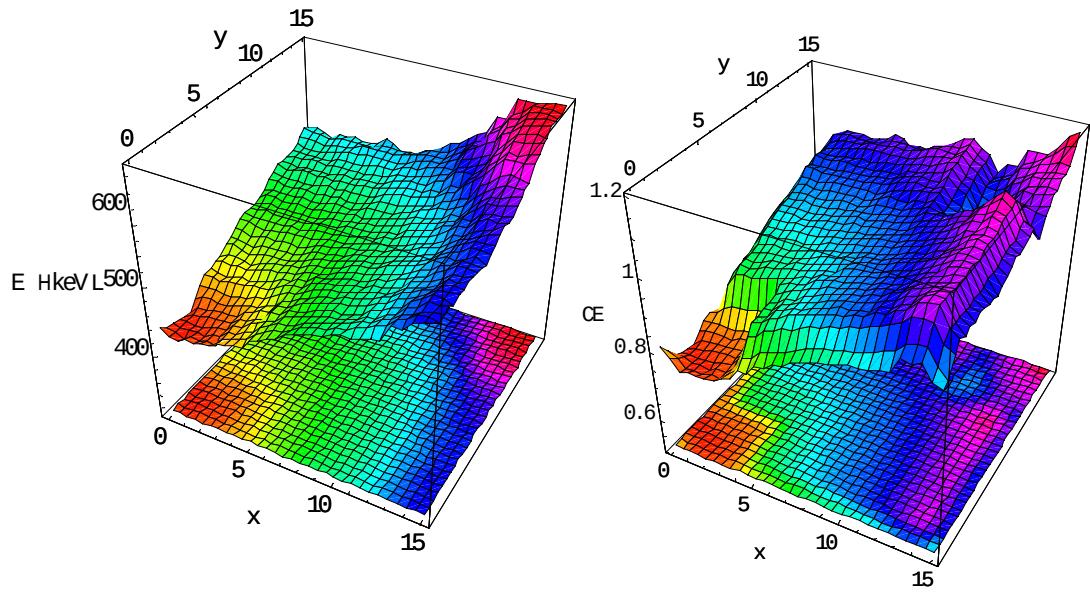


Figure 6.30. (a) Left side, processed microbeam image data for a quarter of the 2 μm SOI diode. (b) Right side, CE calculated from the data on the left using equation (6.53).

6.2.4 Broadbeam Spectroscopy

The aim of this section is to further test the spectroscopy modeling software and again determine the device CE function that provides the best comparison between experimental results and the model. A comparison with 2D device simulation results is also discussed.

Alpha spectroscopy was performed using a 7401 Canberra alpha spectroscopy amplifier which contains a vacuum chamber, preamplifier and shaping amplifier in a single module. A Po-210 (5.3 MeV) alpha source was placed in close contact with the device under test in the vacuum chamber. Energy spectra were recorded using a PC-based multi-channel analyzer (Amptek Pocket MCA8000) connected to the 7401 amplifier output. A note of caution: one should use a new good quality spectroscopy source with constant energy emission. Older sources often exhibit a low energy tail, which extends over time, possibly due to oxidation effects on the source surface. The results in this section supersedes previously published work [194] which was moderately affected by this phenomenon.

The source was placed 5 mm from the diode array. Since the diode array dimensions are 3.63×1.21 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 in section 6.2.1. The calculated energy deposition spectra

have typical FWHM widths of 31 keV composed of 2 keV due to the angle effect, 0.5 keV due to spread in the source energy and 28.5 keV due to ion energy straggling effects.

6.2.4.1 Results for $10 \times 10 \mu\text{m}^2$, $2 \mu\text{m}$ SOI, undamaged and radiation damaged

Both the damaged and undamaged devices were tested at two voltages 0 and 10V bias. Figure 6.31 compares the experimental spectra with the model spectra whilst Figure 6.32 show the CE functions used in the model spectra. The parameters for the CE function were calculated by iterative adjustment of the model to the measured data. Figure 6.32 also shows the CE calculated using 2D device simulation. The surface velocity (2000 cm/s) was adjusted to provide the best match between the CE calculated using the model and the CE calculated using 2D device simulation.

For the 10V unirradiated device the CE parameters (see equation (6.49), and (6.50), $L = 55 \mu\text{m}$, transition points (5,0.97),(9,0.998)) provide a CE with a gradual drop consistent with the relatively large diffusion length ($61 \mu\text{m}$ measured in section 6.3.2) indicated by the microbeam analysis results. Small differences between the 2 MeV alpha and 5.3 MeV alpha spectra such as a slight increase in funneling for the lower energy alpha, due to it higher LET, are not discernable using these analysis methods. Generally, the comparison between calculated spectra and experimental results shown in Figure 6.31 is excellent and the extracted CE functions may be considered to be reasonable models.

The 2D simulations, on the other hand, do not correspond well with the experimentally derived model and do not predict some of the CE features of the radiation damaged device as seen in Figure 6.32. The intention of the simulations is to provide a qualitative understanding of the basic CE function features such as the drop in overall CE with lifetime decreases and the fall in CE away from the junction region. Poor absolute correspondence occurs due to the many inadequacies of the 2D simulation.

In general, 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. Essentially, the 2D model overestimates the area of the collecting junction as seen by charge diffusing from the substrate.

The difference in 2D simulation results from the experimentally derived CE is more than one would expect from device geometrical effects, particularly at 0 V bias. The difference even extends to the depletion region where charge collection is drift dominated and rapid. With 0V bias, drift collection is relatively weak and recombination is dramatically increased as seen by the substantial drop in CE. If we increase recombination in the simulation we may obtain a drop in CE, even in the depletion region: however, the decrease in collection from lateral diffusion becomes much too large (i.e. the parameter L in equation (6.49) 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 ion track geometrical effects, either the correct total charge or the correct charge density can be simulated but not both [223, 236]. 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 [208, 211, 230]. 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. Future work should investigate 3D simulations of the irradiated device with an improved ion track model, in order to accurately investigate the effect of CCS, auger recombination, and trap-assisted Auger recombination. This requires both extensive simulation time and a revised track model provided by the software manufacturers.

The correct simulation of the radiation damaged device is particularly challenging. The simulation included the damage effects of a decrease in lifetime, decrease in mobility and change in effective substrate doping density. The large decrease in CE seen outside of the junction region may be due to the build-up of interface traps at the Si/SiO₂ interface in conjunction with the above substrate effects. The traps are formed initially by the migration of holes arising from ionization in the oxide regions. They can substantially alter the effective surface recombination velocity depending on their

charge state [199]. The simulator used (DESSIS) has a facility for introducing interface traps into a simulation. However, attempts at such simulations met with unsolved convergence problems. In summary, accurate device simulation of SOI structures requires good estimation of recombination parameters, 3D device geometry and reasonable ion track models.

