A STUDY OF MULTILAYER SOLAR CELLS PERFORMANCES BETWEEN GALLIUM ARSENIDE (GaAs) AND SILICON (Si)

by

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LIST OF ABBREVIATIONS

Si	Silicon
GaAs	Gallium Arsenide
NREL	National Renewable Energy Laboratory
InGaN	Indium Gallium Nitride
TCAD	Technology Computer Aided Design
EHP	Electron-Hole Pair
P-N	P-N Junction (P-type, N-type)
I-V	Current-Voltage
FPDs	Flat Panel Display
APSYS	Advanced Physical Models of Semiconductor Devices
GaInP	Indium Gallium Phosphide
Ge	Germanium
ARC	Anti Reflective Coating
SiO_2	Silicon Dioxide
GaP	Gallium Phosphide
AlGaAs	Aluminium Gallium Arsenide
BSF	Back Surface Field
InAlGaP	Indium Aluminium Gallium Phosphide
3-J Solar Cell	Three Junction Solar Cell
ZnO	Zinc Oxide
LCD	Liquid Crystal Display
LED	Light Emitting Diode
AM0	Air Mass 0

IC	Integrated Circuit
Al	Aluminium
In	Indium
LPE	Liquid Phase Epitaxy
GaP/Si	Gallium Phosphide/Silicon
GaP/GaAs	Gallium Phosphide/Gallium Arsenide
$In_xGa_{1-x}P$/Si	Indium$_{(x)}$Gallium$_{(1-x)}$ Phosphide/Silicon
$In_xGa_{1-x}P$/GaAs	Indium$_{(x)}$Gallium$_{(1-x)}$ Phosphide/GaAs
InP	Indium Phosphide
$Al_xGa_{0.5-x}In_{0.5}P$/Si	Aluminium$_{(x)}$Gallium$_{(0.5-x)}$Indium$_{(0.5)}$Phosphide/Silicon
$Al_xGa_{0.5-x}In_{0.5}P$/GaAs	Aluminium$_{(x)}$Gallium$_{(0.5-x)}$Indium$_{(0.5)}$Phosphide/GaAs

LIST OF SYMBOLS

I_L	Light generated current
I_0	Dark saturation current
V	Voltage
n	Ideality factor
kT/q	Thermal voltage at 300k , 0.02586V
N_A	Doping concentration
η	Efficiency
eV	Electron volt, 1.6×10^{-19} Joules
E_g	Band gap
h	Planck constant, 6.63×10^{-34} m^2 kg/s
c	Speed of light, 3.0×10^{8} m/s
λ	Wavelength
v_d	Drift velocity
μE	Electron mobility
I_{sc}	Short-circuit current
V_{oc}	Open circuit voltage
FF	Fill factor
I_{max}	Maximum current
V_{max}	Maximum voltage
P_{max}	Maximum power
P_{in}	Input power

KAJIAN TERHADAP PRESTASI SEL SOLAR MULTI LAPISAN ANTARA GALIUM ARSENIDA(GaAS) DAN SILIKON (Si)

ABSTRAK

Kecekapan sel suria yang rendah kini adalah disebabkan oleh spektrum solar yang tidak digunakan sepenuhnya. Oleh kerana bahan semikonduktor yang berbeza mempunyai jalur tenaga yang berbeza, ia akan bertindak balas secara berasingan pada bahagian lain dalam spektrum solar dan oleh itu, memungkinkan untuk meletakkan beberapa lapis secara sesiri.Sel suria multi-lapisan telah dikaji secara meluas dengan harapan untuk meningkatkan kecekapan dan menghasilkan produk murah bagi keperluan masa depan. Substrat lapisan terdiri daripada bahan Galium Arsenida (GaAs) dan Silikon (Si) di mana setiap jenis bahan mempunyai ciri jurang jalur tenaga, yang menyebabkan ia menyerap cahaya paling cekap pada warna tertentu dan lebih tepat, untuk menyerap sinaran elektromagnet pada sebahagian spektrum. Oleh kerana Galium Fosfid (GaP) adalah salah satu bahan sel solar yang terbaik, GaP semikonduktor dipilih untuk menyerap hampir seluruh spektrum suria,dan akan menjana elektrik sebanyak yang mungkin dari tenaga solar. Peningkatan kecekapan sel suria dan pengurangan ketebalan sel yang aktif adalah amat penting dari aspek ekonomi dan teknologi. Peningkatan telah dilakukan terhadap sel solar GaP dengan memperkenalkan doping seperti Indium (In) dan Aluminium (Al) ke atas struktur GaP. Keputusan yang dihasilkan untuk lapisan tunggal dan dua lapisan untuk melihat keberkesanan bahan yang digunakan dan juga keputusan untuk struktur sel-sel solar multi-lapisan. Bagi lapisan tunggal, kecekapan sel solar GaAs adalah 11.32 %, 2.13 % bagi sel solar Silikon dan 5.89 % bagi sel solar GaP. Dalam sel multi-lapisan $In_xGa_{1-x}P$, nilai kecekapan tertinggi adalah daripada $In_xGa_{1-x}P$/ GaAs pada x=0.7 dengan kecekapan sebanyak 13.23 % dan $In_xGa_{1-x}P$/ Si, dengan kecekapan 13.12 % pada x=0.7. For $Al_xGa_{0.5-x}In_{0.5}P$ cells, kecekapan tertinggi diperoleh daripada $Al_xGa_{0.5-x}In_{0.5}P$/ GaAs, dengan kecekapan 36.99 % dan $Al_xGa_{0.5-x}In_{0.5}P$/ Si dengan kecekapan 35.63 %, kedua-duanya pada x=0.4. Sebagai penambah baikan, kecekapan tertinggi adalah 43.42 % bagi $Al_xGa_{0.5-x}In_{0.5}P$/ GaAs dan 37.11 % dan $Al_x Ga_{0.5-x}In_{0.5}P$/ Si, pada x=0.4 untuk kedua-dua sel dengan adanya salutan anti-pantulan (ARC) menggunakan Zink Oksida (ZnO) pada permukaan atas sel multi-lapisan.

