Developments in microdosimetry and nanodosimetry for space and therapeutic applications

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3 SOI Microdosimeter Testing

3.1 Introduction

SOI microdosimeters have been experimentally tested in a number of different radiation environments, including those produced in proton therapy (PT) [64, 65], fast neutron therapy (FNT) [21, 29], ion-beam induced charge collection studies (IBICC) [26, 27] and various irradiations with radioactive sources including Am-241 and PuBe-238 [66]. Such experiments have the potential to change the response of these devices to radiation induced signal. The SOI devices needed to undergo benchmark testing before the commencement of experimental studies to ensure stable and reproducible performance. Tests included Current-Voltage (I-V) characterisation and alpha particle irradiation that were completed using facilities at the Australian Nuclear Science and Technology Organisation (ANSTO). In addition the devices were calibrated to enable accurate determination of the lineal energy spectra. Finally, systematic studies on the systems electronic noise and shielding properties of the experimental probe assembly were completed. Such tests were important as this system was a prototype having undergone a number of changes from the original system proposed in [21, 25].

3.2 IV Testing & Characterisation

Measurements of the I-V characteristics of both 5 and 10 μm SOI microdosimeters were completed to assess diode integrity and provide initial information on the device performance and noise characteristics. Such information enabled unsuitable devices to be initially tested and discounted from further testing or experimental use. These measurements were completed using a Keithley 237 high voltage measurement unit which is situated at ANSTO and is dedicated to the measurement of I-V characteristics. The accuracy of the meter is within 0.3% in the 10 nA range. Measurements were completed for all devices and arrays in 1 V incremental measurements from 0-20 V reverse bias. As the purpose of these measurements was to identify functioning devices these tests were performed at atmosphere with a temperature of 22±2°C. For each measurement a 1-2 second settling time was employed.
Using the protocol outlined in [21] functioning devices were selected using the following criteria:

- The I-V should be linear with a positive slope
- At 0 V have a nominal current range of -0.25 ≤ I ≤ 0.25 nA
- At 10 V reverse bias have a nominal current range of 0 ≤ I ≤ 200 nA

Characteristic I-V curves for the 10 μm devices are displayed in Figure 3-2, with each array structure contained within a separate graph. Note that the arrays are named as follows:

Array 1 (A1): 120x120x10μm³ with 150 detector elements
Array 2 (A2): 120x120x10μm³ with 50 detector elements
Array 4 (A4): 30x30x10μm³ with 4800 detector elements
Figure 3-2: Characteristic I-V curves for 10 μm devices tested. Note how the 3 separate array structures are contained within separate graphs for easier identification.

It is clear from the I-V characteristics which devices meet the operational criteria for operating and those which should be rejected. For array A1, device 21 clearly displays an exponential rise in current with voltage making it unsuitable for radiation measurements. Furthermore, device 2 has a non-linear response for voltages below 2 V but in the region 2\(\leq V\leq 20\) V a linear relationship between current and voltage is displayed. As the operating voltage for such devices is 10 V and the relationship is linear in this region such devices are deemed to be operational provided they successfully complete all other tests. For array A2 all devices meet the criteria, except device 19 which clearly encounters breakdown at very low reverse bias voltages and was rejected from further testing. The A4 devices have been used most extensively in previous work and the response of these devices indicates this. Both devices 22 and 2 display non-
linearity when the reverse bias voltage is less than 2 V, however above this value all three curves appear linear. For this reason the three A4 devices were utilised in this work for comparative measurements with other microdosimetry systems and arrays. All 10 µm devices selected for further testing on the basis of linear response also met the current requirements at 0 and 10 V.

![SOI 5µm Microdosimeter](image)

**Figure 3-3:** Characteristic I-V curves for 5 µm devices tested. Note how the 3 separate array structures are contained within a single graph for easier identification.

