NUMERICAL SIMULATION OF ONE-DIMENSIONAL SOLAR CELL MODEL

SEAH BOON YUN

BACHELOR OF ELECTRICAL ENGINEERING WITH HONOURS

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SEAH BOON YUN

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DECLARATION

I declare that this thesis entitled “NUMERICAL SIMULATION OF ONE-DIMENSIONAL SOLAR CELL MODEL” is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature : Yun

Name : SEAH BOON YUN

Date : 21 JUNE 2020

APPROVAL

I hereby declare that I have checked this report entitled "NUMERICAL SIMULATION OF ONE-DIMENSIONAL SOLAR CELL MODEL" and in my opinion, this thesis it complies the partial fulfilment for awarding the award of the degree Bachelor of Electrical Engineering with Honours.

Signature : ______________________________

Supervisor Name : DR. RAHIFA BINTI RANOM

Date : ______________________________

DEDICATIONS

To my supervisor,

Dr. Rahifa binti Ranom,

To my beloved father and mother,

Mr. Seah Say Tat and Mdm. Loh Phaik See,

To my supportive sibling,

Seah Boon York,

To all my friends,

Lastly, to all the people who have helped me throughout the journey,

I would not have finished this project without all of you.

Thank you for all the supports and love.

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ABSTRACT

Solar energy is becoming one of the primary sources energy in the world which converts energy from the Sun into electrical energy and thermal. The renewable energy source can gradually replace fossil fuels for domestic, commercial, or industrial use due to its abundance, versatility, and environmental-friendly. According to statistic, there is about 84% of the total energy generated from fossil fuels. However, fossil fuels are non-renewable and unsustainable as well as creating environmental pollution issues due to the emission of greenhouse gases. Therefore, solar energy would be the promising fuel for the humanity's future. The purpose of this project is to provide a better understanding of the operation of solar cell by using one-dimensional (1D) solar cell model. Besides, the model will be solved by numerical analysis through the appropriate tool in MATLAB. Then, the performance of the numerical simulation of solar cell will be analysed. Before starting the simulation process, a deep understanding on literature background of the fundamental of semiconductor will be an essential element to implement the project successfully. For instances, Generation-Recombination Processes, Poisson Equation, Drift-Diffusion Transport Equation and continuity equation of holes and electrons. After that, nondimensionalisation will be done to transform dimensional equations into dimensionless equation. However, the dimensionless equations can be converted back with an appropriate scaling. Then, by applying Method of Lines (MOL), the spatial variable can be discretized by using finite difference method while time variable remains as derivative. Therefore, the partial derivative equations (PDEs) are converted to ordinary differential equations (ODEs) which can then be solved by using ODE solver in MATLAB. As a result, charge density and electrostatic potential against thickness graphs as well as J-V characteristic curve can be obtained and analysed in MATLAB. Efficiency of the silicon solar cell also can be calculated based on J-V characteristic curve. Those simulated results will be compared with the theoretical results from previous research.