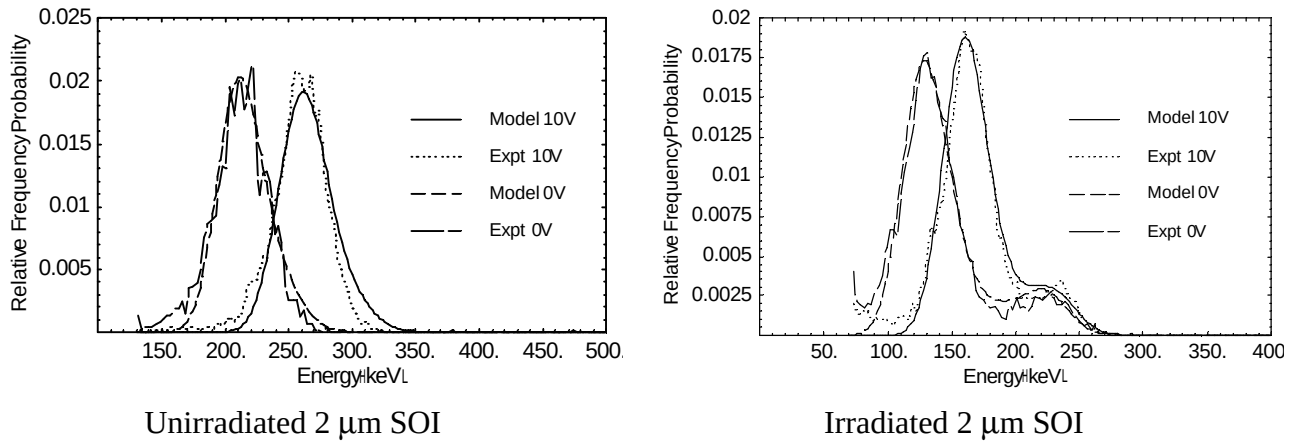


Figure 6.31. Unirradiated (left) and Irradiated (right) 2μm SOI device: 5.3MeV broadbeam alpha spectroscopy and a comparison with spectroscopy model.

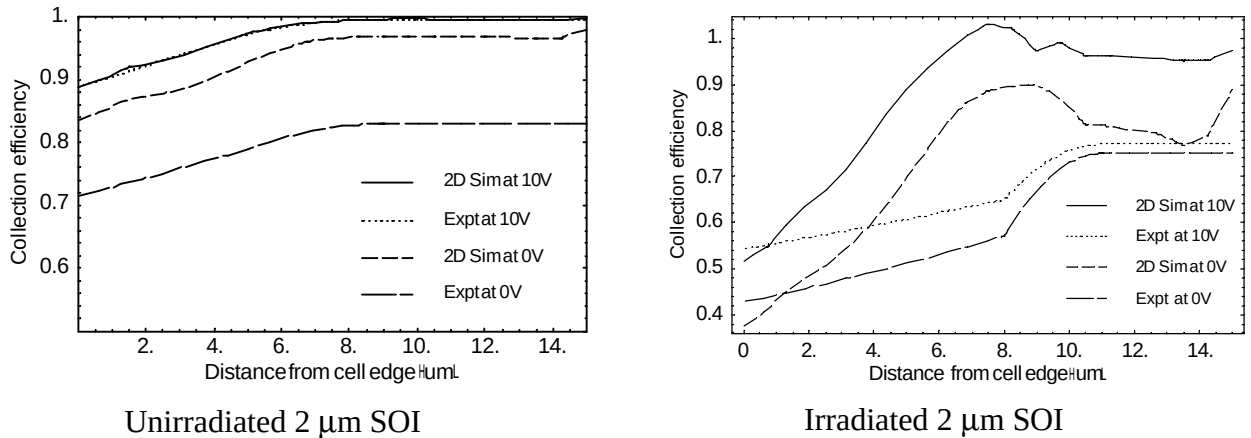


Figure 6.32. Unirradiated (left) and Irradiated (right) 2μm SOI device: Collection efficiency function derived from 5.3MeV broadbeam alpha spectroscopy (Figure 6.32) and a comparison with 2D simulation results.

6.2.4.2 Results for $10 \times 10 \mu\text{m}^2$, 10 μm SOI, undamaged device

The spectroscopy model was applied to the 10 μm SOI device since this device is used in some of the experiments discussed in later chapters. The raw and modeled alpha spectroscopy data collected at 10 V bias, and the derived collection efficiency are shown in Figure 6.33. The model is an excellent fit to the data providing confidence in the models validity. The extracted parameters are $L = 115 \mu\text{m}$ and transition points $((6,0.84),(9,0.86))$. Unlike the 2 μm SOI device, the 10 μm SOI is not fully depleted

under the junction since the depletion depth is about $3\text{ }\mu\text{m}$. Therefore, CE is 86% for ions traversing the junction due to diffusive charge collection and higher recombination below the depletion region. Additional recombination due to slow lateral diffusion creates the drop in CE as we move away from the junction. In many cases, the CE may be approximated to a constant 0.82, since the spatial variation in CE is quite small. For particles of effectively constant LET, the sensitive volume is reasonably modeled as a $8.2\text{ }\mu\text{m}$ thick slab.

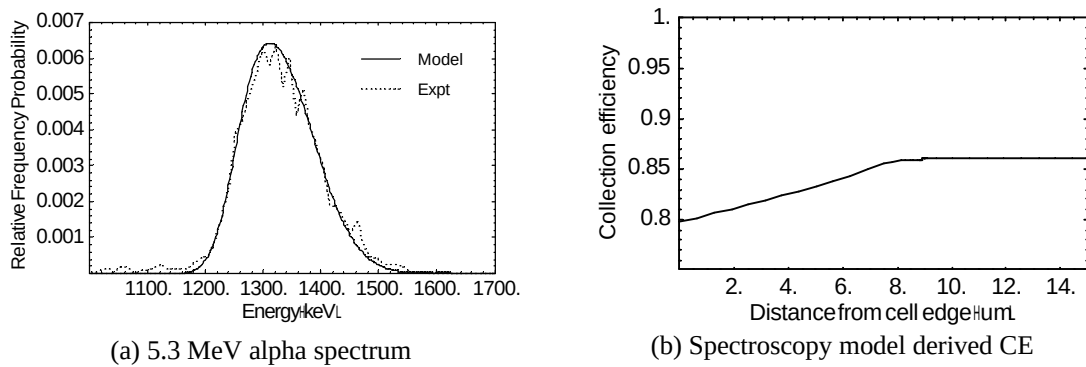


Figure 6.33. 10 μm SOI device, Collection efficiency derived from 5.3 MeV spectroscopy data. Left plot is the measured spectrum compared with the model. Right plot shows the CE function model in 2D form.

