2007

Charge collection in PET detectors

Tony Young
University of Wollongong

UNIVERSITY OF WOLLONGONG

COPYRIGHT WARNING

You may print or download ONE copy of this document for the purpose of your own research or study. The University does not authorise you to copy, communicate or otherwise make available electronically to any other person any copyright material contained on this site. You are reminded of the following.

This work is copyright. Apart from any use permitted under the Copyright Act 1968, no part of this work may be reproduced by any process, nor may any other exclusive right be exercised, without the permission of the author.

Copyright owners are entitled to take legal action against persons who infringe their copyright. A reproduction of material that is protected by copyright may be a copyright infringement. A court may impose penalties and award damages in relation to offences and infringements relating to copyright material. Higher penalties may apply, and higher damages may be awarded, for offences and infringements involving the conversion of material into digital or electronic form.

Recommended Citation

Research Online is the open access institutional repository for the University of Wollongong. For further information contact the UOW Library: research-pubs@uow.edu.au
NOTE

This online version of the thesis may have different page formatting and pagination from the paper copy held in the University of Wollongong Library.

UNIVERSITY OF WOLLONGONG

COPYRIGHT WARNING

You may print or download ONE copy of this document for the purpose of your own research or study. The University does not authorise you to copy, communicate or otherwise make available electronically to any other person any copyright material contained on this site. You are reminded of the following:

Copyright owners are entitled to take legal action against persons who infringe their copyright. A reproduction of material that is protected by copyright may be a copyright infringement. A court may impose penalties and award damages in relation to offences and infringements relating to copyright material. Higher penalties may apply, and higher damages may be awarded, for offences and infringements involving the conversion of material into digital or electronic form.
Charge Collection in PET Detectors

By

Tony Young

Submitted in partial fulfilment of the requirements for the award of the degree of

Master of Science - Research

From

University of Wollongong

Faculty of Engineering

November, 2007
Acknowledgements

Many thanks to Dr Michael Lerch for his continued support and encouragement over the years. His enthusiasm for his research and his dedication to his students must be acknowledged. Without his input and assistance this project would have taken much longer to complete.

I’d also like to thank my family for supporting me as I completed this master’s project. Their concern and encouragement spurred me on to complete this within the allotted time, even though I had started full time employment. Their patience and understanding was much appreciated.

Also, thanks must go to Dr Phil Simmonds and Michael Bailey for their assistance with Scintillation Program and DETECT2000. Thanks also to Dr Alexey Pan for profiling the LYSO crystals.

Also, thanks must go to the staff and post graduate students at the CMRP. Each contributed in some way or another and each effort was very much appreciated, whether it was discussions on different Monte Carlo code, to detector setup, or a break in work for coffee. I am grateful for all their guidance and help.

Thanks also to Sydney South West Area Health Service (SSWAHS), in particular Macarthur Cancer Therapy Centre for employing me whilst I was completing the thesis. The one day of allotted study time was appreciated!

Lastly, my deepest thanks must go to those who were with me during this project.
Abstract

Improving the spatial resolution in PET will increase the chance of accurate diagnosis of cancer. PET detectors are comprised in part of detectors such as photomultiplier tubes or solid state photodetectors optically coupled to scintillation materials, such as BGO or LSO. In this thesis a study of recently developed photodiode detectors, SPAD4 photodiodes, and LYSO crystals has been undertaken to investigate these properties.

As part of this research IV (current-voltage) and CV (capacitance-voltage) characterization measurements were carried out on the photodetectors and results indicate they are of excellent quality. Ion Beam Induced Charge Collection (IBICC) measurements were undertaken to fundamentally investigate the effect of bias on the efficiency and uniformity of charge collection within the photodetector. A reverse bias operating voltage of 50 V was eventually chosen as the optimum bias voltage for the SPAD4 photodiode for the gamma ray spectroscopy and timing resolution experiments that followed the IBICC characterisation. Charge collection uniformity was found to be excellent at this optimum voltage.

An investigation into the surface treatment of LYSO crystal and cladding was also completed. Physical measurements and simulations were conducted and the results are compared. Past simulation results have demonstrated that scintillation crystals produced a higher output when the surface was rough as opposed to the industry standard smooth polished surface [1]. Physical measurements and comparisons have also been completed with saw cut finish crystals and chemically etched crystals [2, 3]. Simulations were completed with “Scintillation Program”, a simulation code developed at the CMRP, and DETECT2000. Measurements completed for this thesis produced no significant change in the deduced scintillator light output after roughening a crystal side.

