



**AIN SHAMS UNIVERSITY**

**FACULTY OF ENGINEERING**

**ELECTRONICS & COMMUNICATIONS DEPARTMENT**

**Implementation and Characterization of X-Ray Medical Imaging  
System**

**A Thesis**

Submitted to the Electronics and Communications Department,  
Faculty of Engineering, Ain Shams University  
For Master Degree in Electrical Engineering

Submitted By

**Abdelhady Ali Hassen Ellakany**

B. Sc. Electronics and Communications -2009

Supervised By

**Prof. Dr. Ismail Mohamed Hafez**

Faculty of Engineering, Ain Shams Univ.

**Prof. Dr. Christian Gontrand**

INSA-Lyon, Lyon, France.

**Assoc. Prof. Mohamed Abdelhamid Abouelatta**

Faculty of Engineering, Ain Shams Univ.

**Cairo, Egypt, 2017**

# **APPROVAL SHEET**

**Thesis title:** Implementation and Characterization of X-Ray Medical Imaging System

**By:** Abdel Hady Ali Ellakany

**Degree:** Master of Science in Electronics Engineering.

**This Thesis for Master Degree has been approved by:**

**Prof. Dr. El-Sayed Mahmoud El-Rabaie**  
Faculty of Electronics Engineering  
Menoufia Univ.

**Signature**  
(.....)

**Prof. Dr. Abdelhalim Abdelnaby Zekry**  
Electronics and Communications Eng. Dept.,  
Ain Shams Univ.

(.....)

**Prof. Dr. Ismail Mohamed Hafez**  
Electronics and Communications Eng. Dept.,  
Ain Shams Univ.

(.....)

Date of Examination: 29 / 7 / 2017

## Abstract

X-ray imaging is a well-known imaging modality that has been used for over 100 years since Roentgen discovered X-rays based on his observations of fluorescence. His initial results were published in 1885. Since 1901, equipment manufacturers started selling X-ray equipment.

Today, X-ray and its three-dimensional (3D) extension, computed tomography (CT), are used commonly in medical diagnosis. Medical imaging system consists of source of x-ray and detectors. The detectors are developed to meet future medical application like decreasing charge sharing.

The 3D silicon detector structure and 3D cadmium telluride (CdTe) detector structure are investigated. The simulation of the 3D structure is carried out by using SILVACO TCAD. The obtained results are used as a proof of concept for investigating the 3D detectors in different scientific applications. Also, it is designed to have a good charge collection efficiency, position resolution and reduced charge sharing effects.

The collection time of 3D silicon detector evaluated 6 nsec at 1.5 V, 4 nsec at 3.3 V and stray capacitance of structure is .14 Pf at 10 V, the leakage current at 3.3 volts is about 9nA.

The collection time of the 3D CdTe structure is about  $4 \times 10^{-11}$ s at 15 V. The fast and hard detection of the structure makes it suitable for stopping power up to 3TeV, which meets the future applications of SLHC. The very low leakage current, which is about 16 pA at 16 volts, is very attractive for most future applications

which allow us to apply higher bias voltage than was possible with previous traditional 2D CdTe detectors. The 3D CdTe technology could be recommended for future high-energy physics and medical applications.

Also, a system of a hybrid pixel detector has been developed. The purpose is to create a flexible and reliable model that simulates the entire system, starting from a 3D detector to a data acquisition system and processing analysis. The model flexibility is achieved by minimizing interdependencies among its entities, so they can be added or removed as needed. The implementation of the system is accomplished using SILVACO and Simulink/MATLAB.

Simulink is used to implement the readout circuit. The front-end readout circuit includes the Charge Sensitive Amplifier (CSA) and Active Shaper. The most suitable approach and parameters for a real system are selected according to the simulation results. Additionally, practical design constraints are also included in the model.

Keywords—SILVACO; Simulink/MATLAB; Silicon Detector; X-ray system; Three –dimensional structure; 3D CdTe Detector; Hybrid pixel detector

## **Statement**

This thesis “Implementation and Characterization of X-Ray Medical Imaging System” is submitted to Faculty of Engineering, Ain Shams University for the degree of master in Electronics engineering.

