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New 3D Silicon detectors for dosimetry in Microbeam Radiation Therapy

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Abstract

Microbeam Radiation Therapy (MRT) involves the use of a spatially fractionated beam of synchrotron generated X-rays to treat tumours. MRT treatment is delivered via an array of high dose 'peaks' separated by low dose 'valleys'. A good Peak to Valley Dose Ratio (PVDR) is an important indicator of successful treatment outcomes. MRT dosimetry requires a radiation hard detector with high spatial resolution, large dynamic range, which is ideally real-time and tissue equivalent. We have developed a Silicon Strip Detector (SSD) and very recently, a new 3D MESA SSD to meet the very stringent requirements of MRT dosimetry. We have compared these detectors through the characterisation of the MRT radiation field at the Australian Synchrotron Imaging and Medical Beamline. The EPI SSD was able to measure the microbeam profiles and PVDRs, however the effective spatial resolution was limited by the detector alignment options available at the time. The geometry of the new 3D MESA SSD is less sensitive to this alignment restriction was able to measure the microbeam profiles within 2 ¿m of that expected. The 3D MESA SSD measured PVDRs were possibly affected by undesired and slow charge collection outside the sensitive volume and additional scattering from the device substrate.

Disciplines

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New 3D Silicon detectors for dosimetry in Microbeam Radiation Therapy

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Abstract. Microbeam Radiation Therapy (MRT) involves the use of a spatially fractionated beam of synchrotron generated X-rays to treat tumours. MRT treatment is delivered via an array of high dose 'peaks' separated by low dose 'valleys'. A good Peak to Valley Dose Ratio (PVDR) is an important indicator of successful treatment outcomes. MRT dosimetry requires a radiation hard detector with high spatial resolution, large dynamic range, which is ideally real-time and tissue equivalent. We have developed a Silicon Strip Detector (SSD) and very recently, a new 3D MESA SSD to meet the very stringent requirements of MRT dosimetry. We have compared these detectors through the characterisation of the MRT radiation field at the Australian Synchrotron Imaging and Medical Beamline. The EPI SSD was able to measure the microbeam profiles and PVDRs, however the effective spatial resolution was limited by the detector alignment options available at the time. The geometry of the new 3D MESA SSD is less sensitive to this alignment restriction was able to measure the microbeam profiles within 2μm of that expected. The 3D MESA SSD measured PVDRs were possibly affected by undesired and slow charge collection outside the sensitive volume and additional scattering from the device substrate.

1. Introduction

Microbeam Radiation Therapy (MRT) is a preclinical radiotherapy modality characterised by use of a synchrotron light source to produce highly collimated, micron-scale striated x-ray fields under development to treat radiation resistant and otherwise untreatable tumours. Typical MRT configurations consist of multiple high dose 'peaks' of 25-75 µm separated by low dose 'valleys' 100-400 µm wide and are produced by a spectrum of X-rays in the range of 50-600 keV with treatment doses that can be delivered via dose rates of up to 20 kGy/s. The high dose rate (>1 kGy/s) and low divergent synchrotron X-rays are required for MRT in order to ensure the delivery of the spatially fractionated treatment dose profile to the tumour site. The Peak to Valley Dose Ratio (PVDR) and geometrical configuration of the microbeams is one of the main factors that are believed to be behind the success of MRT that leads to the minimisation of normal tissue damage while inflicting significant damage to the tumour tissue. A detector suitable for dosimetry of MRT must address the issues of very high dose rate and dose gradients that exist within the striated treatment field. This requires a dosimeter with micron size spatial resolution to resolve individual X-ray microbeams, and a large dynamic range (approximately 10^5) in order to simultaneously resolve instantaneous dose rate in both the peak and the valley. While conforming to both of these criteria, the dosimetry system must also be able to evaluate all of the main beam parameters quickly (ideally in real-time) for fast quality assurance of the treatment plan immediately prior to MRT treatment.

