

The Development of a Novel Silicon Microdosimeter for High LET Radiation Therapy

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Certificate of Originality

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person nor material which to a substantial extent has been accepted for the award of any other degree or diploma of a university or other institute of higher learning except where due acknowledgment is made in the text.

I also declare that the intellectual content of this thesis is the product of my own work, even though I may have received assistance from others on style, presentation and language expression.

(Signed).....

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Abstract

This work is the first comprehensive investigation of the issues confronting silicon microdosimetry and its application to radiotherapy. Four main problems requiring investigation are identified and addressed including requirement specification with particular emphasis on device shape, tissue equivalence, noise minimization, and sensitive volume definition.

Analysis of device shape showed that a rectangular parallelepiped with a tissue equivalent converter on top of device (i.e. a silicon microdosimeter) provides a lineal energy spectrum that is closely equivalent to a sphere using the criteria of equal dose mean lineal energy. The tissue equivalent study demonstrated that under appropriate geometrical scaling (dimensions multiplied by $1/0.63$) silicon detectors with well known geometry will record energy deposition spectra representative of tissue cells of equivalent shape. A novel prototype device using silicon-on-insulator (SOI) is presented. Silicon-on-insulator technology assists in defining the sensitive volume depth although the current device still suffers from lateral diffusion effects. I-V and C-V testing are performed and a noise optimization design model is presented. Methods for characterizing the collection efficiency and radiation hardness of silicon microdosimeters are presented and compared including alpha and proton microbeam spectroscopy, broadbeam alpha spectroscopy and 2D and 3D device simulation.

Results from testing the low noise prototype SOI device at several high LET clinical facilities including BNCT, proton therapy and fast neutron therapy facilities are presented. In the BNCT experiments, a simultaneous thermal neutron flux and microdosimetric measurement at a high spatial resolution is demonstrated. The use of SOI technology in experimental microdosimetry offers simplicity (no gas system or HV supply), high spatial resolution, low cost, high count rate capability and the possibility of integrating the system onto a single device with other detector types. The device also offers applicability in radiation protection and electronic single event upset (SEU) studies.

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List of Publications by the Author

The following publications are by the author, several of which are used in this work:

- (1) P. Bradley, "The effects of ionising radiation on implantable MOS electronic devices," in *Graduate School of Biomedical Engineering*, Sydney: University of New South Wales, 1996, 245 pages.
- (2) P. D. Bradley, A. B. Rosenfeld, K. K. Lee, D. Jamieson, G. Heiser, and S. Satoh, "Charge collection and radiation hardness of a SOI microdosimeter for space and medical applications," *IEEE Trans. Nucl. Sci.*, vol. 45, no. 6, pp. 2700-2710, 1998.
- (3) P. D. Bradley and A. B. Rosenfeld, "Tissue Equivalence Correction for Silicon Microdosimetry Detectors in Boron Neutron Capture Therapy," *Med. Phys.*, vol. 25, no. 11, pp. 2220-2225, 1998.
- (4) P. D. Bradley and E. Normand, "Single event upset in implantable cardioverter defibrillators," *IEEE Trans. Nucl. Sci.*, vol. 45, no. 6, pp. 2929-2940, 1998.
- (5) P. D. Bradley, A. B. Rosenfeld, B. J. Allen, T. Kobayashi, Y. Sakurai, C. Kota, R. L. Maughan, M. Yudelev, J. Coderre, and J. Capala, "Application of silicon diode arrays for microdosimetry in BNCT and FNT," *8th International Symposium on Neutron Capture Therapy for Cancer, La Jolla, USA, 14-18th Sep 1998*, 1998.
- (6) P. D. Bradley, A. B. Rosenfeld, B. J. Allen, J. Corderre, and J. Capela, "Performance of silicon microdosimetry detectors in boron neutron capture therapy," *Radiat. Res.*, vol. 151, pp. 235-243, 1999.
- (7) P. D. Bradley, A. B. Rosenfeld, M. Bailey, M. Reinhard, K. K. Kee, A. Saint, D. Jamieson, F. Lemeilleur, and S. Satoh, "Radiation hardness and charge collection in a SOI based diode array designed for medical microdosimetry," *Nuc. Inst. Meth. Phys. Res.*, In press 1998, submitted Feb 1998.
- (8) A. B. Rosenfeld and P. B. Bradley, "Semiconductor microdosimetry in mixed radiation field and photon fields: present and future," *Radiation Protection Dosimetry*, vol. 85, no. 1-4, pp. 385-388, 1999.
- (9) A. B. Rosenfeld, P. D. Bradley, I. Cornelius, G. I. Kaplan, B. J. Allen, J. B. Flanz, M. Goitein, A. V. Meerbeeck, J. Schubert, J. Bailey, Y. Takada, A. Maruhashi, and Y. Hayakawa, "A new silicon detector for microdosimetry applications in proton therapy," *IEEE Trans. Nucl. Sci.*, vol. 47, no. 4 (In Press), 2000.