The work included in this thesis was carried out by the author. No part of this thesis has been submitted for a degree or a qualification at any other University or Institution.

DATE: 29 /7 /2017

Author: Abdelhady Ali Hassan Ellakany.

Signature:.....

## Acknowledgements

This thesis could not be completed without the help and support from many people.

I would like to express my deepest gratitude to ***Prof. Dr. Ismail Mohamed Hafez***, Electronics and Communication Department, Faculty of Engineering, Ain Shams University, and ***Prof. Dr. Christian Gontrand***, Lyon France, for their guidance, generous assistances, encouragement and supervision of this work.

Also, I would like to express my gratitude to my supervisor, ***Assoc. Prof. Mohamed Abouelatta***, for his continuous guidance. Without his valuable advice, none of this work would have been achieved. His efforts and encouragements will never be forgotten. But my only wish is that guiding me through this M. Sc has not been such a nightmare for him after all. Thanks to ***Assoc. Prof. Ahmed Shaker*** has also contributed in this mentoring process. Working with the SILVACO TCAD team has also been a great privilege. Also, I want to thank ***Prof. Abdelhalim Zekry*** and ***Dr. Gihan Sayah*** for their guidance.

# Table of Contents

<b>Abstract.....</b>	<b>iii</b>
<b>Acknowledgements.....</b>	<b>vi</b>
<b>Table of Contents .....</b>	<b>vii</b>
<b>List of Figures.....</b>	<b>xi</b>
<b>List of Tables.....</b>	<b>xiii</b>
<b>List of Publications.....</b>	<b>xv</b>
<b>Nomenclature.....</b>	<b>xvi</b>
<b>Abbreviation .....</b>	<b>xvii</b>
<b>Chapter 1 Introduction</b>	<b>1</b>
1.1 Background .....	1
1.2 The Problem Domain and the Specific Problem Addressed.....	5
1.3 Research That Has Been Carried out.....	6
1.4 The Expected or Achieved Contributions.....	7
1.2 Thesis Structure.....	8
<b>Chapter 2 literature Review of Medical Detectors.....</b>	<b>11</b>
2.1 Historic Review .....	11
2.2 Present Detection System .....	14
2.2.1 Silicon as Absorption Material in X-Ray Detectors .....	15
2.2.2 Germanium as Absorption Material in X-Ray Detector.....	16
2.2.3 Cadmium Telluride as Absorption Material in X-Ray Detector.....	16
2.2.4 Cadmium Zinc Telluride as Absorption Material in X-Ray	17
Detector.....	
2.2.5 Comparison between Different Materials.....	18
2.3 Planar Detectors and Their Limitation..... ..	19

2.3.1 Charge Coupled Devices (CCDs).....	19
2.3.2 CMOS Pixel Sensors .....	20
2.3.3 Limitations of Conventional Pixel Detector.....	21
2.3.3.1 The Collection Time.....	21
2.3.3.2 Inactive Area .....	22
2.3.3.3 Depletion Voltage.....	22
2.4 Advantages of 3D Detectors.....	23
2.4.1 Fabrication .....	23
2.4.2 Fast Charge Collection Time .....	25
2.4.3 Charge Sharing .....	26
2.4.4 Radiation Hardness.....	26
2.4.5 Active Edge .....	27
2.5 Induced Signals in the 3D Detectors .....	29
<b>Chapter 3 Modeling and Simulation of 3D Detector .....</b>	<b>33</b>
3.1 Simulation of Standard 3D Detector by SILVACO.....	33
3.2 SILVACO Tools.....	34
3.3 Simulation by SILVACO Device.....	37
3.3.1 Physics Models.....	37
3.3.1.1 SHOCKLY–READ-HALL Models Recombination in the Bulk.....	37
3.3.1.2 Auger Recombination Model .....	40
3.4 Heavy Ion Model Simulation (Single event upset effect) .....	41
3.5 Interactions of Photons.....	42
3.5.1 Photoelectric Effect.....	43
3.5.2 Compton Scattering .....	45
3.5.3 Pair Production .....	47
3.6 Mechanisms of Traps Generation.....	49