Timing resolution in commercial PET scanners ranges from 8 to 16ns. Experimentally with a photomultiplier tube coupled to a photodiode, timing resolution as low as 9.4ns FWHM has been achieved [4]. Coincidence timing resolution measurements using standard NIM (Nuclear Instrumentation Module) electronic modules were taken with a
Nal-photomultiplier tube and the LYSO-SPAD4 photodiode module. The best result obtained was a FWHM coincident time resolution of 22 ns, which is similar to past results.

The SPAD4 photodiode and LYSO crystal combination show promise as the basis for a future PET detectors module, although further work needs to be completed to improve the timing performance.
Table of Contents

ACKNOWLEDGEMENTS ......................................................................................................................... II
ABSTRACT .................................................................................................................................................. III
TABLE OF CONTENTS ................................................................................................................................. V
LIST OF FIGURES ........................................................................................................................................ VII
LIST OF TABLES ........................................................................................................................................... VIII
NOTATION/ABBREVIATION ...................................................................................................................... IX
PUBLICATIONS LIST .................................................................................................................................. IX

CHAPTER 1 – INTRODUCTION ............................................................................................................... 1
1.1 OVERVIEW OF PROJECT .................................................................................................................. 1
1.2 REASONS FOR RESEARCH ............................................................................................................. 2
1.3 AIMS/OBJECTIVES .......................................................................................................................... 2
1.4 THESIS OUTLINE ............................................................................................................................ 3

CHAPTER 2 – THEORY ............................................................................................................................ 4
2.1 LITERATURE REVIEW ...................................................................................................................... 4
2.1.1 Positron Emission Tomography .................................................................................................... 4
2.1.2 Ion Beam Induced Charge Collection ...................................................................................... 7
2.1.3 LYSO Scintillator Crystal .......................................................................................................... 8
2.1.4 SPAD Photodiodes ..................................................................................................................... 10

CHAPTER 3 – ION BEAM INDUCED CHARGE COLLECTION .......................................................... 13
3.1 CURRENT – VOLTAGE MEASUREMENTS ....................................................................................... 13
3.1.1 Current - Voltage Measurement Method .................................................................................... 13
3.1.2 Current - Voltage Measurement Results .................................................................................... 13
3.2 CAPACITANCE – VOLTAGE MEASUREMENTS .............................................................................. 16
3.2.1 Capacitance - Voltage Measurement Method ............................................................................ 16
3.2.2 Capacitance - Voltage Measurement Results ............................................................................ 17
3.3 ION BEAM INDUCED CHARGE COLLECTION MEASUREMENTS ........................................... 19
3.3.1 Ion Beam Induced Charge Collection Measurement Method ................................................. 19
3.3.2 Ion Beam Induced Charge Collection Results ........................................................................ 21
3.3.2.1 Both Channels Reverse Biased .............................................................................................. 22
3.3.2.2 Anode Channel Reverse Biased, Guard Ring Floating ......................................................... 26

CHAPTER 4 – LYSO CRYSTAL SIMULATIONS AND MEASUREMENTS ........................................... 30
4.1 CRYSTAL PROFILE .......................................................................................................................... 30
4.2 LIGHT OUTPUT SIMULATIONS ....................................................................................................... 31
4.2.1 Scintillation Program Simulations .............................................................................................. 32
4.2.1.1 Scintillation Program Inputs .................................................................................................. 34
4.2.1.2 Scintillation Program Simulation Results .............................................................................. 35
4.2.2 DETECT2000 Program Simulations .......................................................................................... 38
4.2.2.1 DETECT2000 Input File ....................................................................................................... 38
4.2.2.2 DETECT2000 Simulation Results ........................................................................................ 40
4.2.3 Comparison between Simulation Results .................................................................................. 41
4.3 CRYSTAL MEASUREMENTS .......................................................................................................... 42
4.3.1 Crystal Measurements Method .................................................................................................. 42
4.3.2 Crystal Measurements Results .................................................................................................. 46
4.3.3 LYSO Crystal Measurements Comparison .............................................................................. 50
4.4 LYSO CRYSTAL SIMULATIONS AND MEASUREMENTS DISCUSSION .................................... 51