6.3 Radiation Hardness Characterization

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. 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. A brief summary of radiation damage mechanisms is provided prior to the main calculations.

6.3.1 Basic Radiation Damage Physics

The sensitivity of silicon electrical properties to radiation damage was first discovered in 1948 by Johnson and Lark-Horowitz [237]. Subsequently, many investigators have extensively studied the effect of radiation damage. Excellent summaries of the nature of the damage process and associated electrical property changes have been written [238-240]. This section will draw upon the key elements presented in these summaries to give a brief overview of the current understanding of radiation damage on silicon.

Radiation damage refers to the effect of radiation which produces atomic displacements in a crystal lattice. The first phase of the process is the collision of a high energy particle with an atom in the lattice. The displacement cross-section for neutrons impacting silicon atoms is ~ 3 barns so an incident neutron will probably undergo only one interaction before exiting the device [240]. Thus, most of the damage is actually done by the primary recoil (knock-on) atom (PKA). The PKA rapidly loses energy in the immediate vicinity of the collision due to both ionizing and non-ionizing energy losses. The displacement threshold for silicon is ~ 20 keV so the PKA can continue to produce displacements until its energy is below this threshold. Thus defects form in cascading subclusters with typically 1-3 terminal subclusters per track. Simulations and experiments have provided insight into the damage track structure [241, 242]. Most tracks are less than $1000 \text{ \AA}$ with terminal subcluster dimensions of $50 \text{ \AA}$. The first phase of the damage process ends when the PKA is at rest.

The damage produced consists of Frenkel defects (interstitial silicon and vacancy pairs) along the track and subclusters. Most of the Frenkel pairs are separated by only a few atomic spacings and have a high probability of recombination. Approximately 95% of defects are repaired immediately. The second phase of the damage process involves the diffusion of the remaining vacancies and interstitials, both of which are mobile even at liquid nitrogen temperatures. The interstitials do not appear to form electrically active defect sites which can contribute to damage effects. However, the vacancies are effective recombination and trapping sites capable of diffusing to form stable defect complexes with n-type dopants (E centers), oxygen impurities (A-center) and other vacancies (divacancies). These vacancy defect complexes are effective recombination and trapping sites and are responsible for the observed decrease in minority carrier, and reduction in majority carrier density and carrier mobility. Trapping of majority carriers reduces mobility because the trapped carriers convert the trapping center into fixed charge scattering centers. The scattering centers reduce the mobility of the remaining carriers. Both of these effects reduce material conductivity.

The changes in the electronic properties of the silicon are interpreted by the anomalous defect levels in the band-gap which are often deep levels with behavior unlike the more common shallow dopant levels which are mostly ionized. The divacancy is predominant in p-type material with a trapping and recombination center ~ 0.35 eV above the valance

band and another at mid-band level. Note that all of these defects may be annealed by elevated temperatures.

These radiation damage effects translate into significant differences in device performance. The lower lifetime results in increased leakage current and hence poorer resolution and reduced charge CE whilst the lower effective majority carrier density result in a decreased capacitance for a given reverse bias voltage.

6.3.2 Minority Carrier Lifetime Estimation

The reduction of minority carrier lifetime (τ) is given by the following equation:

$$\frac{1}{\tau} = \frac{1}{\tau_i} + kq_n \quad (6.54)$$

where k is the damage constant and θ_n is the neutron/proton fluence. This proportionality is valid up to neutron levels where the damage regions begin to overlap. An approximate estimate of the fluence where non-linear effects may appear can be made by calculating the reciprocal of the volume of the largest damage regions and applying the equation $q_{n,\max} \sim 1/(sN_aV)$ where s is the displacement cross section ($3 \times 10^{-24} \text{ cm}^2$), N_a = silicon atomic density = $0.5 \times 10^{23} \text{ atoms/cm}^3$ and V is the largest damage volume. Given that most tracks are less than $100 \mu\text{m} \times 50 \text{ \AA} \times 50 \text{ \AA}$ [242] then nonlinear effects will not occur until neutron fluence values exceed $2.5 \times 10^{15} \text{ n/cm}^2$ [240]. This is well above irradiation fluence levels considered in this study.

In order to calculate the damage constant we measure the minority carrier lifetime via charge collection spectroscopy methods as proposed by Edmonds [243]. Edmonds' model considers a planar device as shown in Figure 6.34. The upper surface of the silicon substrate is assumed to consist entirely of a depletion region acting as a perfect charge collection sink. Charge generated by ionizing particles traversing the depletion region is 100% collected by drift processes. Below the depletion region the charge collected by diffusion is given simply by the solution of the one dimensional continuity equations with appropriate boundary conditions. Thus, the charge collected Q_c by the depletion region from charge generated Q_o a distance x_1 below the depletion region is given by

$$Q_c = Q_o \text{Exp}(-x_1 / L_d) \quad (6.55)$$

where L_d is the diffusion length. Given a calibrated system, energy and charge are equivalent. Therefore, the energy collected from both the depletion region of thickness t_{dr} and substrate regions is given by

$$E_{collected} = \int_0^{t_{dr}} \frac{dE}{dx} dx + \int_{t_{dr}}^{R(E_1)} \frac{dE}{dx} e^{-\frac{x-t_{dr}}{L_d}} dx \quad (6.56)$$

where x is measured from the top of the depletion region t_{dr} is the depletion thickness given by equation 4.3, and $E_1 = E_i - \int_0^{t_{ol}} \frac{dE}{dx} dx$.

Note that the depletion region incident energy (E_1) is calculated by correcting for the overlayer thickness t_{ol} . The range of a particle with energy E_1 is given by the function $R(E_1)$.