3.6.1 Increase in Leakage Current under Bias.....	51
3.6.2 Increase in Effective Doping Concentration.....	52
3.6.3 Trapping of Free Charge Carriers.....	53
3.7 Trap Levels is Used SILVACO Simulation.....	54
3.7.1 Trap Level in Silicon.....	54
3.7.2 Acceptor Trap in CdTe.....	54
3.8 Carrier Lifetime in Semiconductor.....	55
3.8.1 Definition of Carrier Lifetime in Semiconductor.....	55
3.8.2 Control of Charge Carrier Lifetime.....	56
3.8.3 Irradiation Effects on Carrier Lifetime.....	57
3.9 The Full Depletion Voltage (VFD).....	58
3.9.1 Cylindrical Junction.....	58
3.10 Charge Collection Time .....	60
<b>Chapter 4 Simulation Results of 3D Detectors .....</b>	<b>63</b>
4.1 Results of 3D silicon detector.....	63
4.1.1 Leakage Current .....	63
4.1.2 Impulse Cathode Current at 1.5 V. ....	64
4.1.3 Impulse Cathode Current at 3.3Volts.....	64
4.1.4 The Small Signal Simulation Results.....	66
4.1.5 Discussions about Simulation Results.....	66
4.1.6 The Electrostatic Potential Distribution.....	67
4.2 Results of 3D CdTe Detector.....	69
4.2.1 Leakage Current of CdTe Detector .....	69
4.2.2 Operation of the3D Detector at Low Voltage.....	70
4.2.3 Operation of 3D CdTe Detector at High Voltage .....	71
4.2.4 Operation of 3D CdTe Detector at High Energy.....	73
4.2.5 Comparison between The Results of 3D CdTe.....	73

4.2.6 The Effect of Temperature on Cadmium Telluride Detector.....	75
4.2.7 The Small Signal Simulation Results of CdTe.....	76
4.2.8 The Potential of the 3D CdTe Detector.....	77
4.2.9 Simulation Comparison with Implemented published Structure.....	78
4.2.10 Stopping power.....	79
<b>Chapter 5 A complete System of X-Ray Detection .....</b>	<b>81</b>
5.1 SILVACO and MATLAB Framework Description.....	81
5.2 MATLAB Implementation Blocks.....	82
2.5.1 Readout Circuit by MATLAB.....	82
2.5.1.1 Preamplifier.....	83
2.5.1.2 Shaper.....	83
5.3 MATLAB Simulation Results.....	84
<b>Chapter 6 Conclusions and Future Work.....</b>	<b>89</b>
6.1 Conclusions .....	89
6.2 Future Work .....	91
<b>References .....</b>	<b>93</b>
<b>Appendices .....</b>	<b>103</b>
Appendix A1: Source Code for Silicon.....	104
Appendix A2: Source Code for CdTe.....	108

## List of Figures

<b>Fig. 1.1</b> Basic structure used in simulation using SILVACO .....	3
<b>Fig. 1.2</b> Structure of a 3D detector with electrodes penetrating through the entire substrate.....	3
<b>Fig. 2.1</b> A conventional planar electrode detector and inactive area.....	22
<b>Fig. 2.2</b> Collecting electrodes of 3D detector whilst induced signal is spread out in time for a planar device. ....	26
<b>Fig. 3.1</b> Basic structure used in simulation using SILVACO .....	34
<b>Fig. 3.2</b> mesh used in 3D detector .....	35
<b>Fig. 3.3</b> Doping concentration in a horizontal cross section .....	36
<b>Fig. 3.4</b> Doping concentration in a horizontal cross section.....	36
<b>Fig. 3.5</b> Details of the indirect recombination via trap center at $E=E_t$ showing the emission and capture Processes of electrons and holes, via the trap center .....	39
<b>Fig. 3.6</b> Schematic illustration of the auger recombination mechanism.	40
<b>Fig. 3.7</b> Concept of attenuation.....	43
<b>Fig. 3.8</b> Concept of photoelectric absorption.....	43
<b>Fig. 3.9</b> Concept of Compton scattering.....	46
<b>Fig. 3.10</b> Concept of pair production.....	47
<b>Fig. 3.11</b> Attenuation coefficient .....	48
<b>Fig. 3.12</b> Dominance of the interaction mechanisms at various energies for given Z-material.....	48
<b>Fig. 3.13</b> Energy band diagram illustrating how traps produce leakage current, space charge and trapping of excess carriers.....	51
<b>Fig. 3.14</b> The Trap model used in silicon .....	54