CHAPTER 5 – COINCIDENCE TIMING RESOLUTION MEASUREMENTS ........................................ 53
List of Figures

Figure 2.1: Basic Physics of Positron Emission Tomography  4
Figure 2.2: SPAD4 Photodiode Schematic 11
Figure 3.1: SPAD4 Reverse Bias IV Results, a) I vs V, b) I vs V^{1/2} 14
Figure 3.2: SPAD4 Forward Bias IV Results 15
Figure 3.3: SPAD4 Guard Ring IV Results 16
Figure 3.4: SPAD4 CV Results, a) C vs V, b) C^{2} vs V 17
Figure 3.5: Charge Collection Colour Bar 21
Figure 3.6: 0V – 50V Reverse Bias, Guard Ring Connected IBICC Results, Anode Output (Left), Guard Ring Output (Right) 23
Figure 3.7: IBICC Results Anode Output with Guard Ring Biased Energy Spectrum 24
Figure 3.8: IBICC Results Guard Ring Output with Guard Ring Biased Energy Spectrum 25
Figure 3.9: 0 V – 100 V Reverse Bias, Guard Ring Floating IBICC Results 27
Figure 3.10: IBICC Results Anode Output with Guard Ring Floating Energy Spectrum 28
Figure 3.11: Energy Map for 50 V Bias Guard Ring Floating Energy Spectrum, Channels 1888 - 1940 28
Figure 3.12: Channels 1970 – 2020, IBICC Results Anode Output with Guard Ring Floating Spectrum 29
Figure 4.1: Crystal 1 Side Allocation 30
Figure 4.2: Crystal 2 Side Allocation 30
Figure 4.3: Schematic figure of the experimental layout model used in Scintillation Program 33
Figure 4.4: Clad, Unclad and Side 2 Unclad Roughness Simulations using Scintillation Program 37
Figure 4.5: LYSO Crystal Measurement Equipment Setup 43
Figure 4.6: I-125 Spectrum with SPAD4 #1 44
Figure 4.7: I-125 Spectrum with SPAD4 #6 45
Figure 4.8: Comparison of SPAD4 Reference Crystal Measurements 46
Figure 4.9: Na-22 Spectrum Measurements Results 48
Figure 4.10: Cs-137 Spectrum Measurements Results 49
Figure 5.1: Leading Edge Timing (left) and Constant Fraction Timing (right) [41] 53
Figure 5.2: Zero Crossing Time Resolution Measurements with a Pulse Generator 55
Figure 5.3: Zero Crossing Time Resolution Measurements with a PMT
Figure 5.4: Gated Zero Crossing Time Resolution Measurements with a PMT
Figure 5.5: Time Axis Calibration Spectrum
Figure 5.6: Signal Centroid as a Function of Signal Rise Time
Figure 5.7: Timing Signal FWHM as a Function of Signal Rise Time
Figure 5.8: Gated TAC Spectrum
Figure 5.9: Ungated TAC Spectrum
Figure 5.10: Single Gate Time Resolution Equipment Diagram
Figure 5.11: Single Gated PMT – PD TAC Spectrum
Figure 5.12: PMT – PD Ungated TAC Spectrum
Figure 5.13: Double Gate Time Resolution Equipment Diagram
Figure 5.14: 74LS04N Hex Inverting Gate Connection Diagram
Figure 5.15: Double Gated TAC Spectrum
Figure 5.16: Ungated TAC Spectrum

List of Tables
Table 2.1: Properties of Scintillators
Table 4.1: Average Roughness of each side of the profiled LYSO crystals
Table 4.2: Scintillation Program SPAD4 Transmission Files Configurations
Table 4.3: Comparison of the LYSO states without roughing with Scintillation Program
Table 4.4: Varying Side 2 Roughness under different crystal conditions using Scintillation Program
Table 4.5: DETECT2000 Light Output Simulations Results
Table 4.6: Comparison between Scintillation Program and DETECT2000 of Results
Table 4.7: Comparison of SPAD4 Reference Crystal Measurements
Table 4.8: Na-22 Measurements Results
Table 4.9: Cs-137 Measurements Results
Table 4.10: Comparison Between Simulations and Measured Results
Table 5.1: Results of Varying Rise time
Table 5.2: Function Table for 74LS04N Hex Inverting Gate
Notation/Abbreviation
CMRP = Centre for Medical Radiation Physics
UOW = University of Wollongong
PET = Positron Emission Tomography
CT = Computed Tomography
MRI = Magnetic Resonance Imaging
IBICC = Ion Beam Induced Charge Collection
PMT = Photomultiplier Tube
PD = Photodiode
LYSO = Lutetium Yttrium Oxyorthosilicate
LSO = Lutetium Oxyorthosilicate
BGO = Bismuth Germanium Oxide
GSO = Gadolinium Silicate
FWHM = Full Width at Half Maximum
IV = Current Voltage
CV = Capacitance Voltage
SLICE = Scintillator Light Collection Efficiency
Int = Integration
Diff = Differentiation
CFD = Constant Fraction Discriminator
TFA = Timing Filter Amplifier
TAC/SCA = Time to Amplitude Converter/Single Channel Analyser
Na–22 = Sodium 22
Cs–137 = Caesium 137
I-125 = Iodine 125
NECR = Noise Equivalent Count Rate

Publications List