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ABSTRACT

The present low efficiency of solar cells is due to the incomplete use of the solar spectrum. Since different semiconductor materials have different band gaps, it responds separately to different parts of the solar spectrum and therefore, it is possible to put several layers in a series. The multilayer solar cell has been extensively studied with the hope of improving the good efficiency and low-cost for future trends. A substrate layer which consists of Gallium Arsenide (GaAs) and Silicon (Si) will give different characteristic band gap energy, which causes it to absorb light most efficiently at a certain color and more precisely, to absorb electromagnetic radiation over a portion of the spectrum. Since Gallium Phosphide (GaP) is one of the favored material for solar cell, the GaP semiconductor is chosen to absorb nearly the entire solar spectrum, thus generating electricity from as much of the solar energy as possible. Improvement of solar cell efficiency with selected material composition are very important from economical and technological aspects. The improvements are made to Gallium Phosphide (GaP) solar cell by introducing doping such as Indium (In) and Aluminium (Al) into the GaP structure. The results are produced for single layer and dual layer to observe the effectiveness of the material used and also included the result for multilayer structure. For single layer, the efficiency of the GaAs solar cell is 11.32 % , 2.13 % for Silicon and 5.89 % for GaP solar cell. In multilayer $In_xGa_{1-x}P$ cells, the highest efficiency obtained from $In_xGa_{1-x}P$/ GaAs at x=0.7 with the efficiency of 13.23 % and for $In_xGa_{1-x}P$/ Si, the efficiency obtained is 13.12 % at x=0.7. For $Al_xGa_{0.5-x}In_{0.5}P$ cells, the highest efficiency obtained from $Al_xGa_{0.5-x}In_{0.5}P$/ GaAs, which is 36.99 % and for $Al_xGa_{0.5-x}In_{0.5}P$/ Si solar cell, the efficiency obtained is 35.63 %, both at x=0.4. As an improvement, the highest efficiency is 43.42 % for $Al_xGa_{0.5-x}In_{0.5}P$/ GaAs and 37.11 % for $Al_x Ga_{0.5-x}In_{0.5}P$/ Si, at x=0.4 for both by having Anti-Reflective Coating (ARC) using Zinc Oxide (ZnO) on top of multilayer cells.

CHAPTER 1

INTRODUCTION

1.1 Background

The multilayer solar cell has been studied with the hope of achieving better efficiency and low-cost of energy production for future trends. A solar cell layer which consists of Silicon (Si) and Gallium Arsenide (GaAs) as a substrate material and a few materials on top of cells were developed, where each material has their own energy gap which causes the absorption of light more efficient. Since GaAs based devices are the most efficient solar cells, this type of semiconductor is chosen because it could absorb the energy of light and generates electricity from as much of the solar energy as possible. Multilayer is a technology that offers high efficiencies compared to the conventional solar cells made of a single layer of semiconductor material. Depending on the particular technology, multilayer solar cells are capable of generating approximately twice as much power as conventional solar cells which made of Silicon. Unfortunately, this multilayer are very expensive and only use in high performance applications such as satellites due to their cost (Steven Lansel, 2005).