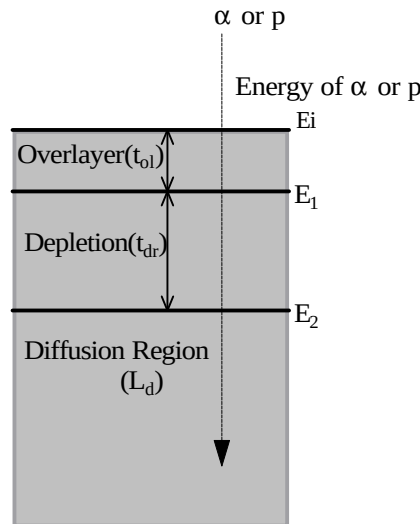


Figure 6.34. Parameters of Edmonds' charge collection model for large bulk devices.

The diffusion length L_d is calculated for various input ion energies E_i using a numerical non-linear curve fitting routine (Levenberg-Marquardt method) [141]. This routine minimizes the least square difference between the measured and calculated energy collected given by equation (6.56). Minority carrier lifetime then follows from:

$$t = L_d^2 / D_n \quad (6.57)$$

where D_n is the diffusivity of electrons in silicon ($37.6 \text{ cm}^2/\text{s}$ in pure silicon). Diffusivity is related to mobility m_n via the Einstein relation.

$$D_n = \left[\frac{kT}{q} \right] m_n \quad (6.58)$$

where k = Boltzmanns constant, T = temperature, and q = electron charge. At $T = 300\text{K}$, $kT/q = 0.026 \text{ V}$.

As mentioned previously, radiation damage may reduce mobility. Experiments by Leroy [244] indicate that the mobility of electrons in silicon is reduced linearly from $1345 \text{ cm}^2/\text{V-s}$ to $1060 \text{ cm}^2/\text{V-s}$ when exposed to 24 GeV/c protons. The linearity is observed up to $5 \times 10^{-13} \text{ p/cm}^2$ after which saturation occurs. Thus we may express the mobility (in $\text{cm}^2/\text{V-s}$) as a function of 24 GeV/c proton fluence f_p (in p/cm^2)

$$m_n = 1345 - 6.95 \times 10^{-12} f_p \quad (6.59)$$

Equation (6.55) 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 $100 \times 100 \text{ }\mu\text{m}$ bulk device operating at 10V bias since the junction/depletion region covers a relatively high proportion of chip area (75%) as shown in Figure 6.10. Deviations from complete charge collection at the upper surface result in an underestimation of diffusion length.

The above method was applied to both the irradiated and unirradiated bulk devices. The bulk devices were irradiated at CERN with 24 GeV/c protons at a fluence of $4.1 \times 10^{13} \text{ p/cm}^2$ using the CERN Proton Synchrotron (PS) T7 beam [245]. An image of the PS beam line exit is shown in Figure 6.39. Fluence measurements were performed with aluminium foils having the same area as the microdosimeter. The error in fluence measurements was estimated to be $\pm 7\%$ [246].

Measurements of charge collection were performed on the large diode array ($100 \times 100 \text{ }\mu\text{m}^2$) bulk devices biased at 10V , using 1, 2 and 3 MeV proton microbeam data. The energy collected was taken as the energy of a particle traversing the middle of the diode. The maximum error in the measured collected energy was estimated to be $\pm 40 \text{ keV}$. Figure 6.35 shows the excellent fit to the data achieved by the model and Table 6.2 gives the extracted diffusion length and minority carrier lifetime. The diffusion length was reduced from $61.4 \text{ }\mu\text{m}$ to $7.9 \text{ }\mu\text{m}$ following irradiation due to the effects of displacement damage reducing the minority carrier lifetime from $1 \text{ }\mu\text{s}$ to only 23 ns .

Also shown in Figure 6.35 are measurements for protons incident on the small diode array ($10 \times 10 \mu\text{m}^2$) bulk device under identical conditions. The junction/depletion area occupies a smaller fraction of the upper surface area in the small diode array (20%) compared with the large diode array (75%) as shown in Figure 6.9 and Figure 6.10. This reduced junction area results in a 20-30% loss of charge due to surface recombination at the upper Si/SiO₂ interface. Clearly, Edmonds' one dimensional model given by equation (6.56) is inappropriate for the smaller diode array. However, the minority carrier lifetime may still be estimated given an improved model, which accounts for the surface recombination and reduced junction area. Such a model may be derived analytically using a 3 dimensional solution of the electron continuity equations or solved numerically using a simulation package such as DESSIS. Moreover, such a model may be used to derive both the bulk lifetime and the recombination surface velocity by fitting to measurements performed on both the small and large diode arrays.

Proton microbeam measurements have significant advantages over alpha broadbeam experiments since the lower LET protons are much less susceptible to funneling (as shown in section 6.2.2.3) and the imaging method allows us to select the ion position which best satisfies the model assumptions. As a comparison, alpha broadbeam measurements were also used to extract the diffusion lengths. In this case, the depletion width was included as a fit parameter since funneling has historically been modeled by an artificial increase in the depletion width [212]. The energy collected is estimated by extracting the peak in the alpha spectrum corresponding to ion traversal through the depletion region. A Po-210 (5.3 MeV) source was placed in a vacuum with incident alpha energy varied by using thin plastic films. The results shown in Table 6.2 indicate a large difference between proton microbeam and alpha broadbeam methods (a factor of 4.3 lower) 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.

For the proton microbeam modeling, the depletion width and majority carrier density were determined from C-V measurements as per previous measurement discussed in section 4.2.2. Note that trapping levels introduced by displacement damage may reduce the majority carrier density. The decrease in capacitance due to the change in effective substrate doping is shown in Figure 6.37. The junction capacitance per unit area was calculated and corrected for stray and track capacitance (as per section 4.2.2) with the

results displayed in Figure 6.38. These measurements indicate a drop in substrate doping density from 1.6 to $1 \times 10^{15} \text{ cm}^{-3}$, which is directly reflected in the slope differences of Figure 6.38. Such a reduction will increase the depletion width following irradiation from 3.1 to $3.8 \text{ } \mu\text{m}$ (at 10V) as a shown in Table 6.2

In summary, the effects of radiation damage on reducing lifetime and majority carrier density have been measured using spectroscopy techniques and C-V measurements. The importance of using measurements conforming with the assumptions of Edmonds' model is highlighted. In particular, proton microbeam measurements on large area diodes should be used for accurate results.