ABSTRAK

Tenaga solar merupakan salah satu sumber tenaga utama di dunia yang akan menukar tenaga daripada Matahari menjadi tenaga elektrik dan haba. Sumber tenaga boleh diperbaharui secara beransur-ansur boleh menggantikan bahan api fosil bagi kegunaan domestik, komersial, atau perindustrian atas sebab bekalan yang berkekalan, serba boleh, dan mesra alam. Menurut statistik, terdapat 84% daripada jumlah tenaga yang dihasilkan daripada bahan api fosil. Walau bagaimanapun, bahan api fosil tidak boleh diperbaharui dan tidak mapan serta mewujudkan isu pencemaran alam sekitar akibat pelepasan gas rumah hijau. Oleh hal yang demikian, tenaga solar akan menjadi bahan api yang menjanjikan untuk masa depan manusia. Tujuan projek ini adalah untuk memberi pemahaman yang lebih mendalam berkaitan denagan operasi sel solar dengan menggunakan model sel solar dalam satu dimensi (1D). Selain itu, model ini akan diselesaikan melalui analisis berangka melalui alat yang sesuai dengan MATLAB. Kemudian, prestasi simulasi berangka sel solar akan dianalisis. Sebelum memulakan proses simulasi, pemahaman yang mendalam mengenai latar belakang sastera asas semikonduktor akan menjadi elemen penting untuk melaksanakan projek dengan lancar. Sebagai contoh, proses penggabungan semula dan generasi, persamaan Poisson, persamaan pengangkutan Drift-Diffusion dan persamaan kesinambungan lubang dan electron. Selepas itu, nondimensionalisasi akan dilakukan untuk mengubah persamaan dimensi menjadi persamaan tanpa dimensi. Walau bagaimanapun, persamaan tanpa dimensi boleh ditukar kembali dengan penskalaan yang sesuai. Kemudian, dengan menggunakan Kaedah Garisan (MOL), pembolehubah ruang boleh didiskritikkan dengan menggunakan kaedah perbezaan terhingga manakala pembolehubah masa kekal sebagai derivatif. Oleh itu, persamaan derivatif separa (PDEs) ditukar kepada persamaan pembezaan biasa (ODEs) yang kemudiannya boleh diselesaikan dengan menggunakan penyelesai ODE dalam MATLAB. Akibatnya, ketumpatan caj dan potensi elektrostatik terhadap graf ketebalan serta lengkung ciri J-V boleh diperolehi dan dianalisasikan dalam MATLAB. Kecekapan sel solar silikon juga boleh dikira berdasarkan lengkung ciri-ciri J-V. Keputusan simulasi tersebut akan dibandingkan dengan keputusan teori daripada penyelidikan terdahulu.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS AND ABBREVIATION

1-D	-	One-dimensional
MATLAB	-	Matrix Laboratory
PV	-	Photovoltaic
UNSW	-	University New South Wales
IBC	-	Interdigitated Back Contact
c-Si	-	Crystalline silicon
mono-Si	-	Monocrystalline silicon
Multi-Si	-	Polycrystalline silicon
a-Si	-	Amorphous silicon
CdTe	-	Cadmium Telluride
CIGS	-	Copper Indium Gallium Selenide
DSSC	-	Dye-sensitized solar cell
UV	-	Ultraviolet
IEA	-	International Energy Agency
IRENA	-	International Renewable Energy Agency
ITRPV	-	International Roadmap for Photovoltaic
SRH	-	Shockley-Read-Hall
ADEPT	-	A Device Emulation Program and Toolbox
AMPS	-	Analysis of Microelectronic and Photonic Structures
SCAPS	-	Solar Cell Capacitance Simulator
ODE	-	Ordinary differential equation
PDE	-	Partial differential equation
MOL	-	Method of Lines
FF	-	Fill Factor
FEM	-	Finite Element Method
FD	-	Finite Difference

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Background

The Sun that has been burning over 4 billion years supplies an incredible solar energy to the Earth. However, solar radiation is a radiant energy given off by the Sun because of its nuclear fusion reactions [1]. It provides enough energy in one minute to meet the world demand of energy for one year. According to an assumption, this renewable source of energy can replace the demand of electricity that community get from 650 barrels of oil per year [2]. Over the years, photovoltaic technologies (PV) showed a remarkable improvement in their efficiency. Solar cells are composed of various semi-conducting materials. Generally, semiconductors are materials that become electrically conductive when supplied with heat or light.

Photovoltaic cells (solar cells) are unique in that they directly convert the incident solar radiation into electricity without any noise or pollution, making them robust, reliable, and durable [3]. Photovoltaic (PV) technology is one of the foremost ways harness solar energy and photovoltaic effect was discovered in 1839 by the French physicist, Alexandre Edmond Becquerel. Alexandre discovered that conductance increases with illumination while experimenting with metal electrodes and electrolyte [4]. In 1905, Albert Einstein understood that this effect can be explained by assuming that the light consists of well-defined energy quanta, called photons [5]. In 1954, the scientists Darly M. Chapin, Calvin S. Fuller and Gerald L. Pearson invented the first modern silicon-based photovoltaic cell at Bell Laboratories in United States, registering an efficiency of about 6% [6].