The 5 µm devices displayed a much more uniform response with all devices tested meeting criteria for further testing. Non-linearity at reverse bias voltages less than 2 V was not observed in 5 µm devices, with the only non linear response occurring with applied voltages larger than 18 V in the case of device 18 A4. This could be caused by device heating or breakdown. Due to the high reverse bias at which this occurs, it does not rule the device out for further electronic testing.
3.3 Alpha Source Testing

Alpha source testing using an Am-241 electroplated source provides a means for further testing of devices with an applied radiation field prior to deployment. Such measurements are useful as they provide a benchmark for chip performance to radiation by comparing the following parameters:

- Noise level
- Alpha Peak position
- Alpha Peak amplitude

These tests were completed at a dedicated radiation metrology laboratory at ANSTO and involved the use of an electroplated Am-241 source of approximately 5 mm in diameter. The entire experimental assembly was situated within a vacuum chamber to minimise attenuation of the incident radiation field in addition to shielding the device from light contamination. The source was situated parallel to the SOI microdosimeter chip separated by a distance (in vacuum) of approximately 1 cm with the centre of the Am-241 source corresponding to the centre of the SOI chip.

![Figure 3-4: Pictures of the experimental set-up at ANSTO for alpha source irradiations of SOI microdosimeters. The picture on the left illustrates the complete experimental set-up including vacuum chamber, pulser, main amplifier, cathode ray oscilloscope (CRO) and power supplies. The picture on the right gives a view inside the vacuum chamber with a SOI microdosimeter and circuitry board mounted in the experimental measurement position.](image-url)
All microdosimeter arrays which passed initial I-V testing were subjected to alpha irradiation to assess performance. Representative 5 and 10 μm device results are displayed in Figure 3-5 and Figure 3-6 for each of the three array structures. Spectra were collected for 5 and 10 minutes in the case of the 5 and 10 μm devices respectively. In addition a pulser with energy of 3 MeV (for 10 μm devices) and 2 MeV (for 5 μm devices) was applied to the spectra post-collection to give an indication of how the varying capacitance of the three arrays affected the energy calibration.

![Graph](image)

**Figure 3-5:** Normalised alpha spectra for 10 μm SOI microdosimeter 8 for the three working arrays.

Figure 3-5 provides the alpha spectra for a 10 μm SOI microdosimeter chip. It is clear from the results that this is a well performing chip which further supports the results from I-V testing. Firstly, the lower noise level remains constant for the three arrays. Further, the position of the pulser peak also remains relatively stable. Variation in position is inherent on the changes in capacitance between the three arrays, however, variation is only of the order of ±40 keV or approximately ±1% which is considered within the operational limits of the device. The alpha peak amplitude and position also
varies depending on the array selected. The amplitude depends on the cross sectional area of the given array and hence collected signal. The position of the alpha peak also varies as a function of chosen array for a number of reasons:

- The capacitance difference between the arrays causes a shift in energy calibration which can be quantified through comparisons with pulser measurements as being ±40 keV.

- The arrays vary in position on the chip and the radiation field may vary as a function of position relative to the radiation source. This could result in a small shift in the response of the device.

- As the source was not collimated onto the SV the radiation is not perpendicular to the array but has some divergence which is dependant on the position of the array relative to the source. Hence, the path length through the SV may vary depending on SV position.

Figure 3-6: Normalised alpha spectra for 5 μm SOI microdosimeter 22 for the three working arrays.
Figure 3-6 illustrates the alpha spectra for a functional 5 µm device. The results are very similar to those reported in the 10 µm case with minimal variation in position of the pulser peak with differing array structure. Again the alpha amplitude and position varies depending on the selected array structure for the same reasons as described above. While such tests are important for determining the response of different array structures in relation to one another, this testing is also used to select functioning devices. As such tests are completed to compare all array structures of a given type, an example of which is displayed in Figure 3-7.