In addition, the author has presented work at the following conferences:

- (1) IEEE Nuclear Science and Medical Imaging Conference, Seattle USA, October 26-30, 1999. Poster: "A New Silicon Detector for Microdosimetry Applications in Proton Therapy"
- (2) 5th National Workshop Experimental Radiation Oncology, Sydney Australia, Nov 27 1998. Poster: "Application of silicon diode arrays for microdosimetry in High LET Radiation Oncology"
- (3) Engineering and the Physical Sciences in Medicine (EPSM98), Hobart, Australia, Nov 1998. Poster: "The Development of a Novel Silicon Microdosimeter for Radiation Oncology" (presented by A.B. Rosenfeld on authors behalf)
- (4) 8th International Symposium on Neutron Capture Therapy for Cancer, La Jolla USA, Sep '98. Presentation: "Application of silicon diode arrays for microdosimetry in BNCT and FNT" (presented by A.B. Rosenfeld on authors behalf)
- (5) IEEE Nuclear and Space Radiation Effects conference, Newport USA, July 20-24 1998. Presentation: "Single event upset in implantable cardioverter defibrillators" Presentation: "Charge collection and radiation hardness of a SOI microdosimeter for space and medical applications"
- (6) Hiroshima@Melbourne Symp. semi-conductor tracking detectors, Melbourne Aust., Nov 1997 Presentation: "Radiation hardness and charge collection in a SOI based diode array designed for medical microdosimetry"
- (7) 1st Symposium on Soft Errors, Radiation effects and Reliability in VLSI: Terrestrial Applications NASA/SEMATECH/SRC, NASA/Goddard Space Flight Center, Oct 27, 1997, Presentation: "Cosmic Ray Induced Single Event Upsets in Implantable Cardioverter Defibrillators", (presented by E. Normand (Boeing Defense and Space) on authors behalf)

1. Introduction

1.1 Background

Ionizing radiation deposits energy within matter via the processes of ionization and excitation. These interactions deposit energy in discrete highly concentrated packages distributed non-uniformly throughout an irradiated body. Although, the standard quantity for specification of irradiation is the absorbed dose, defined as the average energy deposited per unit mass, radiation effects are largely determined by the microscopic pattern of energy distribution relative to the sensitive structures of the irradiated body. For the case of biological effects, it is well known that radiation types with differing patterns of energy distribution will have different effects for the same absorbed dose. This effect is quantified by the term relative biological effectiveness (RBE). The field of microdosimetry evolved from a desire to understand the effects of different radiation sources through an analysis of the absorption of ionizing radiation at a scale comparable to the affected structures.

Microdosimetry is formally defined by Rossi and Zaider as [1] “the systematic study and quantification of the *spatial* and *temporal* distribution of absorbed energy in irradiated matter”. Although, much of the historical development of microdosimetry has focused on its applications to radiobiology, the concepts have utility in a diverse range of applications such as radiation effects on electronics. The fields of radiation protection, radiobiology, radiotherapy and radiation effects on electronics require microdosimetry methods for measuring the pattern of energy deposition in small cell-sized volumes.

The scale of measurements in microdosimetry is typically at the micron level. At such small dimensions, the primary tool of experimental microdosimetry has been the low-pressure proportional counter. Although generally considered the best currently available detector, the proportional gas counter has several shortcomings. These include a relatively large physical size which limits spatial resolution and increases vulnerability to pileup effects (p198 [1]), the use of gas in the detection volume which leads to phase effects and wall effect errors [2], and an inability to simulate an array of cells.

In certain applications silicon based detectors offer significant advantages particularly with regard to spatial resolution. McNulty [3] proposed the use of arrays of silicon

reverse-biased p-n junctions for characterizing complex radiation environments inside spacecraft and aircraft primarily. The work was intended to have applications in determining single event upset (SEU) risks to microelectronics and as a biological microdosimeter for personnel monitoring. The detector is connected to a spectroscopic system in which charge collection induced by radiation interactions is recorded by a multi-channel analyzer. Such a detector removes several of the previously mentioned problems associated with proportional gas counters. Silicon diode array microdosimetry exploits the small size, rapid development, and current manufacturing capabilities of integrated circuit technology. Furthermore, the capabilities of such technology continue to grow at an astonishing pace enabling the development of new detector designs.