The first vast oil crisis, which occurred during the 1970s, gave a first vital boost to the promotion of photovoltaic as an alternative energy-generation process for terrestrial use. As a result, solar cells began to increase their energy conversion efficiency rapidly (Figure 1.1). and commercial use led to a significant reduction in solar cell manufacturing costs. In 1970s and 1980s, the first thin film solar cell based on copper sulphide/cadmium sulphide junction amounted to an efficiency above 10% since photovoltaic systems were focused on terrestrial applications [7]. In 1985, University New South Wales (UNSW) built crystalline silicon solar cells and achieved efficiency above 20% and in 1999 they stated a new record of 25% [8,9]. At the end of 2016, Yoshikawa et. al from Kaneka Corporation built an interdigitated back contact (IBC) c-Si-based solar cell, obtaining the world's highest conversion efficiency of 26.33% [10].

Figure 1.1: Evolution of conversion efficiency for different types of solar cells since 1975. Taken from www.nrel.gov/pv/

The photovoltaic industry, however, groups silicon into two distinct categories which are crystalline silicon and not classified as crystalline silicon (c-Si). For crystalline silicon, it is used in traditional or conventional or wafer based solar cells. For examples, mono-crystalline silicon (mono-Si) and poly-crystalline silicon (multi-Si) are categorized as first generation of solar cells. While those not classified as crystalline silicon normally used in thin film and other solar cell technologies. For instances, amorphous silicon (a-Si) as well as other non-silicon materials such as Cadmium Telluride (CdTe), and Copper Indium Gallium Selenide (CIGS) are second generation of solar cells. However, emerging photovoltaic is third generation which often considered as emerging technologies by using organometallic compounds as well as inorganic substances. For examples, dye-sensitized solar cell (DSSC), hybrid solar cell, perovskite solar cell and others.

Accordingly, photovoltaic cells are now, after hydro and wind power, the third most important renewable energy source in terms of global installed capacity (Figure 1.2) [59]. Solar power is the primary source of electrical and thermal energy, produced by directly exploiting the highest levels of irradiated energy from sun to our planet. This characteristic provides to all living creatures a sustainable and clean energy source that will not be in short supply anytime soon. On top of that, the cost of solar panels had declined substantially over the last decade as the industry had matured and reached production at the largest global scale. Solar panel prices had fallen by roughly 90% while global solar deployment has grown by over 400%, owing to the incredible growth rate along the entire global solar supply chain had dramatically reduced prices (Figure 1.3) [11].

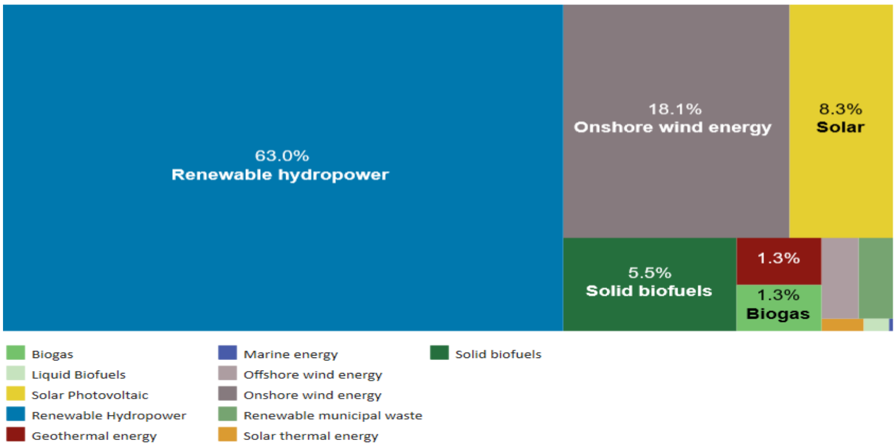

Figure 1.2: Worldwide's renewable energy technologies in year 2018 [59]