![Figure 3-7: Normalised array A1 alpha spectra for all 10 µm SOI microdosimeter chips used in this experimental work.](image)

Figure 3-7 provides a comparison for all the array A1 10 µm SOI microdosimeter arrays tested for use in radiation characterisation experiments. What is immediately apparent is that the alpha peak position and amplitude is uniform across the devices showing not only that they have comparable capacitance (one reason stated above for differences between array structures) but also that they are functioning correctly. This
conclusion is strengthened through the uniform position of the pulser peak in the spectra. What is also encouraging from these results is that the lower noise threshold is uniform across the devices. In this instance all chips displayed were selected for experimental use.

3.4 Final Chip Selection

Using the data from I-V and alpha particle testing it was possible to select suitable devices for further experiments both at Loma Linda University Medical Center, and the NASA Space Radiation Facility at Brookhaven National Laboratory. The devices selected for the experimental SOI microdosimetry portion of this work are contained within Table 3-1.

<table>
<thead>
<tr>
<th>Device 10 μm</th>
<th>Array 1</th>
<th>Array 2</th>
<th>Array 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Selected</td>
<td>Rejected</td>
<td>Selected</td>
</tr>
<tr>
<td>22</td>
<td>Selected</td>
<td>Selected</td>
<td>Selected</td>
</tr>
<tr>
<td>19</td>
<td>Selected</td>
<td>Rejected</td>
<td>Rejected</td>
</tr>
<tr>
<td>8</td>
<td>Selected</td>
<td>Selected</td>
<td>Selected</td>
</tr>
<tr>
<td>21</td>
<td>Rejected</td>
<td>Selected</td>
<td>Rejected</td>
</tr>
<tr>
<td>24</td>
<td>Selected</td>
<td>Selected</td>
<td>Rejected</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Device 5 μm</th>
<th>Array 1</th>
<th>Array 2</th>
<th>Array 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>Selected</td>
<td>Rejected</td>
<td>Rejected</td>
</tr>
<tr>
<td>22</td>
<td>Selected</td>
<td>Selected</td>
<td>Selected</td>
</tr>
<tr>
<td>18</td>
<td>Rejected</td>
<td>Selected</td>
<td>Selected</td>
</tr>
</tbody>
</table>

*Table 3-1: SOI microdosimeters selected for further experimental studies in proton and heavy ion fields.*
3.5 Experimental Probe Design

For SOI microdosimetry studies of both proton and heavy ion radiation fields a new experimental probe assembly was designed and constructed. This system was a hybrid system incorporating the ideas and methods previously outlined in [21] with further improvements for both proton, heavy ion and mixed radiation field sampling. The basis of the system involved a probe which would hold the SOI microdosimeter, pre-amplifier, buffer-amplifier, and associated circuitry (see Figure 3-8). To allow for a low-noise environment this probe assembly was made out of 0.9 mm thick aluminium sheet that was folded and welded to create a light tight box with a removable end cap. This probe formed a Faraday cage for the device during experimental measurements, and further reduced noise by providing a dark environment devoid of external lighting. The end cap was machined from a piece of aluminium and was through drilled to allow for the installation of pass throughs for detector bias, pre-amplifier power, incident pulser and signal. Such an arrangement maintained the integrity of the Faraday cage whilst allowing the transfer of power and signal.

![Image of microdosimeter probe assembly](image)

**Figure 3-8:** Picture of microdosimeter probe assembly developed for this study.
Situated inside the experimental probe assembly was a Perspex spacer, which allowed for reproducible placement of the SOI microdosimeter electronics board. This was achieved through the use of locator holes within the spacer that matched up with projections from the electronics board, locking it in place. In [21] the spacer assembly completely surrounded the SOI microdosimeter and electronics board with a given thickness of Perspex both in-front and behind electronic assembly. This meant that not only was the electronic assembly reproducibly placed within the aluminium experimental probe, but it also meant that a converter of a given thickness was situated at all times immediately anterior to the SOI microdosimeter array. The presence of a converter allows for the detection of neutrons in a free air environment, but in combination with a 0.9 mm thick aluminium probe wall thickness, can prevent low range secondaries produced within a phantom material from reaching the SV.