The Centre for Medical Radiation Physics (CMRP) has developed the X-Tream dosimetry system for use in quality assurance of MRT [1]. The system has a sampling rate of 1 µs and is coupled to a silicon strip detector (SSD). A variety of SSDs have been produced to address the challenges of high spatial resolution, high dynamic range, and real time response. The use of silicon detectors in an edge-on orientation [2] (rather than face-on where the face is perpendicular to the beam) has been investigated by CMRP as a way to increase spatial resolution - as in this geometry the spatial resolution is determined mainly by the thickness of the detector as opposed to the cross-sectional width when face-on. However, this introduces a non-water equivalent response due to interaction in the silicon surrounding the Sensitive Volume (SV) and substrate backing. The 3D MESA SSD was developed as a first step in overcoming some of the disadvantages of silicon dosimeters such as their energy dependence via selective etching of the silicon surrounding the sensitive volume (SV). The system and two generations of SSD (EPI and 3D MESA) were tested and characterised at the Australian Synchrotron (AS) on the Imaging and Medical Beam Line (IMBL) in hutch 1B. This hutch has installed a multislit collimator that produces horizontal microbeams of width 25 µm or 50 µm and pitch of 200 µm (denoted as '25/200' and '50/200' respectively).

2. Materials and Methods

The EPI SSD is a 10 µm wide silicon diode fabricated on a 50 µm thick epitaxial substrate, and then grown on top of a 370 µm thick p-type substrate, schematic shown in Figure 1. The structure itself incorporates an n+ guard ring which limits the SV of the device to approximately 30 µm, a detailed description of the device can be found in [3].

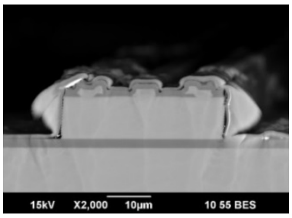


Figure 1. Schematic diagram of EPI SSD [3].

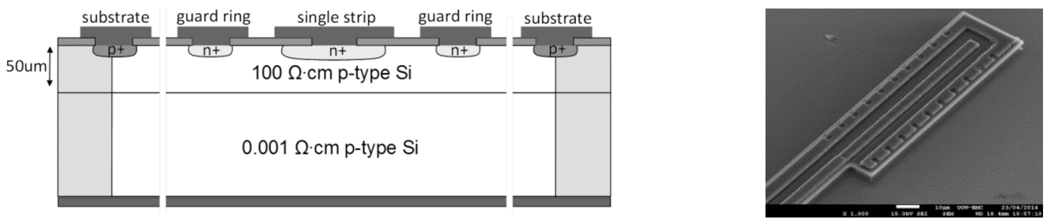


Figure 2. 3D MESA SSD: (left) top view of SV and bridge; (right) cross section of SV.

The 3D MESA SSD is an n-type Silicon-on-Insulator (SOI) device on a 300 µm thick silicon substrate with a SV 36 µm x 250 µm that has had surrounding silicon etched away 10 µm deep to the SiO_2 insulating layer. The middle contact is p+ doped and surrounded by a continuous n+ doped contact. Electron microscope images of the 3D MESA taken at the Australian Institute of Innovative Materials (AIIM) are shown in Figure 2. The 3D MESA and EPI devices were characterised at CMRP and tested in an MRT irradiation field at the AS, with readout of the devices performed by the X-*Tream* System. An operational reverse bias voltage of 60 V and 5 V for the EPI [3] and 3D MESA devices respectively was used. The filter configuration used at the AS is shown in Table 1 and experimental setup shown in Figure 3.

Before characterisation of the MRT treatment field profile, both devices were subjected to pre-irradiation in order to stabilise their response with irradiation that was performed in broadbeam mode (where the Multi-Slit Collimator (MSC) is removed) for a 2 x 10 mm² field. The EPI SSD was placed at the surface of a solid water (RMI-457) phantom (10 x 10 x 10 cm³) in face-on orientation and exposed for a five second exposure. The same procedure was performed for the 3D MESA SSD but for only 200 ms exposure was required to demonstrate the stability of its response.