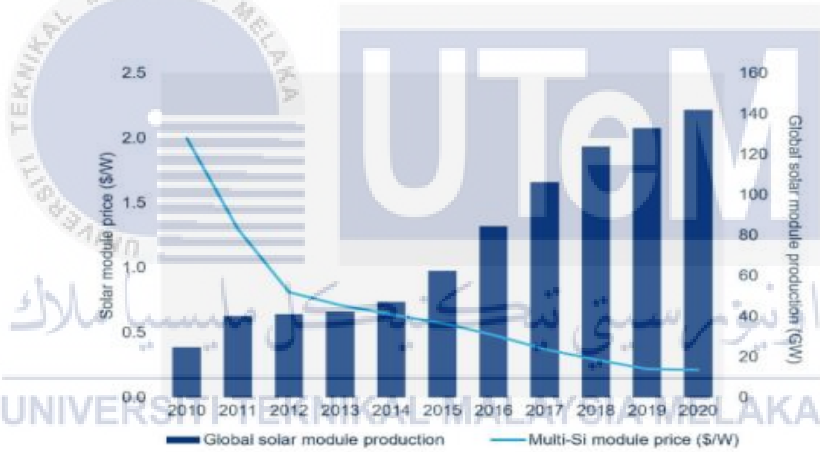

Figure 1.3: Global solar supply from year 2010 till year 2020 [11]

Nonetheless, the efficiency of solar panel will be affected by several conditions. For instances, wind is one of the most predicted causes of solar cell damage while snow also will affect the normal operation of solar cells. A solar cell structure can be delaminated by UV induced degradation and consequently can be the discolouration of individual solar cells. Apart from that, humidity also can lead to corrosion and module connection failure and an overall decrease of solar panel efficiency. Thermal cycling can also cause solar panel components to fail. These components include solar cells, interconnections, solder bonds and module connections. Upon installation, it is important to consider all the factors that could influence solar panel efficiency. Moreover, it is vital to maximize output from the get-go [12].

Solar panels are progressively used renewable energy sources that are extensively utilized from domestic applications to power up large scale smart grids [65]. As a result, various solar panels with different voltage and power ratings are commercially available [66, 67, 68, 69]. Nowadays, the major element silicon in its crystalline and amorphous form is an immensely 99%. However, the photovoltaic market has a slower trend but steady improvement of conversion efficiency as well as a gradual reduction of the cost of modules and systems which making a significant contribution to the global energy system [70].

1.2 Motivation

The motivation of this project is due to the potential and future prospect of solar cell. Solar energy is one of the best choices to meet future energy demand since it is superior in terms of abundance, cost effectiveness, accessibility and efficiency compared to other resources. The solar electricity including solar photovoltaic (PV) is anticipated to contribute to the primary energy with a share of about 20% and 70% in 2050 and 2100. It respectively occupies in the total energy of the world, according to the recommendation (World Energy Vision 2100) by the German Advisory Council on Global Change [13]. In 2016, research had shown that cumulative PV system installation in world achieved 300GW. The world's PV system installation outlook reported by International Energy Agency (IEA) [14], International Renewable Energy Agency (IRENA) [15], Solar Power Europe [16], International Technology Roadmap for Photovoltaic (ITRPV) [17] and TW Workshop [18] has shown in Figure 1.4. The rapid increase in installation of PV system provides powerful and attractive motivation to the future prospect of solar energy. Other than conventional use, developments in new application field such as automobile and agriculture applications also will utilize solar energy as the main source in future.