The spacer used in these studies is fundamentally different in that it was situated behind the electronics board only, and ensured not only reproducible placement of the SOI microdosimeter, but also ensured that the SV was immediately inside the anterior wall of the aluminium probe. In addition, a circular hole was cut in the aluminium probe immediately anterior to the SV location and replaced with an aluminium foil of 4 µm thickness. Such an arrangement allowed for the detection of low range secondaries by the SV as they need only traverse a 4 µm thick aluminium window. To allow for the detection of neutrons in a free air situation, provision was also made such that a 0.5 mm thick polyethylene converter could be affixed immediately anterior to the SV within the probe assembly.

As in previous work a CMRP circuitry board complete with Amptek A-250 and x10 (variable) buffer amplifier was utilised in this work. This was completely housed within the probe assembly. To enable reproducible placement within layered phantom structure a special Perspex probe holder was built. This consisted of a 20x20x3 cm³ slab of Perspex with a channel machined along the central axis with the same dimensions as the Aluminium probe. A Perspex rod allowed for the microdosimetry assembly to be situated anywhere along this channel (typically with the SV at the central axis) allowing for central and off axis measurements to be completed.
The complete SOI experimental assembly was kept as simple and compact as possible to allow for a high level of portability and is displayed in Figure 3-9. It consists of a regulated battery pack which supplies 10V reverse bias to the SOI microdosimeter, and ±6 V power to the A-250 pre-amplifier. Signal from the device was transferred to a Tennelec TC244 Spectroscopy Amplifier. The amplified signal was then transferred to an Amptek Pocket MCA and the resulting signal displayed using the packaged MCA software on a laptop. This software allowed for real time analysis and visualisation of the acquired data with 0.5 second updates via a PC-card to RS-232 interface. The real advantage of this system was that it was highly portable being completely contained within a standard briefcase. The only limitation of this system was that it required NIM power supply for the amplifier. Future developments of this system should incorporate a stand alone amplifier that is either battery powered or has provision to be connected to filtered mains power (120-240 V).
3.6 Apparatus Calibration

The apparatus needed to be calibrated for all possible experimental configurations. As four circuitry boards and two Amptek A-250 pre-amplifiers would be utilised, it was important to determine an energy calibration curve for each combination. The same experimental set-up used for alpha particle irradiations (described in Section 3.3) was utilised in device calibration. For initial tests, the SOI microdosimeter was replaced with a 1 mm² silicon planar detector that was mounted on the SOI circuitry board. A reverse bias of 40 V was applied via a Fluke 415B GW power supply providing a situation of full depletion in the ion implanted detector. The advantage of this device was that it had a similar capacitance to the SOI microdosimeter and allowed for a spectroscopy measurement of the Am-241 alpha spectra. When mounted in the vacuum chamber and irradiated with the Am-241 electroplated alpha source, a spectra was measured (Figure 3-10) and correlated with established results.

![Energy Deposited (keV) vs Counts](image)

**Figure 3-10**: Alpha spectra as obtained using the 1 mm² silicon planar detector. Note, the four discernable characteristic peaks corresponding to 5.389 MeV (1.3% abundance), 5.443 MeV (12.8% abundance), 5.486 MeV (85.2% abundance) and 5.545 MeV (0.35% abundance). A fifth peak is also present at 5.513 MeV (0.12% abundance) but this is not discernable on the graph.
The main 5.486 MeV alpha peak of the spectra was used to normalise an Ortec Model 448 precision pulse generator. The silicon planar detector was then replaced with a 10 μm SOI microdosimeter with array 4 selected. Array 4 was utilised for all calibration work as this has the mean capacitance of the three useable arrays. For each perspective gain setting and pre-amplifier/circuitry board combination a range of pulser amplitudes (corresponding to calibrated input energies) were collected to provide a relationship between channel number and collected energy. From this relationship a calibration curve for each gain setting and pre-amplifier/circuitry board combination was established to provide accurate calibration of all experimental results.

