ELECTRICAL CHARACTERIZATION OF 4H SILICON CARBIDE SCHOTTKY DIODES UNDER ELECTRON RADIATION

BY

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ABSTRACT

Electronic components utilized in space missions are required to be radiation hard to maintain optimized electrical performance. Because of its wide bandgap, 4H-SiC based devices have been demonstrated to be the most suitable candidate for this purpose. This research investigates the effects of electron radiation on the electrical characteristics of 4H-SiC Schottky diodes. This thesis comprises of two parts: simulation and experimental part. The first part presents the simulation of current-voltage (I-V) characteristics of the Au/4H-SiC Schottky diode before and after irradiation. Simulation was performed using Silvaco Atlas TCAD simulation tool, where radiation induced traps was added into the structure of the simulated diode. The simulation results showed decrement in the forward (FB) and reverse bias (RB) leakage current after irradiation. This is believed to be caused by dopant deactivation due to the radiation induced traps. In the second part of the study, commercial 4H-SiC Schottky diodes were irradiated using EPS-3000 electron beam machine. After high dose of electron irradiation, FB current decreased while, RB leakage current increased. It is believed that, the increment in the RB leakage current is caused by generation-recombination (G-R) centers associated with electron-induce displacement damage. In addition, high temperature effects on the I-V characteristics of the diodes was also investigated. Temperature-dependent I-V simulations and measurements performed in the temperature range of 298 K–448 K. It was observed that FB and RB leakage current, series resistance Rs, barrier height Φb and saturation current Is are strongly dependent on the temperature.

خلاصة البحث

المكونات الإلكترونية المستخدمة في البعثات الفضائية يشترط أن تكون مقاومة للإشعاع ولكن من الصعب الحفاظ على أدائها الكهربائي الأمثل. الأجهزة التي تعتمد على4H-SiC قد أثبتت فاعليتها وحس ادائها في مثل هذه الضروف لان لديها نطاق طاقة واسع، هذه الأطروحة تبحث في آثار الإشعاع الإلكتروني على الخصائص الكهربائية للصمامات شوتكي الثنائية. وتضم هذه الدراسة قسمين: قسم المحاكاة و قسم الدراسة المختبرية. يعرض القسم الأول محاكاة خصائص التيار والجهد الكهربائي لصمام شوتكي الثنائيAu/4H-SiC قبل وبعد تعرضها للاشعاع. تم إجراء المحاكاة باستخدام اداة المحاكاةSilvaco Atlas TCAD. تم تنفيذ المحاكاة من خلال إضافة الإشعاع المستحث الى هيكل الصمام الثنائي. وأظهرت نتائج نقص في التيارالمتسرب سواء كانت الدارة مباشرة او عكسية. ويعتقد أن سبب ذلك يعود إلى تعطل عامل الإشابة الناجم عن الإشعاع المستحث. في الجزء التجريبي من الدراسة تم استخدام مولدEPS-3000 الاشعاع الكتروني على صمام شوتكي الثنائي4H-SiC الموجود في السوق. بعد التعرض لجرعة اشعاع عالية انخفض التيارالمتسرب في الدارة مباشرة في حين لوحظ ارتفاع في التيارالمتسرب في الدارة العكسية. ويعتقد أن الزيادة في في التيارالمتسرب ناجم عن مراكز الالتئام – التوليد (Generation-Recombination) المرتبطة بتروح الإلكترونات الفاعلة. بالإضافة إلى ذلك، كما تم التحقيق من آثار ارتفاع درجة الحرارة على خصائص الثنائيات. المحاكاة علىالتؤثير الحراري على خصائص التيار والجهد الكهربائي أجريت في درجات حرارة تتراوح بين298 و 448 كلفن. لوحظ أن التيارالمتسرب في الدارة المباشرة و العكسية ، وكذا مقاومة سلسلة روبية (R_s) وارتفاع الحاجز (Φ_b) وتيار التشبع يعتمد بشدة على درجة الحرارة.

APPROVAL PAGE

I certify that I have supervised and read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Master of Science in Electronics.

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DECLARATION

I hereby declare that this dissertation is the result of my own investigations, except where otherwise stated. I also declare that it has not been previously or concurrently submitted as a whole for any other degrees at IIUM or other institutions.

Sabuhi Ganiyev

Signature………………………..…… Date……………………………..

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I dedicate this research work to my beloved family, friends and the ummah...

