

10. Conclusions and Future Recommendations

10.1 Key Findings

This work is the first comprehensive investigation of the issues confronting silicon based microdosimetry and its application to radiotherapy. The literature review and a detailed comparison of proportional counter microdosimetry to silicon microdosimetry identified four main problems requiring investigation;

1. The *requirements* of silicon microdosimetry and particularly the influence of detector *shape* have not been dealt with thoroughly in the literature.
2. The *low noise* requirements on the silicon microdosimeter are demanding and particular attention must be made in the design process to minimize electronic noise.
3. The *tissue equivalence* of silicon microdosimeters has not been addressed in detail in the literature.
4. The *sensitive volume boundary* and charge collection suffers from uncertainty in almost all previous attempts at silicon microdosimetry. *Radiation damage* may affect silicon microdosimeter performance by reducing charge collection.

An analysis of the requirements of silicon microdosimetry provided in chapters 2 and 3 enables a complete requirement summary as shown in Table 10.1. This extends the previous work of Schroder [68] presented in Table 2.1. The work of Kellerer [129] on the criteria for equivalence of spherical, cylindrical and cubic shapes was extended to include RPP shapes with an overlayer and converter structure above the detector. The effect of finite particle range on the criteria for shape equivalence was explored in greater detail. In addition, the equivalence in terms of $\bar{y}_d$ and the effect of straggling on the lineal energy spectra were determined.

The requirements for tissue equivalence were determined in chapter 5. To obtain tissue equivalence, the silicon detector/ TE converter should have a geometrical TE scaling factor of $z = 0.63$, a converter composition closely approximating tissue, and a minimum silicon detector size subject to shape and noise considerations (as discussed in chapters 3 and 4, respectively) in order to reduce the probability of nuclear interactions with silicon.

Table 10.1. Summary of requirements and design rules for silicon based radiation therapy microdosimetry

Detector Feature	Requirements/Findings
Shape	- A RPP with an overlayer/converter structure is appropriate. Such a structure is easily manufacturable. Furthermore, it was shown that a RPP under c-randomness is closely equivalent to a sphere and RPP under μ-randomness. The equivalence holds within 10% for particle ranges $R > 2(a + \bar{l})$ and within 2% for $R > 4(a + \bar{l})$ where a = overlayer thickness. - The elongation of the RPP should be as close to unity as practicable in order to minimize shape relative variance. A cube is the optimum RPP shape.
Size	- Given a reference tissue sphere with a MCL = $\bar{l}_{Kt}$, the required MCL of a silicon volume K is $\bar{l}_{Ksi} = \bar{l}_{Kt} h z$ where $h z = 0.5$ for a cube. Therefore, a silicon cube with side length $0.5 \mu\text{m}$ will have a similar TE lineal energy spectrum and $\bar{y}_d$ as a $1 \mu\text{m}$ tissue sphere. In addition, $\bar{l}_{Kt}$ ($0.66 \mu\text{m}$ in this case) and not $\bar{l}_{Ksi}$ is used for calculating the TE lineal energy in the silicon volume. - The ideal silicon microdosimeter should have dimensions that approximate a tissue sphere of diameter ranging from around $13 \mu\text{m}$ (the typical cell diameter) to the minimum achievable given the device construction. Radiobiological studies such as TDRA indicate site sizes less than $2 \mu\text{m}$ are of most interest. - The detector should use an array of sensitive volumes to improve collection statistics. The total sensitive area of the volumes should be approximately 100 cm^2 for radiation protection applications and as small as 1 mm^2 for fast proton therapy measurements.
Materials	- A tissue equivalent converter should be used with a thickness greater than the maximum particle range expected to ensure charged particle equilibrium. - The overlayer thickness separating the converter and detector should be minimized (see shape comments above). - The geometrical TE scaling factor for the silicon detector ($z=0.63$) should apply to all ion products - The T.E converter must closely approximate tissue atomic composition with respect to atoms generating the dominant secondary charged particles. - The proportion of interactions with silicon must be negligible in comparison with converter interactions. That is, events should originate from converter recoil products or primary ions rather than from within silicon. - The range of recoil particles should be such that crossers and stoppers dominate the microdosimetric spectrum as discussed extensively in chapter 3
Operation	- An accurately defined sensitive volume. Minimization of charge collection complexity in particular diffusion and funneling effects. - Capable of measuring a lineal energy down to a minimum of $\sim 1 \text{ keV}/\mu\text{m}$ (tissue). Above this value of lineal energy the radiobiological effectiveness begins to rise above unity. Low noise design and optimization is necessary to met such requirements. - The charge collection behavior should be resistant to radiation damage at typical application fluences.