![Figure 3-11](image_url)

**Figure 3-11**: On the left is a pulser spectra collected for a coarse gain of 20 and with the buffer amplifier activated. Each pulse is calibrated to a given energy value. On the right, is a calibration curve created from the energy/channel relationship. Note the equation which is used for the calibration of all experimental spectra collected using this gain setting and device/pre-amplifier/circuitry board combination.

To ensure that the calibration remained constant, periodic checks with both pulse generators and alpha particle irradiation were also completed both pre and post experiment. This method of calibration ensured accurate results for each gain setting and device/pre-amplifier/circuitry board combination, which was especially important as variations in experimental setup (i.e. changing board and/or A-250) had a measurable effect on the energy calibration through variations in system capacitance. It should be noted that in order to obtain the correct energy scale for an experimentally obtained spectra using the SOI device a CCE of 0.8 [26] needs to be applied to the energy scale.
3.7 Experimental System Noise Assessment

The final test for the experimental probe assembly was to ensure that the noise limitations of the device were understood and could be accounted for when comparing to Monte Carlo simulations of the experimental system. To determine the intrinsic noise of the system, signal pulses from an Ortec Model 448 precision pulse generator was input into the system over a range of energies (0.1-8 MeV using the calibrated energy scale) and main amplifier gain settings. Such measurements provided the intrinsic noise of the entire experimental system and determined if this changed with main amplifier gain. In each instance these measurements were made with a 10 µm SOI microdosimeter chip connected in the experimental assembly, as this was most representative of a typical experimental setup.

![Graph showing energy deposited vs counts with two FWHM values: 5.202 keV and 4.842 keV, and 4.728 keV.]

**Figure 3-12:** Incident pulser spectra collected using the experimental probe and amplifier assembly.

Figure 3-12 shows the incident pulser spectra collected using the experimental setup for 0.1-1 MeV. It is clear from these measured values that the full-width at half maximum (FWHM) ranges from approximately 4.7-5.2 keV. To illustrate this more
clearly, an expanded pulser spectra is displayed in Figure 3-13. Across all energy and gain settings tested an average value of approximately 5 keV at FWHM was measured which remained relatively constant. This value will be applied as a Gaussian distribution of $\sigma=5$ keV to Monte Carlo simulations to better reflect the intrinsic noise of the experimental system. This agrees well with what has been measured and used previously [26].

![Figure 3-13](image.png)

**Figure 3-13**: Magnified incident pulser spectra collected using the experimental probe and amplifier assembly.

The other important noise characteristic of the experimental system which needed to be quantified was the lower level noise threshold. This is extremely important, especially in low-LET radiation environments, as the noise level ultimately determines the sensitivity of the instrument. This was determined both with the pulser connected but turned off (as is typically the case in device testing), and then with the pulser disconnected completely from the system (typical for external beam radiation measurements) and the results are displayed in Figure 3-14. It was clear that the presence of the pulser did introduce some additional noise to the system. However, as this was not be the case in experimental studies it could largely be disregarded. With the pulser
removed from the system a lower level noise threshold of approximately 15 keV was measured for the 30x30x10 μm³ microdosimetry array A4 which again compares favourably with what is published in [21]. This corresponds to a tissue equivalent (TE) lineal energy limit of approximately 0.8 keV/μm using a mean tissue equivalent chord length of 19.05 μm that was determined using the method outlined in [32] and Section 2.5.

![Graph showing counts vs. energy (keV)](image)

**Figure 3-14**: Lower noise threshold of the experimental microdosimetry system with a 10μm SOI microdosimeter.

The noise levels of the modified experimental assembly compare well with the previous published benchmark values of the SOI microdosimeter [21, 25]. As such the improvements that were made to the experimental probe assembly to enable the transport of low range secondaries into the SV did not have a detrimental effect of the noise characteristics of the system. The benchmarks established in this section of research will be utilised in subsequent SOI microdosimetry studies.