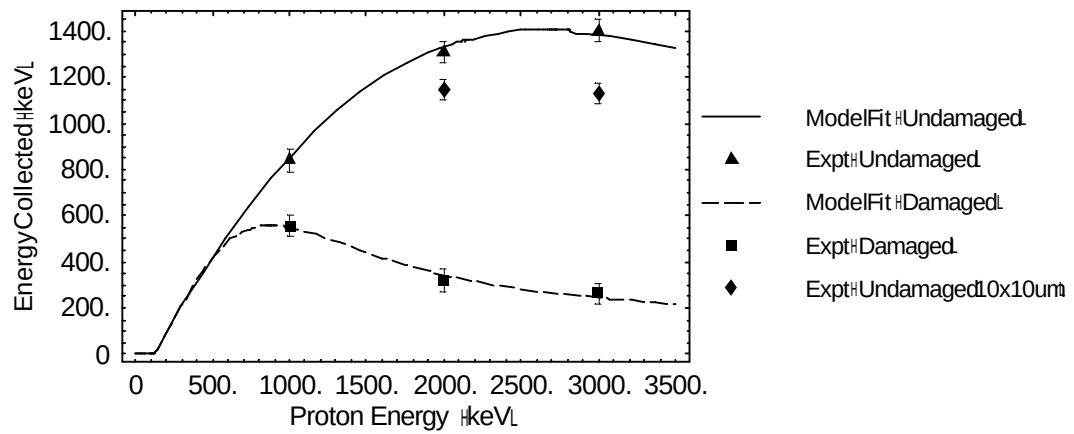


Figure 6.35. Fit of diffusion model to proton microbeam peak charge collection data. All data is for $100 \times 100 \text{ } \mu\text{m}^2$ diode size bulk devices except for the diamond which is for a $10 \times 10 \text{ } \mu\text{m}^2$ diode size bulk device.

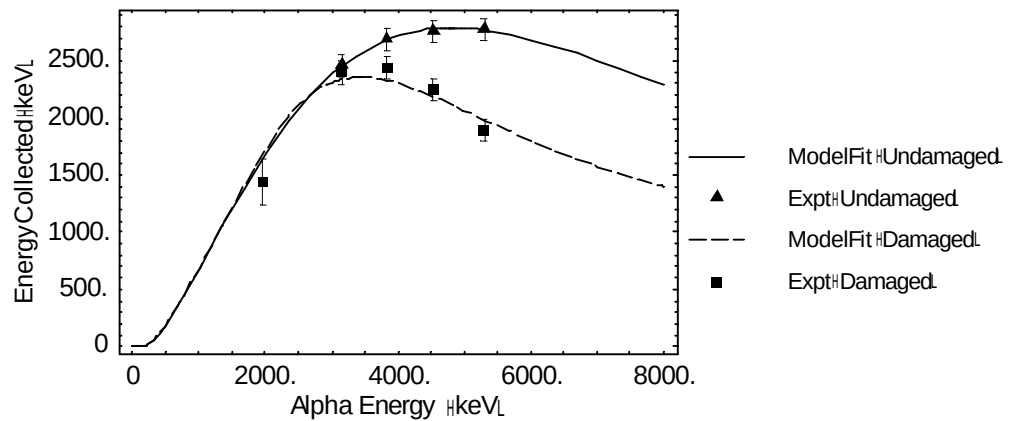


Figure 6.36. Fit of diffusion model to alpha broadbeam peak charge collection data. All data is for $100 \times 100 \text{ } \mu\text{m}^2$ diode size bulk devices. Error in energy collected is estimated at $\pm 100 \text{ keV}$ for alpha energy $> 2000 \text{ keV}$. The low energy data at 2000 keV has a larger error ($\pm 200 \text{ keV}$) due to poorer resolution of incident alpha spectrum.

Table 6.2. Lifetime parameters for damage constant estimation

	Proton μ beam			α broadbeam (Note 1)		
	Drift (μm)	L_d (μm)	τ (nsec)	Drift (μm)	L_d (μm)	τ (nsec)
Unirradiated	3.1	61.4	1080	3.9	14.3	59
Irradiated	3.8	7.9	23	5.4	6.6	16
Damage Constant	$1.5 \times 10^{-6} \text{ cm}^2/\text{n/s}$			$1.7 \times 10^{-6} \text{ cm}^2/\text{n/s}$		

Note 1: Results indicate that α broadbeam measurements are severely affected by funneling enhanced charge collection. Drift or depletion width is determined by C-V measurement data for the proton μ beam and by Edmonds model fitting for the α -broadbeam.

Note 2: The minority carrier lifetime has been calculated using equations (6.57) to (6.59) which correct for a decrease in mobility due to radiation damage.

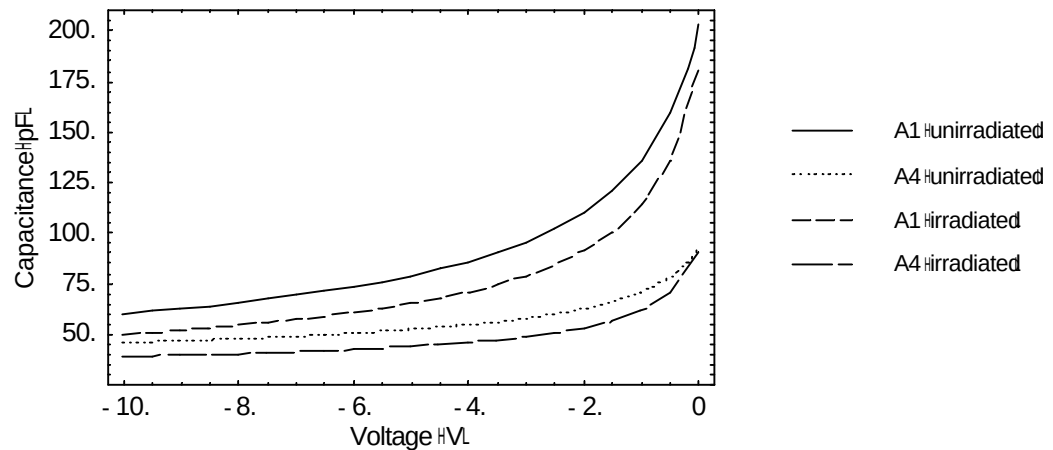


Figure 6.37. Capacitance versus voltage data for bulk devices before and after irradiation with 24 GeV/c protons at a fluence of $4.1 \times 10^{13} \text{ p/cm}^2$. Irradiation was performed using the CERN-PS-T7 beam. A1 is an array with $100 \times 100 \mu\text{m}^2$ sized diodes and A4 has $10 \times 10 \mu\text{m}^2$ sized diodes.