A Monte-Carlo program was developed to simulate the energy deposition of ions in a BNCT radiation field. The Monte Carlo results confirm that with appropriate geometrical scaling ($z = 0.63$) silicon detectors with well-known geometry will record energy deposition spectra representative of tissue cells of equivalent shape. That is, silicon is tissue equivalent for BNCT ion products under appropriate linear geometrical scaling. The scaling factor is also applicable to FNT but may need to be reduced for PT to around 0.56.

A brief study comparing tissue and silicon neutron interactions in FNT was described. For neutron energies less than 5 MeV, microdosimetric measurements in silicon volumes with dimensions of the order of 1 μm will not be significantly affected by events generated within the silicon. At higher neutron energies, the spectrum at high lineal energies may be affected by silicon elastic and inelastic reactions. A more detailed study is required to fully ascertain design requirements and the conditions under which satisfactory operation may be achieved.

The requirement for a lineal energy measurement range down to a least 1 keV/ μm conflicts with the desire for a small sensitive volume that reduces the total charge collected. A noise optimization model for the microdosimeter and charge sensitive amplifier system was developed in chapter 4 that enables optimum selection of components and system parameters such as amplifier shaping time. The prototype diode array device used in this work was originally developed by Fujitsu as a test device for memory single event upset studies. Silicon-on-Insulator technology is used to assist in defining the sensitive volume and was the principle reason for selecting this test device as a prototype microdosimeter.

I-V and C-V testing of the device were performed to determine device integrity and quantify parameters required for noise optimization calculations (such as reverse bias current and capacitance). A model for device capacitance that includes metal-oxide track capacitance and the traditional pixel array depletion capacitance was presented. The method presented for calculating the model parameters (C_c , N_B , and V_{bi}) is simple and provides a reasonably accurate estimate of substrate doping concentration that corresponds well with the manufacturer's value. The model indicates the importance of minimizing metal-oxide track capacitance by having a thick oxide layer separating the metal from the substrate and ensuring a minimum metal area.

The collection efficiency and radiation hardness of silicon microdosimeters were characterized in chapter 6 using three methods; alpha and proton microbeam spectroscopy, broadbeam alpha spectroscopy and 2D and 3D device simulation. A summary comparing the methods is provided in Table 6.3. Potentially microbeam spectroscopy offers the most accurate estimation of device CE due to the unambiguous spatial information provided, 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.

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. A spectroscopy software model was presented which accurately fits both broadbeam and microbeam data and assists in correctly interpreting data by including, as far as practicable, all the sources of variation that contribute to the measured spectral character.

Semiconductor device simulation was extensively used in chapter 6 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. 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 $K_{1\text{MeV}} = 1.5 \times 10^{-6} \text{ cm}^2/\text{n-sec}$. 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, bipolar and JFET technology are available with complete isolation between device structures. Furthermore, smaller cell volumes would reduce the dependence of charge collection on minority carrier lifetime and thus enhance radiation hardness.

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 $1.78 \text{ }\mu\text{m}$ and $8.15 \text{ }\mu\text{m}$, respectively. The device width is $1214 \text{ }\mu\text{m}$ and length is $3626 \text{ }\mu\text{m}$.

Despite this non-ideal shape and corresponding chord length distribution, chapters 7, 8, and 9 test the current device in BNCT, FNT and proton therapy 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 which is complicated by the elongated sensitive volume. Four different methods for determining the most appropriate mean chord length for the device are discussed in section 6.4.2.