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LIST OF ABBREVIATIONS

DTLS	Deep level transient spectroscopy
FB	Forward bias
G-R	Generation-Recombination
I-V	Current -Voltage
I-V-T	Temperature dependence current-voltage
KITE	Keithley Interactive Test Environment
MCTS	Minority carrier transient spectroscopy
MNA	Malaysian Nuclear Agency
NASA	*National Aeronautics and Space Administration*
RB	Reverse bias
RTD	Resistance Temperature Detector
TCAD	Technology computer aided design
TEM	*Transmission electron microscopy*

LIST OF SYMBOLS

Si	Silicon
C	Carbon
Ge	Germanium
SiC	Silicon Carbide
GaAs	Gallium arsenide
GaN	Gallium Nitride
E_g	Energy Bandgap
E_c	Conduction band
E_F	Fermi energy level
E_0	Vacuum energy level
Φ_S	Work function of semiconductor
Φ_M	Work function of the metal
Φ_B	Schottky barrier height
χ	Electron affinity
I	Current
I_s	Saturation current
q	magnitude of electronic charge
V	Forward-bias voltage
V_A	Applied external voltage
V_{bi}	Built-in potential
T	Temperature in Kelvin
A	Active diode area

A^*	Richardson constant
J	Current density
N_d	Donor density
N_D	Dopant density
$N_{def.}$	Defect concentration
ε	Permittivity
Q_d	Depletion region charge
R_s	Series resistance

CHAPTER ONE

INTRODUCTION

1.1 BACKGROUND

Electronic devices utilized in harsh radiation environments especially in outer space needs to be radiation hard to maintain the optimized electrical performance. Premature death of satellites is normally related to the degradation of electrical characteristics of the satellites electronic devices when exposed to space radiation. Diodes from various materials have been studied for application under harsh radiation environment. Due to its high radiation hardness, 4H-Silicon Carbide (4H-SiC) Schottky diodes have been shown to be the most suitable candidate for this purpose. This is because it has superior thermal and electrical characteristics such as wide band gap, higher thermal conductivity high critical breakdown field, high saturation electron drift velocity, high electron mobility, high chemical stability and strong mechanical strength. These properties makes it more attractive in many applications such as at satellite-based systems, detectors and high temperature electronics in the nuclear power industry (Philippe Godignon, 2011; Kübra Çınar, Cevdet Coşkun, 2010; Zhang Lin, 2009; S. Khanna, 2011). For these reasons researchers have actively conducted many experiments on 4H-SiC Schottky diodes during last decade.

1.2 PROBLEM STATEMENT

Diodes are one of the main components in an electronic circuit. Utilizing diodes in harsh radiation environment may create electrical damages to the diodes which affects their electrical properties and reliability, limiting its useful lifetime. For example, diodes are used in satellites as a component of solar inverters, as well as control panel used for radiation detection and monitoring applications in the nuclear power reactors and electrical circuits of teleoperated robots utilized in harsh environments. Therefore, it is very important to develop and investigate radiation sustainable diodes which can operate under radiation. SiC Schottky diodes are one of the most suitable candidates for these applications. The wide band gap of SiC compared to other conventionally used semiconductors such as Si and Ge makes it more attractive due to its increased resistance to radiation effects and the capability to operate stably in elevated and changing temperatures.

1.3 RESEARCH OBJECTIVES

i. To investigate the electrical characteristics of 4H-SiC Schottky diodes under electron radiation for different radiation doses.

ii. To simulate and analyze I-V characteristics of 4H-SiC Schottky diodes under electron radiation using Silvaco Atlas simulation tool.

1.4 RESEARCH SCOPE

- Electrical characterization

Current-voltage (I-V) characterization of 4H-SiC Schottky diodes by means of probing station and Keithley Interactive Testing Environment modules.

- Simulation

Simulation I-V characteristics of 4H-SiC Schottky diode under electron radiation using Silvaco Atlas simulation tool.

- Electron radiation

Electron irradiation of commercial SiC Schottky diodes using facilities provided by Malaysian Nuclear Agency (MNA).

1.5 RESEARCH METHODOLOGY

1.5.1 Simulation

The simulation will be conducted through the following steps:

- Literature study
  - Literature review related materials on Silvaco Technology computer aided design (TCAD)
- Identifying of TCAD product type
  - Identifying required TCAD product in order to simulate electrical characteristics of the diode
- Structure specification
  - Defining of mesh, regions electrodes and doping specificacion
- Material and numerical models specification
  - Definig of material, models, contact interface, methods, traps and operation temperatures
- Solution specification
  - log, solve, load, save
- Comprehensive analysis of simulation results
  - extraction of data and plotting of the result
- Final report

1.5.2 Experimental

The experiment will be conducted through the following steps:

- Literature study
  - Literature review related papers on 4H-SiC Schottky diodes and identifying their main prporties.