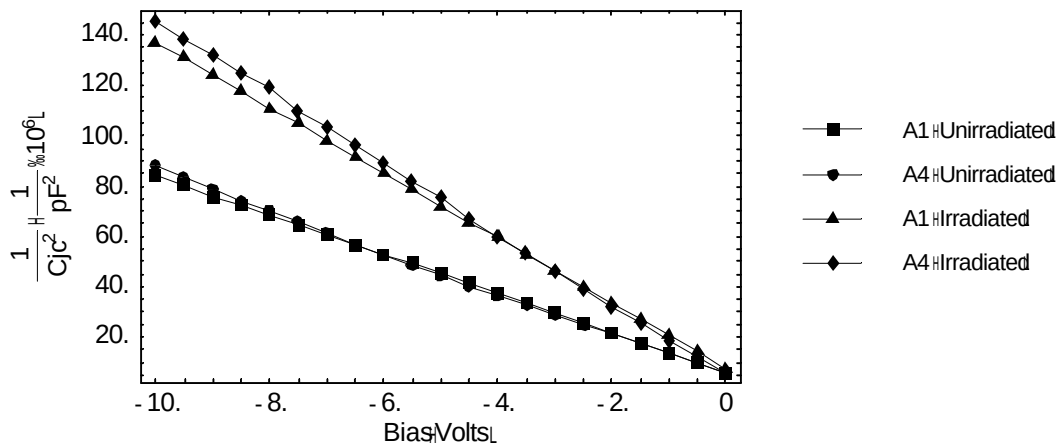


Figure 6.38. Correction Diode Array Junction Capacitance versus voltage data for bulk devices before and after irradiation with 24 GeV/c protons at a fluence of $4.1 \times 10^{13} \text{ p/cm}^2$. Irradiation was performed using the CERN-PS-T7 beam. A1 is an array with $100 \times 100 \mu\text{m}^2$ sized diodes and A4 has $10 \times 10 \mu\text{m}^2$ sized diodes. The slope of the data is related to the substrate doping density

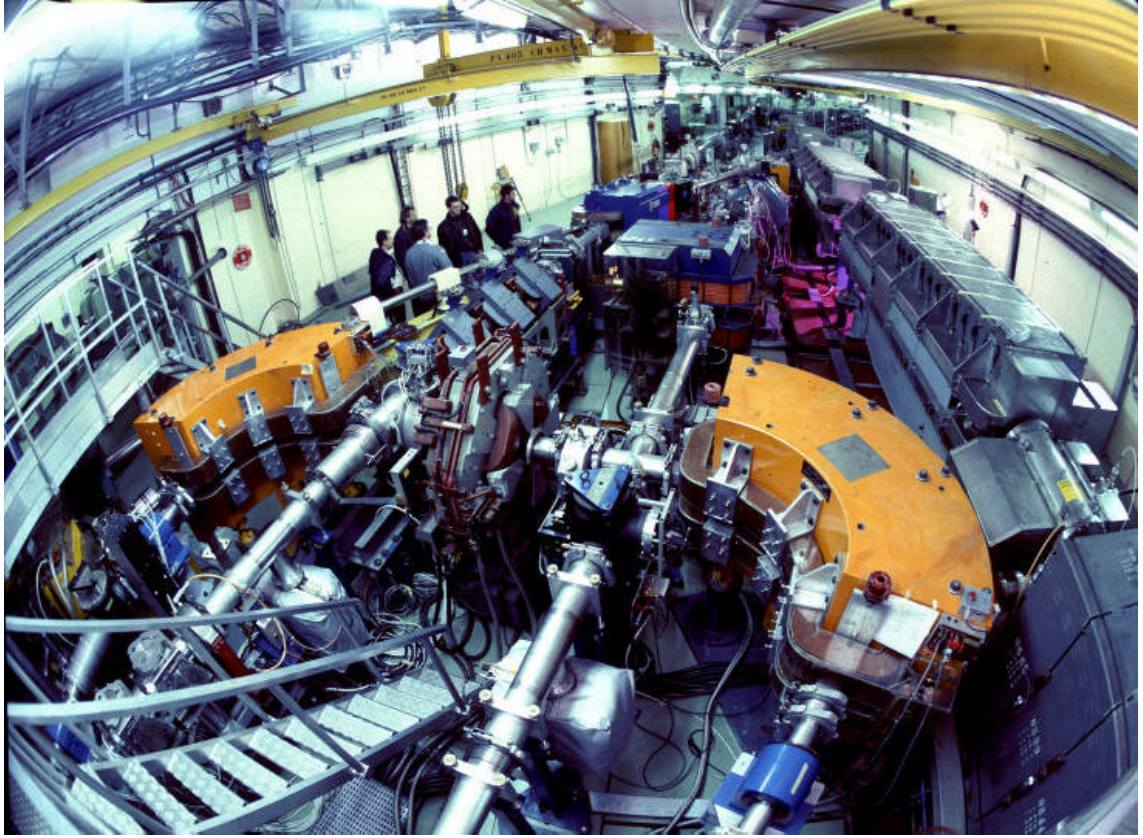


Figure 6.39. CERN Proton Synchrotron transfer lines inside the tunnel. (Photo courtesy of CERN)

6.3.3 Damage Constant

It has been demonstrated in several papers [247-249] that the displacement damage effects from a variety of particles may be correlated based on the nonionizing energy loss (NIEL). NIEL is the calculated energy loss per unit mass due to atomic displacements and does not include any energy loss to ionizing effects (i.e. creation of electron-hole pairs). The calculation of NIEL S_{di} for a monoatomic material consists of evaluating the expression [250]:

$$S_{di} = \frac{N}{A} \sum s_j(E) T_j(E) \quad (6.60)$$

where N is Avogadro's number, A is the atomic mass of the target atom, E is the energy of the incident particle, $s_j(E)$ is the displacement cross-section, and $T_j(E)$ is the average energy of the recoil atom for the j -th type of interaction .

The NIEL factor is frequently applied to normalize bulk radiation damage effects induced by various particles to that induced by 1 MeV neutrons [239, 240, 247-249]. The theoretical relative hardness of the 24 GeV/c protons, which is the ratio of the NIEL factors of the 24 GeV/c protons to that of 1 MeV neutrons is approximately 0.5-0.7

from [247, 248]. Note that the displacement cross-sections are 65.15 MeVmb for 24 GeV/c protons and 95 MeVmb for 1 MeV neutrons [251] which provide a similar ratio.