Chapter 7 demonstrates the first application of silicon p-n junction SOI arrays for microdosimetry in radiation oncology and particularly for BNCT. The interaction of thermal neutrons with each of the materials present in the device construction was thoroughly analyzed in section 7.2. The important materials are (in order of thermal neutron sensitivity), B-10 in a 1% Lucite coat or cover (optional, if present), B-10 in the p^+ region, N-14 in air (if present, may not have an air gap above the device), N-14 from the TiN barrier layer.

Experiments at BNL, as presented in section 7.3, were primarily directed at investigating various converter options for the device (Lucite with B-10 and U-235) and for a comparison with a TEPC measurement. Direct coating of the device with 1% B-10 in Lucite did not change electrical characteristics and produced a microdosimetric spectrum similar to the 1% B-10 lid. Discrepancies between these spectra and Monte Carlo simulations were attributable to simplistic overlayer and charge collection modeling. More detailed investigation of charge collection modeling of high LET particles is encouraged. In addition, preliminary results with the U235 converter suggest that the SOI p-n junction is a promising microdosimeter for heavy ion therapy provided the bias voltage is greater than 5 V to minimize recombination. Measurement of the spectra generated from B-10 deposited within the device p^+ regions demonstrated that typical medical concentrations of B-10 may be introduced in the device design via ion implantation. Such a microdosimeter can be used under full reactor power with any device orientation.

Experiments at KUR, as presented in section 7.4, demonstrated the importance of minimizing the air gap above the device due to the large number of proton events originating from nitrogen thermal neutron reactions. Monte Carlo simulations of this

effect were in good agreement with observed experimental spectrum. A comparison of the 2 μm and 5 μm SOI devices highlighted the importance of a small sensitive volume in order to maximize the sensitivity to particle LET rather than particle total energy. The ability of the 2 μm SOI microdosimeter to discriminate between fast neutron recoil protons and BNCT products facilitates simultaneous thermal neutron flux measurements and microdosimetry at a high spatial resolution. Excellent agreement in the neutron flux profile, between the gold foil measurements by Kobayashi [269] and the microdosimeter, was demonstrated as shown in Figure 7.22. The number of ion-implanted B-10 atoms within the p^+ region used for these measurements was a factor of 6 lower than expected based on isotope natural abundance suggesting that the ion-implantation process may alter the relative isotope concentrations. If the ion-implanted B-10 proportion is known, accurate absolute thermal neutron flux may be estimated without any need for normalization to a known flux value.

In summary, the improvements in traditional microdosimetry possible using silicon diode arrays may help to bridge the gap between proportional counter microdosimetry in BNCT and the more realistic high-resolution quantitative autoradiography method developed by Solares and Zamenhof [81].

Chapter 8 presented the first demonstration of a SOI based microdosimeter in a neutron radiation therapy beam (Harper Hospital, Detroit) with results sufficiently promising to confirm the feasibility of the device in this application. A detailed comparison with a proportional counter is performed. Despite some deficiencies in the existing design, microdosimetric radiation quality variations may still be characterized qualitatively. General trends in microdosimetric spectra as a function of position within the beam (e.g. small depth dependence, lateral variation) were in good agreement with the proportional counter. However, quantitative analysis based on calculation of $\bar{y}_d$ and y^* is not recommended with the current design as indicated by a poor correspondence with proportional counter trends. Shortcomings in the current design arise primarily from the large sensitive volume and the chord length distribution of the SOI device along with the need for improved low noise performance.

The third and final application in which the device was tested was proton therapy as discussed in chapter 9. Testing at the recently constructed NPTC facility in Boston demonstrated the capability of the device at recording lineal energy spectra with high

spatial resolution. The spectra were consistent with simulations performed using SRIM and PRISM and qualitative expectations based on previous proportional counter measurements in protons beams and an understanding of the beam characteristics.