The SSDs were then calibrated at 2 cm depth in the solid water phantom in a 2x2 cm^2 uniform X-ray field (same photon energy spectrum as MRT), via a PTW Pinpoint^{TM} ion chamber (model 31015). Characterisation of the MRT profile was then performed with the MSC in place by the EPI SSD and 3D MESA in edge-on orientation at 2 cm depth. Profiles were obtained by scanning the SSDs through the intrinsic MRT field containing 5 horizontal microbeams. The two microbeam geometries used in this experiment were 25/200 and 50/200. The measured FWHM of the microbeams as well as the PVDRs were then able to be deduced from the profiles.

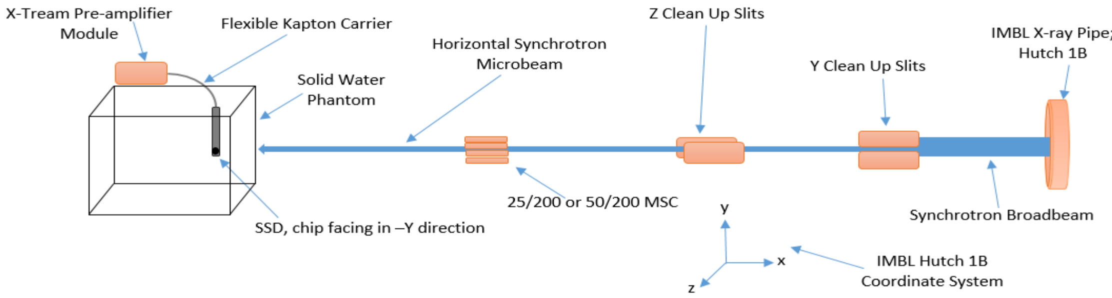


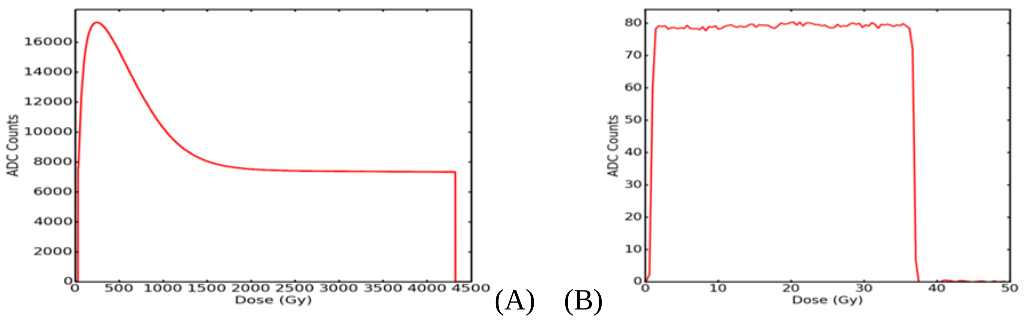
Figure 3. Experimental setup of experiments performed at AS IMBL, hutch 1B.

Table 1. Filter configuration used at AS.

Paddle	#1	#2	#3	#4	#5
Material	C	C[HD]	C[HD]	Cu	Cu
Thickness	4.5 mm	5 mm	10 mm	1 mm	1 mm
Angle	90°	45°	45°	45°	45°

3. Results

Figure 4 shows the pre-irradiation of the (A) EPI and (B) 3D MESA SSDs. Figure 5 shows the 50/200 MRT intrinsic field profiles measured by the (A) EPI and (B) 3D MESA SSDs. The PVDRs and FWHM measured by the detectors for both beam geometries are shown in Table 2.



(A) (B)

Figure 4. Pre-irradiation of the EPI SSD (A) and 3D MESA SSD (B).