<b>Fig. 3.15</b> Illustration of the acceptor trap model that is used in CdTe.....	55
<b>Fig. 3.16</b> Effective minority carrier lifetime versus doping concentration .....	57
<b>Fig. 3.17</b> The cylindrical junction.....	59
<b>Fig. 4. 1</b> The dark I-V characteristics of 3D detector.....	64
<b>Fig. 4.2</b> Cathode current pulse shape produced by the 3D detector at 1.5 and 3.3 V. ....	65
<b>Fig. 4.3</b> The C-V characteristic of detector .....	65
<b>Fig. 4.4</b> 3D Detector electrostatic potential contours at $V_k=3.3$ V.....	66
<b>Fig. 4.5</b> 3D Detector electrostatic potential contours at $V_k=100$ V.....	67
<b>Fig. 4.6</b> Electrostatic potential contours in a vertical cross-section at $V_k=100$ V.....	68
<b>Fig. 4.7</b> Potential distribution in the planar detector at 200V.....	68
<b>Fig. 4.8</b> The Leakage current is presented to the 3D detector from 0 to 16 V.....	69
<b>Fig. 4.9</b> Output current of 3D CdTe at 3.3 V.....	71
<b>Fig. 4.10</b> Output current at 3TeV and 10 V. ....	72
<b>Fig. 4.11</b> output of 3D CdTe current at 15 V.....	72
<b>Fig. 4.12</b> Output current of 3D at 3TeV and 15 V.....	73
<b>Fig. 4.13</b> I-V characteristic of 3D CdTe detector at different temperatures.....	76
<b>Fig. 4.14</b> The C-V curves of the 3D CdTe detector.....	77
<b>Fig. 4.15</b> Electrostatic potential distribution off 3D CdTe detector at 16 V.....	77
<b>Fig. 4.16</b> Simulation comparison of CdTe at (a) 30 °C. and (b) 70 °C...	79

<b>Fig. 4. 17</b> (a) Silicon at 0.1 keV energy, 10-8cm diameter and 1000	
(b) CdTe at 0.1 keV energy, 10-8cm diameter and 1000 ...	80
<b>Fig.4. 18</b> (a) Silicon at 100 keV, 1000 photon and 10-8cm diameter	
(b) CdTe at 100 keV, 1000 photon and 10-8cm diameter....	80
<b>Fig. 5.1</b> Combined simulation workflow .....	81
<b>Fig. 5.2</b> Block diagram of an x-ray model. ....	83
<b>Fig. 5.3</b> Output signal from SILVACO as MATLAB input.....	85
<b>Fig. 5.4</b> Block diagram of read out circuit .....	86
<b>Fig. 5.5</b> Output signal from MATLAB.....	87
<b>Fig. 5.6</b> Output signal from shaper.....	87
<b>Fig. 6.1</b> Smart detector system.....	91

## **List of Tables**

<b>Table 1.1</b>	Physical properties of semiconductors materials .....	18
<b>Table 4.1</b>	Mobility of electron and hole in CdTe.....	70
<b>Table 4.2</b>	Comparison between the output results.....	69
<b>Table 4.3</b>	Physical models equations.....	75

## List of Publications

- [1] A. Ellakany, A. Shaker, M. Abouelatta, I. M. Hafez and C. Gontrand, "Modeling and simulation of a hybrid 3D silicon detector system using SILVACO and Simulink/MATLAB framework," *28th International Conference on Microelectronics (ICM)*, Giza , pp. 377-380, 2016.
  
- [2] A. Ellakany, A. Shaker, M. Abouelatta, I. M. Hafez, and C. Gontrand, "Development and simulation of 3D CdTe Pillar detector", *IEEE Transactions on Radiation and Plasma Medical Science*.(submitted)
  
- [3] A. Ellakany, M. Abouelatta, A. Shaker, I. M. Hafez, and C. Gontrand, E. El-Rabaie, "Towards 3D Nuclear Detectors".( It will be submitted to *Menoufia Journal of Electronic Engineering Research, MJEER*)