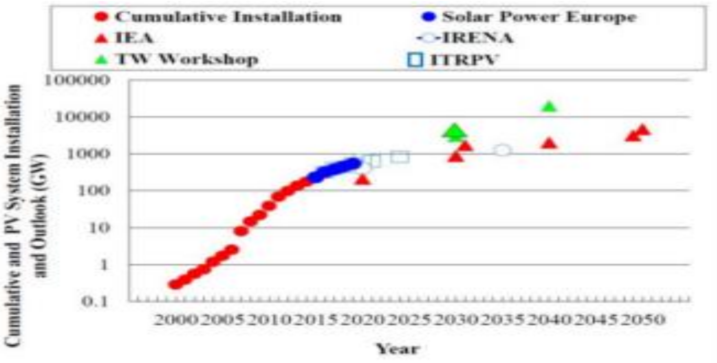

Figure 1.4: World's PV system installation outlook [14, 15, 16, 17, 18]

1.3 Problem Statement

The state of art of solar cell model is greatly improved with its efficiency, However, the complexity of the transport equations is one of the most concerned part in the process of analysing the derivation of equations. With the understanding of carrier transport mechanism in a solar cell, it will be easier to relate the equations involved (such as Poisson equation, drift diffusion transport equation and continuity equation) with the behaviour of charge carriers. Other than that, the factors that will influence the efficiency of the operation of solar cell must also be highlighted. Lastly, the skill of utilizing MATLAB is very important to analyse and tabulate the performance of solar cell by applying the knowledge of numerical in it. The difficulty in writing the programming code also becomes one of the challenges in solving numerical simulation. This means that high numerical competency is needed due to its complexity of the solution.

1.4 Objective

The objectives of this project are:

i) To investigate the mechanism of solar cell model.

ii) To establish the solar cell model through numerical analysis.

iii) To analyse the performance of numerical simulation for one-dimensional solar cell model at blend phase.

1.5 Scope

The scopes of this project are listed in the following:

i. The drift-diffusion solar cell model used is in one-dimensional which involved one spatial variable only while ions can only move to the left or to the right (in one direction only).

ii. Solar cell model simulation in blend phase is analysed. Diffusion in acceptor and donor region is neglected as the thickness of both phases are assumed to be very thin while light absorption mostly occurs in blend phase.

iii. The solar cell model experiment is run by using numerical approach, namely Method of Line (MOL) which ordinary differential equations are obtained through discretization of spatial variable by using finite difference approximation method in MATLAB.

iv. Using the parameters of monocrystalline silicon material in blend phase.

v. The experimental data from previous research will be used to compare with simulation result produced on the behaviour of charge carriers and efficiency of solar cell on different thickness.

1.6 Thesis Organization

This paper is studied about the operation of one-dimensional solar cell model based on numerical simulation. This study is divided into five chapters which are included as follows:

Chapter 1 introduced the general background for solar cell and its limitations which provide insight to implement the numerical approach as a solution for this project. Besides, chapter 1 also involved the details about problem statement, motivation, objective, scope, and thesis organization for the whole project.

Chapter 2 covered the literature review related to the working principle of solar cell and the concept of physical behaviour of charge carriers. The literature is based on previous research and focusing more on numerical method in 1-D solar cell. Numerical analysis will be proposed as the best solution to conduct this project.

Chapter 3 goes into more detail about the research methodology for numerical simulation to understand the mechanism of solar cell. The whole process for this research will be explained thoroughly which it will be adapted for this study to be carried out.

Chapter 4 presented the stage of result that has been conducted throughout the whole process of this project by using MATLAB simulation approach. Method of Lines Technique has been used to discretize the spatial variables by using finite different method. Then, the output will be discussed in detail for further understanding.

Chapter 5 provides a summary for the research to conclude and analyse the presented result in the project. In this chapter, the recommendation has been made based on the study findings and the direction for the future work will be explained as well.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter will discuss about the mechanism and working principles of solar cell. Literature on one-dimensional of solar cells is explained thoroughly with references from previous studies focusing on drift-diffusion solar cell model using numerical approach.