In general, pile up and perturbation effects were avoided due to the small area (0.04 cm^2) of the total pixel array. Pileup did occur for experiments at PMRC when the vertical momentum slit width was greater than 2 mm. Under these conditions, an even smaller area detector is required. Note that the area requirements are still well within the design capability of silicon technology. The detector was coupled to a radiation-hard charge sensitive amplifier with the probe assembly capable of measuring an LET down to $1.2 \text{ keV}/\mu\text{m}$ (Silicon). The device offers much improved spatial resolution compared with a proportional gas counter particularly in the critical high dose region around the proton Bragg peak. These measurements potentially provide valuable information for radiobiological studies of the varying effectiveness of the beam as a function of depth. Future work may be directed towards the analysis of beam relative biological effectiveness such as performed at Loma Linda by Coutrakon [155] at a higher spatial resolution than previously attempted.

We have demonstrated a new approach to microdosimetry in radiation oncology using a silicon SOI p-n junction array applied to various high LET therapy beams. A consistent difficulty in experimental evaluation was the uncertainty in the mean chord length to be used evidenced by the variety of calculation methods employed for different applications. The large elongation of the devices sensitive volume (see section 6.4.2) introduces MCL uncertainty and is a compelling motivation for using unity elongation shapes such as a cube with a minimum relative variance.

Nevertheless, the potential advantages of silicon microdosimetry in radiation oncology applications are multitudinous. The diode array is a portable, low cost system without the need for gas flow technology and high voltage supplies. Of particular benefit is the devices excellent spatial resolution. Measurements, such as in proton therapy near the Bragg peak and off axis measurements in FNT, may then be performed at a spatial resolution commensurate with the application needs. The diode array also offers such advantages as a measurement in the solid phase and thus removal of wall effects, simulation of a two dimensional array of cells for improvement in collection statistics, small physical size (possible in-vivo capability), and high count rate capability that

enables operation at clinical dose rates. Furthermore, the possibility exists that future devices may be constructed with sizes and morphology more nearly representative of biological cells using real tissue cells surrounding the detector. Specific boron implantation in various cell/diode regions may be introduced along with simultaneous macrodosimetry using other detectors on the same silicon substrate. The construction of such devices may exploit the rapid development and current manufacturing capabilities (integration of components and quality control) of silicon based integrated circuit technology.

10.2 Future Recommendations and Proposed Design Outline

More work is required to completely address the four main problems confronting silicon microdosimetry. In particular, the following areas are worthy of future research:

1. The problem of determining the effect of nuclear interactions with non-TE materials in the device, such as the silicon and overlayer materials, requires further examination. In this work, the silicon device is shown to be TE provided these interactions are relatively infrequent compared to secondary products arriving from the TE converter. Hence one must maximize TE material surrounding the detector and minimize the silicon volume. The studies in clinical beams emphasized the need for minimizing the sensitive volume of the detector to around the 1 μm region and employing a cubic shape with a smaller relative variance, well defined mean chord length and a chord length distribution more nearly approximating a sphere. Such a design will reduce the proportion of silicon interactions and increase the percentage of crossers contributing to the microdosimetric spectrum. A proposed cross-section of such a device is shown in Figure 10.1. The device construction seems feasible based on recent developments in etching and 3D device construction that enable complex detector shapes as presented by Kenney [301] and Allier [302]. Monte-Carlo code, that models the interaction of neutrons (0-60 MeV) with such a device, is required to determine the relative contribution of secondary products from the TE material and the device materials as a function of sensitive volume size. For such a task, one may first attempt to modify existing code already developed for silicon and tissue materials.
2. Low noise performance may be significantly improved by integrating the charge sensitive amplifier with the detector. Achievable optimum performance for such a

system was addressed in section 4.5.6. It was estimated that an array of $2400 \times 1 \mu\text{m}^3$ diodes would have a noise level of 19 electrons and a minimum lineal energy of $0.26 \text{ keV}/\mu\text{m}$ (Tissue, NB: $1 \mu\text{m}^3$ Si cube is equivalent to $2 \mu\text{m}$ spherical TE). This noise level is sufficiently low for accurate quantitative determination of $\bar{y}_d$ and y^* in neutron therapy beams. In addition, the energy resolution of the silicon microdosimeter will now exceed the capabilities of the TEPC over the entire range of measured energies as shown in Figure 2.6. The total area of the proposed device is 200 times smaller than the prototype tested in this work. To achieve reasonable count rates for small detector arrays several detector/preamplifier channels would be required to increase the total device area. Care should be taken in the device layout design to ensure that the metal track capacitance is kept to a minimum and included in device noise modeling, as discussed in section 4.2.2.