Using the proton microbeam data for the 100×100×bulk large diode array (Table 6.2) applied to equation (6.54) we obtain the 24 GeV/c damage constant as $K_{24\text{GeV/c}} = 1 \times 10^{-6} \text{ cm}^2/\text{n-sec}$. Applying the NIEL factor of 0.7 gives a final 1 MeV neutron equivalent damage constant of $K_{1\text{MeV}} = 1.5 \times 10^{-6} \text{ cm}^2/\text{n-sec}$. This result is in reasonable agreement with damage constants estimated by Messenger and Ash [239] assuming high injection ratios. The variation of diffusion length with equivalent 1 MeV neutron fluence is shown in Figure 6.40. Note that diffusion length is closely linked to CE. Given that 1 cGy is approximately equivalent to $4.1 \times 10^8 \text{ n/cm}^2$ (1MeV neutrons) [252] and assuming 100 cGy per patient treatment, then we may expect a 10% change in diffusion length after 3.4 treatments. This is a reasonable result given the low cost of each device and the possibility of using shorter exposure times during phantom measurements. Future devices may be designed to minimize radiation damage effects by operating the entire sensitive volume in a fully depleted mode and by using a smaller sensitive volume with faster collection times.

Bulk devices were also irradiated at the Australian Nuclear Science and Technology Organization (ANSTO) using 1MeV 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 40%. We can conclude that the damage constant calculated above is quite conservative.

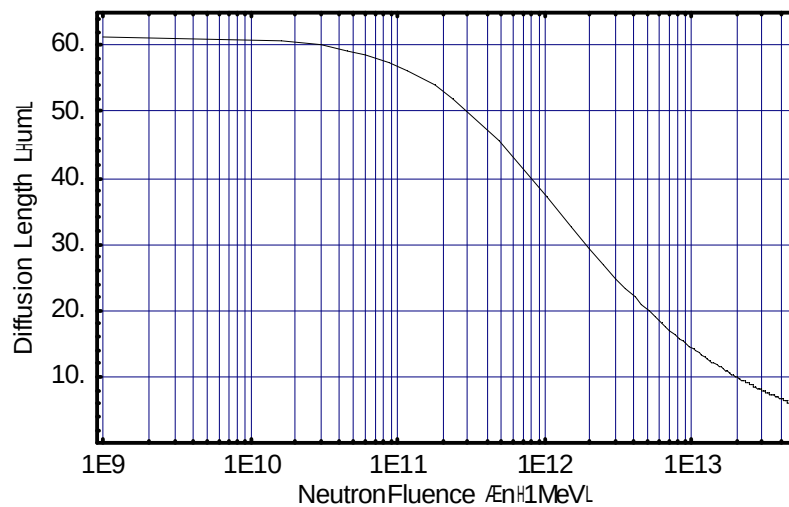


Figure 6.40. Estimated change in diffusion length with 1 MeV equivalent neutron fluence given a damage constant $K_{1\text{MeV}} = 1.5 \times 10^{-6} \text{ cm}^2/\text{n-sec}$

6.4 Summary of Charge Collection Modeling

6.4.1 Collection Efficiency and Radiation Damage Summary

The three basic methods employed in this analysis for charge collection modeling are summarized in Table 6.3. Potentially microbeam spectroscopy offers the most accurate estimation of device CE due to the unambiguous spatial information provided. 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. However, in our experiments the sub-micron resolution of the microbeam system could not be achieved due to radiation damage effects limiting exposure time and thus statistical accuracy. The microbeam measurements should use the highest energy alpha available in order to minimize the influence of the overlayer. A proposed further improvement in microbeam analysis would be to use data from a minimum of two other alpha energies and simultaneously extract the CE, overlayer thickness and SOI thickness without any a-priori information regarding device structure.

Table 6.3. Summary comparison of charge collection modeling methods

Characterization Method	Advantages	Disadvantages
Microbeam Spectroscopy	- proton beam available which minimizes funneling effects - mono-energetic source - localization of charge collection and capable of directly extracting spatial CE	- Difficult and expensive experiment not readily available - Care must be taken to avoid radiation damage => require low current single ion control for best results
Broadbeam Spectroscopy	- Inexpensive and readily available	- limited source energies - proton not available - no spatial charge collection data => Easy to incorrectly associate peaks in the spectrum with various charge collection regions
Device Simulation	- Fast evaluation of new designs - Increases understanding of charge collection process - Provides basic CE profile	- Requires 3D simulation with accurate track profile models and recombination parameters for accuracy => Very time consuming - Does not model statistical variations in CE - 2D modeling has limited accuracy

The broadbeam results are used for CE definition in this work due to the greater availability of such measurements and the previously mentioned difficulties with microbeam experiments. 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 CE. The spectroscopy modeling presented assists in correctly interpreting data by including, as far as practicable, all the sources of variation that contribute to the measured spectral character.

The CE parameters for the 2 and 10 μm SOI devices are summarized in Table 6.4. The results indicate that the CE does not vary greatly with (x,y) position. Small decreases in CE away from the junction are observed, consistent with a diffusion length larger than diode cell dimensions. The area averaged broadbeam derived CE at 10 V was 0.944 for the 2 μm SOI and 0.825 for the 10 μm SOI device. Note that the CE was extracted from 5.3 MeV alpha measurements. The CE using other radiation types and energy may differ due to funneling and recombination variations. These difference are not expected to introduce significant changes in CE since the efficiency is quite high and relatively uniform. However, further study of CE variations with ion type and energy is encouraged. Such future studies may use 3D device simulation with more accurate track modeling than presented in this work.

Table 6.4. Collection efficiency parameters for 2 and 10 μm SOI devices

Device	CE (see equation (6.49), and (6.50))
10V undamaged $10 \times 10 \mu\text{m}^2$ junction size, 2 μm SOI	Broadbeam measurement (5.3 MeV alpha): $L = 55 \mu\text{m}$, $(x_b, c_f) = (5, 0.97)$ and $(x_d, c_d) = (9, 0.998)$ see Figure 6.31, Figure 6.32, section 6.2.4.1. Microbeam measurement (2 MeV alpha): (a) 100% CE using spectroscopy model, section 6.2.3.1. (b) Slight decrease in CE away from junction, consistent with broadbeam measurement see Figure 6.30, section 6.2.3.2.
10V undamaged $10 \times 10 \mu\text{m}^2$ junction size, 10 μm SOI	Broadbeam measurement (5.3 MeV alpha): $L = 115 \mu\text{m}$, $(x_b, c_f) = (6, 0.84)$ and $(x_d, c_d) = (9, 0.86)$ see Figure 6.33, section 6.2.4.2.