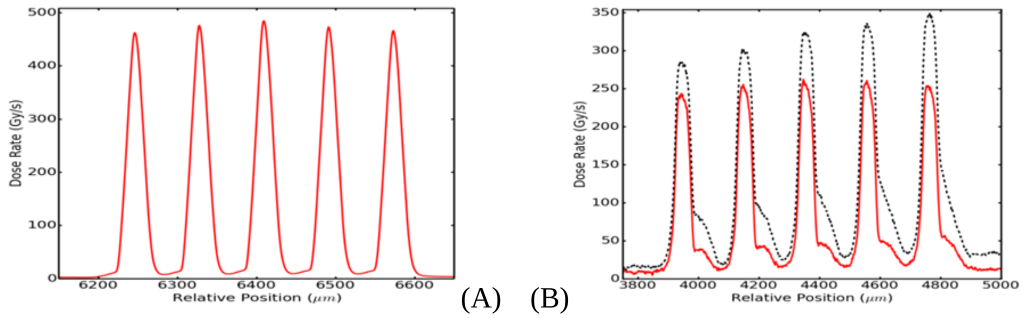


Figure 5. Measured 50/200 MRT profile using the (A) EPI SSD and (B) 3D MESA SSD showing initial scan in solid red and subsequent scan in dotted black (B).

Table 2. Comparison of FWHM and PVDR for the 3D MESA and EPI SSDs.

	EPI		3D MESA	
Beam geometry	PVDR	FWHM (μm)	PVDR	FWHM (μm)
25/200	41±3	45±4	35±4	26±1
50/200	38±2	56±5	14±2	52±1

4. Discussion

The significant change in EPI SSD response with total irradiation dose is due to the reduction in the undesired charged collection from under the wire bonding pads. Beyond 2.5 kGy of pre-irradiation the response is stable (reduces by 1% per kGy). For the 3D MESA SSD, the response is stable immediately upon irradiation. Minimising the surrounding silicon from the bonding pads and sensitive volume appears to make the pre-irradiation of the 3D MESA redundant. The response of the 3D MESA is ~100 times less than the EPI due to its much smaller SV.

The EPI SSD measured larger FWHMs than expected (especially for the 25/200 MSC) due to volume averaging effects over the larger effective SV resulting from the detector misalignment with respect to the microbeams (see Figure 5A). The result clearly highlights one of the challenges in MRT dosimetry. On the other hand, the 3D MESA measured FWHMs within ±2 μm expected value defined by the microbeam defining slots in the MSC (see Table 2).

The PVDRs for the 25/200 MSC geometry agreed for both SSDs. For the 50/200 MSC geometry however, the EPI SSD measured PVDRs that were significantly larger than that measured by 3D MESA. PVDRs are poor for 3D MESA due to the structure observed in the valley regions. Further investigation shows that the 3D MESA profiles were affected in two ways. The edge-on orientation led to small ‘bumps’, to the left of the peak profiles (see Figure 5B) which is the ‘substrate’ side of the SSD. It is possible that these due to a contribution from electrons generated in the substrate as previously reported by Rosenfeld [2]. In addition, repeated profile scans produced an increase in baseline during these consecutive scans which we attribute to very slow charge collection generated under the bridge between the active volume and the wire bonding pads. This effect was subsequently investigated using Ion Beam Induced Charge Collection (IBICC) studies (not shown), which indicated determined that this effect did not occur at reverse biases less than 3 V. The experimental methodology will therefore be adjusted for future experiments to address these issues.

5. Conclusion

Two generations of single silicon strip detectors (EPI SSD and 3D SOI MESA) have been developed at the Centre for Medical Radiation Physics, University of Wollongong, for real-time MRT dosimetry. The SSDs were compared by characterising the 25/200 and 50/200 intrinsic MRT fields at the Australian Synchrotron. The geometry of the new 3D MESA SSD was found to be less sensitive to mechanical alignment restrictions and was clearly able to measure the FWHM of the X-ray microbeam profiles however features observed in the valley affected the PVDR estimation in the MRT field. Future work will include investigation into reducing thickness of the silicon substrate in edge-on orientation and examination of the effect of bias on the observed valley features and PVDRs.

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