2.2 Formation of P-N Junction

The invention of the junction transistor in the late 1940s was founded on Russell Ohl's discovery of the P-N junction [19]. P-N junction can be formed by assembling P-type and N-type of semiconductor together. It is known that these materials are formed by adding impurities to the pure semiconductor material (silicon) [20]. To form a P-type semiconductor, the silicon is needed to dope with boron which acts as an acceptor impurity due to its three valence electrons, forming excess of holes (Figure 2.1).

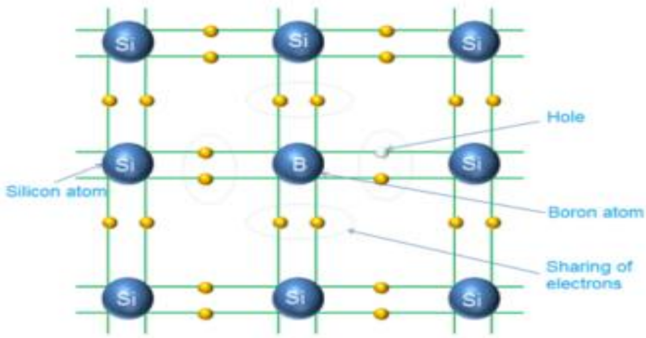

Figure 2.1: P-type semiconductor [20]

In addition, N-type semiconductor is formed by doping phosphorus into silicon. This is because phosphorus has five valence electrons which able to form excess of electrons and becomes a donor impurity (Figure 2.2). The charge carriers will diffuse from a higher concentration region (excess carriers' region) to a lower concentration region (fewer carriers' region) (Figure 2.3) [21].

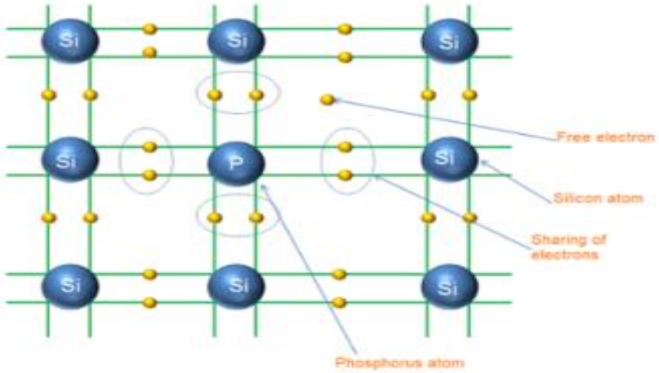

Figure 2.2: N-type semiconductor [20]

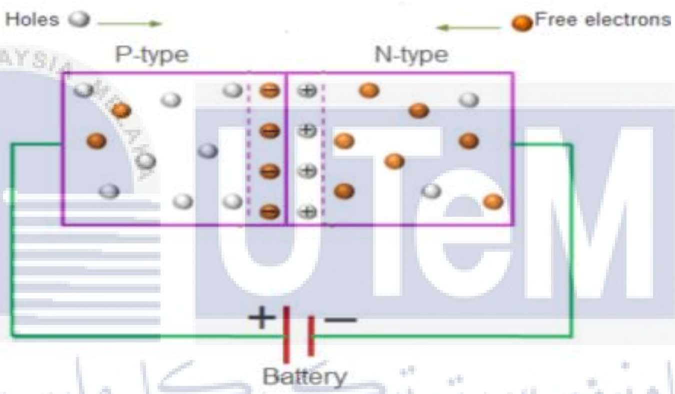

Figure 2.3: Diffusion of charge carriers [21]

On top of that, there is a space charge region which called depletion region formed during diffusion of charge carriers across concentration gradient. In the order word, it is described by an electron in N-type semiconductor diffuses across the junction to combine with hole, forming negative ions in P-type region. However, positive ions are formed due to the leaving of electron at N-type semiconductor. Until a state of equilibrium is achieved, Coulomb force from ions will prevent further diffusion in P-N junction anymore. This happens when electrons in N-type cannot diffuse to P-type because they are repelled by negative ions in that region and attracted by positive ion in N-type region.