Device simulation was extensively used in this chapter to assist in understanding the charge collection process. Collection efficiency simulations described in section 6.2.2.2 and 6.2.4.1 were in poor absolute agreement with broadbeam spectroscopy modeling as shown in Figure 6.32. The differences were attributable to inadequacies in 2D simulations. Accurate device simulation of SOI structures requires good estimation of recombination parameters, 3D device geometry and reasonable ion track models. Nevertheless, despite the possible inaccuracies of 2D simulations they do provide

qualitatively useful information such as the reduction in CE away from the junction and identification of funnel dominated charge collection.

In particular, simulations on bulk devices indicated that protons would be largely immune from funneling effects in contrast to alpha particles. Radiation damage studies determined the minority carrier lifetime before and after radiation damage. Edmonds' spectroscopy method for determining lifetime was employed. Accurate results demanded, firstly, the use of proton microbeam methods to reduce funneling effects and, secondly, large area bulk diodes to conform with the Edmonds model. The reduction in lifetime with radiation damage is described by the calculated 1 MeV neutron equivalent damage constant of $K_{1MeV} = 1.5 \times 10^{-6} \text{ cm}^2/\text{n-sec}$. In addition, C-V measurements quantified the drop in majority carrier density from 1.6 to $1 \times 10^{15} \text{ cm}^{-3}$ following irradiation with 24 GeV/c protons at a fluence of $4.1 \times 10^{13} \text{ p/cm}^2$.

In summary, the ability of SOI technology to create a well-defined sensitive *depth* has been confirmed by the charge collection studies. In using a p-n diode array it was initially hoped that the *lateral* charge collection would be dominated by drift in the junction region with much reduced charge collection outside that region. However, the charge collection studies demonstrated that lateral diffusion and funneling are dominant processes due to a diffusion length ($61 \text{ }\mu\text{m}$) much larger than cell dimensions. Reducing diffusion by lifetime reduction methods such as radiation damage was found to also affect charge collection in drift dominated regions.

The main implication is that future SOI microdosimeter designs should introduce methods such as oxide isolation boundaries to minimize lateral diffusion. Such technology has recently (1998) been developed for radiation hard applications. The TEMIC Matra MHS D-MILL 10 MRad process available from Europractice ASIC service [253] is a good example process in which CMOS and bipolar and JFET technology are available with complete isolation between device structures. Smaller cell volumes would reduce the dependence of charge collection on minority carrier lifetime and thus enhance radiation hardness.

6.4.2 Implications for Mean Chord Length Estimation

Lateral diffusion has created a sensitive volume for the SOI devices that closely approximates an infinite slab (or a very elongated RPP) rather than the desired RPP, discussed in chapter 3, with small or preferably no elongation. For the $2 \text{ }\mu\text{m}$ and $10 \text{ }\mu\text{m}$

SOI devices, the average sensitive depths (corrected for CE and SOI thickness variations) are 1.78 μm and 8.15 μm , respectively. The device width is 1214 μm and length is 3626 μm .

Despite this non-ideal shape and chord length distribution, later chapters test the current device in clinical beams. The potential of the device and useful future design information may still be gauged by experimenting with the current prototype microdosimeter. Microdosimetric spectra in these studies require an estimate of the mean chord length, $\bar{l}$, for the sensitive volume.

Assuming μ -randomness, the $\bar{l}$ for an infinite slab of thickness h is $2h$ (from Table 3.3). However, the assumption of μ -randomness or infinitely long isotropic random tracks, is questionable for volumes with exceedingly high maximum chord lengths and high CLD variance. For many practical radiation types the charged particles are not longer than the maximum device dimension (~ 3.8 mm) and the irradiation from the TE converter is not always isotropic. Therefore, it is appropriate to explore alternative estimations of $\bar{l}$ that are appropriate for the radiation field under investigation. In addition, geometrical considerations made in chapter 3 regarding equivalence to a sphere and in chapter 5 regarding TE corrections should be incorporated where possible.

Four basic methods are employed in the remainder of this work.

1. **Monte-Carlo simulation:** An accurate value of $\bar{l}$ may be obtained via Monte-Carlo simulation methods which transport charged particles through the experimental setup and determine the path length traversed through the device. In the case of BNCT, Monte-Carlo software was developed and applied to $\bar{l}$ determination as discussed in chapter 7. Corrections to the calculated $\bar{l}$ to obtain y_d equivalence to a spherical shape and TE correction are discussed in detail in section 7.3.1.5 and 7.4.1.4.
2. **Dose Mean Lineal Energy y_d Equivalence:** In chapter 3, the dimensions of a cube required for equivalence to a spherical proportional counter were calculated based on providing equal y_d for both shapes. Where TEPC measurements exist, the mean chord length for the silicon microdosimeter measurements may be iteratively adjusted to provide the same value of y_d as the proportional counter. This method is applied to fast neutron therapy measurements discussed in chapter 8.

3. **Proton Peak or Edge Methods:** Another method for estimating $\bar{l}$ simply involves adjusting $\bar{l}$ to provide the best alpha and proton peak fit between the TEPC and silicon microdosimeter $yd(y)$ spectra. Again this method is applied to fast neutron therapy measurements discussed in chapter 8. Related to this technique is an excellent method of calibrating microdosimetric measurements involving the use of the "proton edge" described earlier in section 2.3.1.2. The proton edge represents the maximum lineal energy that protons can have in the detector volume. This occurs at the end of the proton range in the Bragg peak. For sensitive volumes that have a well defined maximum chord length, the proton edge provides an excellent and convenient calibration technique that is independent of beam energy spectrum. Note, that adjusting $\bar{l}$ and calibrating the spectra via a gain adjustment have the identical effect of scaling the lineal energy axis in the $yd(y)$ spectra. For elongated RPPs the maximum chord length is improbable and the proton edge method is difficult to implement. However, if the incident radiation is largely normal to the device then the proton edge may be more clearly defined corresponding to the sensitive depth of the detector.
4. **Normally Incident:** For some radiation types, such as proton beams discussed in chapter 9, the secondary particles are approximately normal to the device. In this case, a reasonable first order approximation approximates $\bar{l}$ as the sensitive depth of the device. (i.e. $1.78\ \mu\text{m}$ for the $2\ \mu\text{m}$ SOI and $8.15\ \mu\text{m}$ for the $10\ \mu\text{m}$ SOI). For the proton therapy application discussed in chapter 9 device operation is emphasized and results are presented using the silicon mean chord length without TE correction.

Clearly, high elongation RPPs introduce uncertainty in mean chord length estimation. This is an additional compelling reason for using cubic shaped devices.