- Experimental setup
  - Identifying required instrumentation for experiments and familiarization with them.
- Selection of commercial 4H-SiC Schottky diodes
  - Selection of commercial diodes based on required criteria.
- Electrical measurements before irradiation
  - Room temperature I-V (current–voltage) measurements, temperature dependence I-V measurements will be conducted.
- Exposure to electron radiation
  - Irradiation of the diodes will be implemented in Malaysian Nuclear Agency at various dose levels.
- Electrical measurements after irradiation
  - Room temperature I-V (current–voltage) measurements, temperature dependence I-V measurements will be conducted.
- Result analysis
  - Based on the I-V characteristics, leakage current mechanism of SiC Schottky diodes will be analyzed.
- Final report

1.6 FLOW CHART

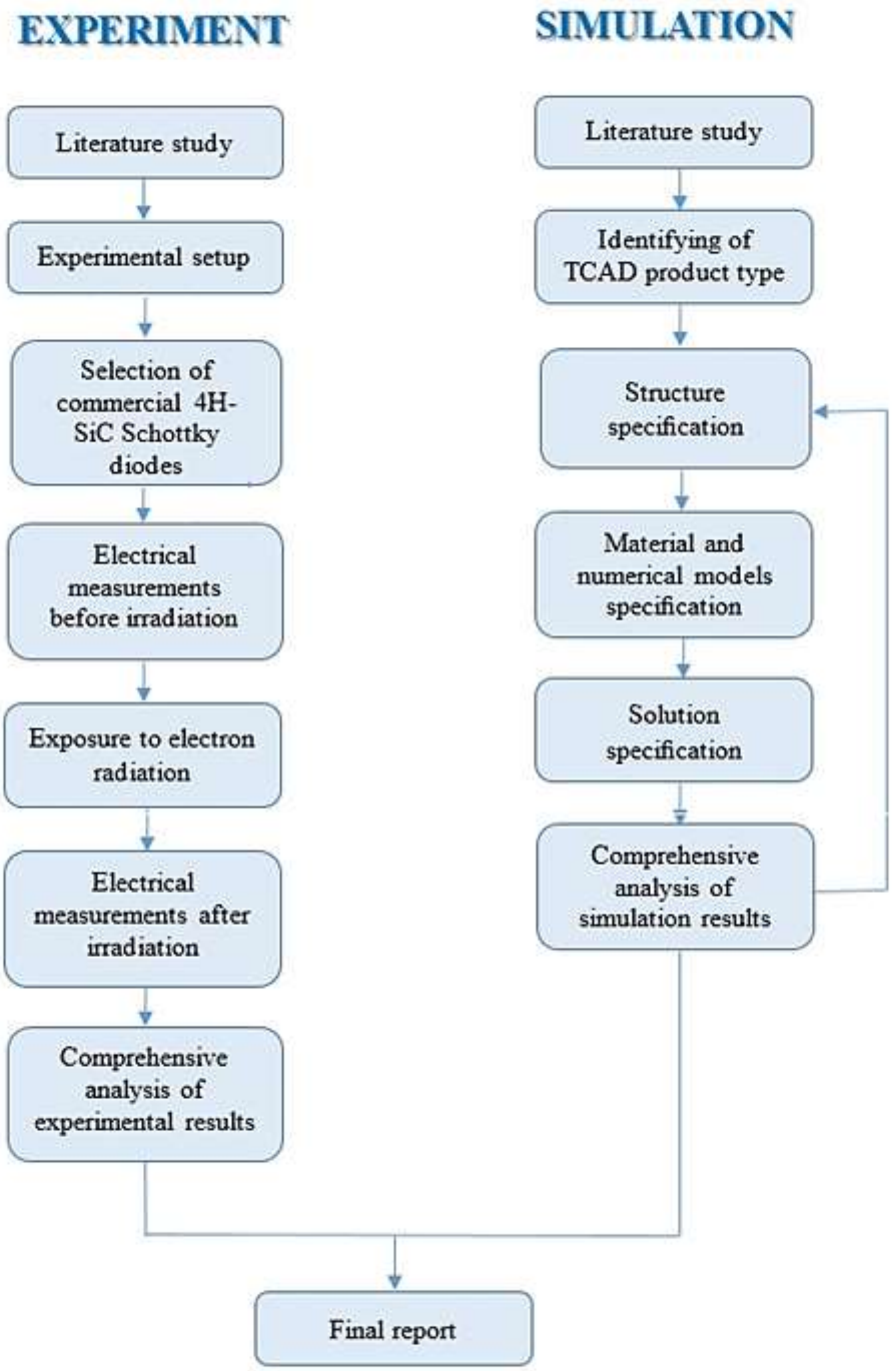

Figure 1.1 Flow chart of research methodology

1.7 OUTLINE OF THE THESIS

This thesis is organized as below:

Chapter 1 of the thesis comprise introduction that present a short background of the current research, problem statement, objectives, research scope and a methodology. **Chapter 2** covers the theoretical background and result findings of related previous works. **Chapter 3** presents the simulation and technical details and description of the equipment that used in this study. Moreover, it give information about irradiation facilities involved throughout the investigation. **Chapter 4** includes simulation results of electrical characteristics of 4H-SiC Schottky diodes under electron radiation. **Chapter 5** describes the experimental results that obtained after electron radiation. **Chapter 6** includes the main conclusion of the overall research findings and limitations of the conducted research. Lastly, recommendations for future works are discussed.

CHAPTER TWO

LITERATURE REVIEW

2.1 INTRODUCTION

This chapter will discuss theoretical aspects of SiC and its polytypes followed by type of radiation effects and its damages on semiconductor materials. Moreover, this chapter also includes the previous related works on related semiconductor devices as well as the effects of electron irradiation on 4H-SiC Schottky diodes.

2.2 SEMICONDUCTORS

Semiconductors are solid state materials that have intermediate conductivity between those of insulators and metals. In general, semiconductors can be classified under two groups: elemental and compound semiconductor materials. Elemental semiconductors can be found in group IV of the Mendeleev's periodic table, while compound semiconductor materials are created from combinations of II-IV and III-V groups. The most common semiconductor used in electronics is silicon (Si) which is one of the elemental semiconductors. However, development of the technology reached the point that application of Si based electronic does not meet needed requirements especially for high power application. The requirements include reliability, efficiency, switching frequency, high breakdown voltage and etc. To overcome these limitation, wide band gap compound semiconductors such as Silicon Carbide (SiC) and Gallium Nitride (GaN) with their superior properties are suitable candidate to replace Si. Thus, wide band gap semiconductor based devices offer significant performance improvements and can operate at harsh environments where Si based devices has its limitations.

2.3 CRYSTAL STRUCTURE OF SiC AND ITS POLYTYPES

Silicon carbide, is a compound of silicon (Si) and carbon (C) elements with chemical formula SiC. It has various stable crystal structures. The C atom is located at the centre of mass of the tetragonal structure and surrounded with the four neighboring Si atoms (Figure 2.1). The distance between C atom and Si atoms is about 2.52 Å, while the distance between neighboring C or Si atom is approximately 3.08 Å for all polytypes. Polytypism is a one dimensional variant of polymorphism which is the ability of a solid material to exist in more than one form or crystal structure. Polytypes only differs for the stacking sequence of atomic layers along one crystalline direction. Different polytypes has different height of unit cells (c). Therefore, the ratio of unit height and distance between neighboring atoms (c/a) differs from polytype to polytype. This ratio is 1.641, 3.271 and 4.908 for the 2H-SiC, 4H-SiC and 6H-SiC polytypes, respectively. It was proved by scientists that above mentioned polytypes are dependent on the orientation of seed (Park, 1998; Lee, 2002; Zetterling, 2002).

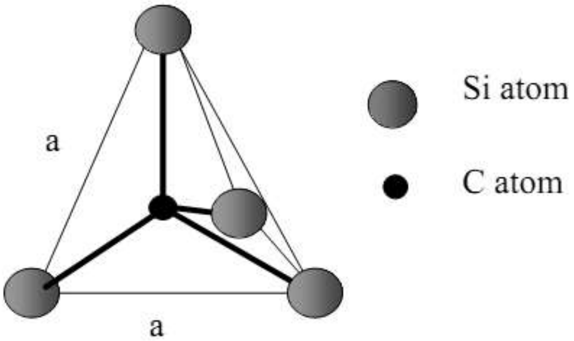

Figure 2.1 The tetragonal bonding of a C atom with the four nearest Si atoms (Lee, 2002)

Based on the reports it can be concluded that SiC has around 200 polytypes. 3C, 2H, 4H, 6H, 8H, 9R, 10H, 14H, 15R, 19R, 20H, 21H, and 24R are some of them,