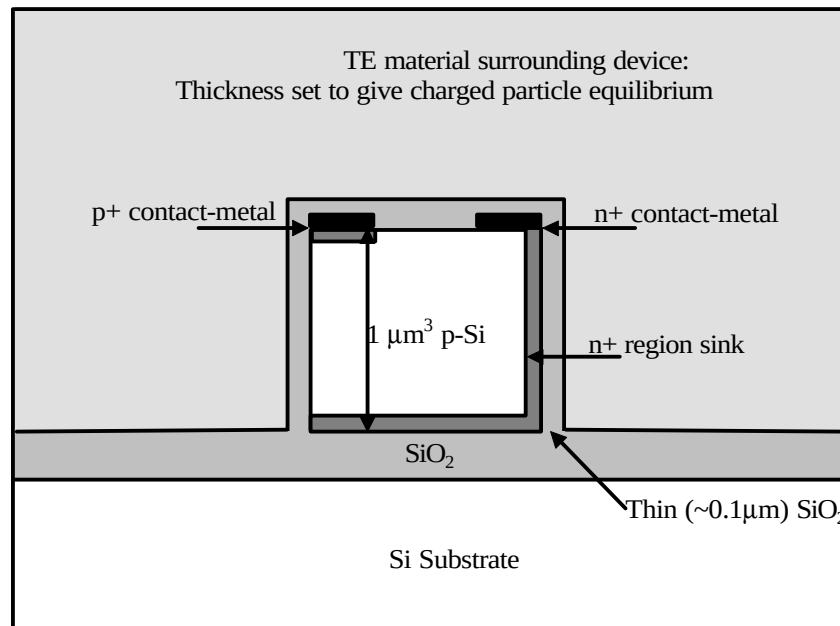


Figure 10.1. Cross-section of ideal proposed silicon microdosimeter. The TE material may be constructed with either A150, some other TE plastic or even the deposition of real tissue cells. Note that the protective qualities of the SiO_2 passivation overlayer are quite robust.

3. The next generation device should use lateral isolation technologies on a SOI substrate, as shown in Figure 10.1, to minimize lateral charge collection effects. A sensitive volume with near unity elongation (e.g. cube) may then be constructed with a well-defined sensitive volume and small chord length distribution relative variance. The detector shown in Figure 10.1 has a $1 \mu\text{m}^3$ sensitive volume designed to approximate the response of a $2 \mu\text{m}$ diameter TE spherical proportional counter. A thin ($\sim 0.1 \mu\text{m}$) isolation boundary of SiO_2 provides two benefits, aside from

defining the sensitive volume. Minimizing the overlayer thickness both improves TE and reduces radiation damage effects in the oxide (such as charge buildup that may increase reverse bias current noise and modify surface recombination). The oxide thickness of $\sim 0.1 \mu\text{m}$ was selected as a reasonable minimum achievable value. Note that the oxide, metal and contact thicknesses, are all manufacturing process dependent parameters.

4. The new device should be tested using full 3D device simulation (an easier task with the smaller device dimensions). 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. Surface recombination (Si-SiO_2) will be a more significant factor than bulk recombination due to the relatively large surface area to volume ratio. Methods for determining surface recombination should be determined prior to device fabrication since a dedicated lifetime test structure on the device may be useful.

Having addressed the key issues, the next generation device should be applied to high LET applications for comparison with proportional counter performance. The device should find particular utility where spatial resolution demands are high. Such a device would provide an excellent test structure for experimental microdosimetry both in the biological domain of radiotherapy/radiation protection and for SEU studies. In the later category, an important application is the verification of neutron burst generation rate models, central to the SEU prediction software used in modern memory chip design. Applications in radiobiology include the study of dosimetry in space and avionics and radiation oncology modalities such as BNCT, heavy ion, fast neutron, and proton therapy in which dosimetry has traditionally been quite difficult.