Fortunately, the requirements of a device designed to study SEU phenomena coincide with the requirements of a biological microdosimeter. This is a manifestation of the close correlation between SEU phenomenon, biological cell death, and microdosimetry [1, 4]. For example, an electronic memory state change (or bit flip) is analogous to cell death in radiobiology. Both applications demand an accurately defined sensitive volume (region of charge collection), an array of identical diodes to improve collection statistics and diode structure sizes of the order of a few microns. Therefore, in developing a silicon microdosimeter one may draw upon the wealth of study in single event upset phenomenon in electronic devices.

However, several problems have impeded the widespread application of silicon based microdosimetry in medical applications. These problems include the tissue equivalence of the device, insufficient low noise capability and a poorly defined sensitive volume. In this work, a novel high spatial resolution silicon based microdosimeter using silicon-on-insulator (SOI) technology is presented. The aim of this work was to develop methods that address the key problems impeding silicon microdosimetry using the SOI microdosimeter as a prototype test device. The feasibility of using the device in high linear energy transfer (LET) clinical environments was verified by experimentation at boron neutron capture therapy (BNCT), fast neutron therapy (FNT) and proton therapy facilities. Such an encompassing study of the problems affecting silicon microdosimetry and the application of such devices to medical radiation environments has not previously been attempted.

1.2 Thesis Outline

The organization of the thesis is shown in detail in the Table of Contents and described briefly as follows:

- Chapter 1. Brief introduction and thesis outline
- Chapter 2. The literature review summarizes past and current research in the areas relevant to the thesis topic. Emphasis is given to experimental methods in microdosimetry and particularly, previous research in developing and testing silicon based microdosimeters. The rationale behind utilizing silicon based microdosimetry in medical radiotherapy applications is discussed. Four main problems requiring investigation are identified (and addressed in chapters 3, 4, 5 and 6) including requirements especially device shape, noise minimization, tissue equivalence, and sensitive volume definition. Additional literature reviews occur throughout the thesis where it is necessary to introduce background material for improved understanding.
- Chapter 3. The *requirements* of a silicon microdosimeter are discussed with a particular emphasis on *detector shape* considerations. Criteria for the equivalence of measurements made using a rectangular parallelepiped shaped silicon device, with a tissue equivalent converter, are determined.
- Chapter 4. The *design* of the silicon-on-insulator (SOI) prototype device and associated electronics is described along with a *noise optimization* model used in the prototype design. I-V and C-V testing of the prototype is presented. Although not meeting all the desired requirements the device is an improvement on previously constructed silicon microdosimeters.
- Chapter 5. The problem of *tissue equivalence* correction for silicon microdosimetry is addressed. A method for correcting microdosimetric measurements in silicon to tissue volumes is derived and confirmed using Monte-Carlo simulations.
- Chapter 6. The device *sensitive volume* and *radiation hardness* is determined. Methods for characterizing the collection efficiency and radiation hardness of silicon microdosimeters are presented and compared including alpha

and proton microbeam spectroscopy, broadbeam alpha spectroscopy and 2D and 3D device simulation.

- Chapter 7. Having fully characterized the device behavior and addressed the key problems the prototype was tested in several major high LET clinical facilities. In this chapter, initial testing of the device at three *boron neutron capture therapy* facilities is presented (BNL, MIT and KUR). The interaction of thermal neutrons with each of the device materials is analyzed. Simultaneous thermal neutron flux and microdosimetric measurement at a high spatial resolution is demonstrated.
- Chapter 8. This chapter presents the first demonstration of a SOI based microdosimeter in a *neutron 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.
- Chapter 9. Initial testing of the device in two *proton therapy* facilities (PMRC, and NPTC) is presented. Testing at the recently constructed NPTC facility in Boston demonstrated the capability of the device to record lineal energy spectra with high spatial resolution. High count rate measurements not previously performed were made at PMRC.
- Chapter 10. Conclusion providing a summary of main results and suggested directions for further research.

In summary, the identified problems are addressed in chapters 3, 4, 5 and 6 whilst initial clinical facility testing follows in chapters 7, 8, and 9.

Finally some notes on presentation.

- The spelling in this thesis conforms to US English.
- References are presented in IEEE format. The use of "et.al" for references to papers with multiple authors is not used. The vast majority of papers have multiple authors and as such multiple authors may be assumed by default.