The concept of multilayer solar cell begins from Martin Wolf and Walukiewicz, who proposed the impurity photovoltaic effect in 1960. The experiment starts by having impurities with the electronic properties into a semiconductor and make a single-layer solar cell that absorbs more energy (Paul Preuss, 2014). In 1990, Walikiewicz and others at Berkeley Lab were working with solar-cell designers at the National Renewable Energy Laboratory (NREL), who were trying to build a three-junction cell (U.S Dept. Energy, 2014). The NREL researchers created the first photovoltaic semiconductor with a split band gap that needs a new material with a 1 eV band gap and a crystal lattice structure that matched the other layers of the cell. According to Paul Preuss in 2014, the research conducted in the year 2002 produced that Indium Gallium Nitride (InGaN) would respond to different wavelengths of light if the proportions of Indium and Gallium in the alloy are being adjusted and possible to create a photovoltaic cell by stacking multiple negative and positive doped layers to form several current-producing junctions (Paul Preuss, 2014).

Current solar cell simulation tools typically use discrete components to model solar cell operation. The Silvaco Atlas software, which was developed by Silvaco International predicts the electrical characteristics of physical structures by simulating the two-dimensional grid. In this research, Silvaco Atlas was used by having a deckbuild run-time environment. The code will be executed and finally Tonyplot was used to view the output of the simulation.

1.2 Objectives and Scope of Study

The objectives of this project are;

i) To characterize the performance of Gallium Arsenide (GaAs) and Silicon (Si) as a solar cell substrate.

ii) To analyze the efficiency for single-layer and dual layer solar cells by introducing Gallium Phosphide (GaP) materials.

iii) To study the effect of Indium (In) to Gallium Phosphide (GaP) solar cell on the top of GaAs and Si solar cell.

iv) To study the effect of Aluminium (Al) to Indium Gallium Phosphide (InGaP) solar cell on top of Si and GaAs solar cell.

v) To study the effect of Zinc Oxide (ZnO) as an Anti-Reflective Coating (ARC) to the multilayer solar cell.

The scope of this project covers on the simulation of the single layer multilayer solar cell by using Silvaco software to determine the output, which is overall efficiency and some other characteristic produced from the material used in single and multilayer itself. Comparisons were made to analyze the performance between single layer and multilayer solar cell in a Gallium Arsenide (GaAs) and Silicon (Si) substrate.

1.3 Thesis Structure and Organization

This report consists of five chapters. **Chapter 1** presents the introduction, which is the background of the research, objectives and scope of the study. Chapter 1 also presents the thesis structure for overall topics in the thesis.

Chapter 2 reviews the theory that related to this research project. It starts with the solar cell history, that introduce the inventors of a solar cell from previous years. The concept of photovoltaic effect will be reviewed as part of the basic solar cell mechanism followed by a solar cell operation which describe the light generated current in solar cell application. This chapter also presents the characteristics of the solar cell and the design of solar cell which focus more on the consideration of designing single and multilayer solar cell including the used of Anti-Reflective Coating (ARC). The last topic of this chapter presents the list of material used in the research and the history of selected material.

Chapter 3 consists of the development of single layer and multilayer solar cell using Silvaco. A brief introduction of Silvaco TCAD tools is also presented together with another application as a variety of techniques used in solar cell simulation. The methodology which consists of the flow charts for this project will be discussed in this chapter, including the component used for the development of solar cell structure. In this chapter, the design of single layer and multilayer solar cell is presented with the illustrated figure.

Chapter 4 completes the work of the previous chapter by presenting the simulation results obtained from Silvaco TCAD. A graph of extracted parameters is presented, analyzed and discussed in this chapter. The chapter begins with the single layer solar cell results for GaAs, Si and GaP followed by the discussion of the result obtained. The next topic describes the results for multilayer solar cell using GaAs and Si material as a substrate layer for GaP, InGaP and InAlGaP solar cell together with the anti-reflective coating layer.

Chapter 5 covers the conclusions and recommendations for future work. Based on the characteristics of the solar cell using Silvaco Atlas, the conclusions have been made by analyzing the results and data presented in the previous chapter. The single layer and multilayer has been summarized by this chapter. Some recommendations have been described related to the research work.

CHAPTER 2

LITERATURE REVIEW

2.1 Solar Cell History

A solar cell is a device that directly converts the energy of light into electrical energy through the process of photovoltaics. The development of solar cell technology begins in 1839 by a French physicist Antoine-César Becquerel (R.S Rohela, 2013). Becquerel et.al observed the photovoltaic effect while experimenting a solid electrode in an electrolyte solution when they saw a voltage develop when light fell upon the electrode. According to Encyclopedia Britannica, the first genuine single solar cell was built around 1883 by Charles Fritts (Stephen Joseph Fonash, 2014) form a junction by coating selenium (a semiconductor) with an extremely thin layer of gold. However, the energy conversion efficiencies only produce less than one percent.

In the year of 1900 to 1929, the variation of electron, energy and light frequency has been observed by Philipp Von Lenard. During these years, a solar cell made of copper and copper oxide has been introduced by Wilhelm Hallwachs in 1904 and also the experiment that proves the process of photovoltaic effect has been made by Robert Milikan in 1916. The next two years, a Polish scientist named Jan Czochralski, creates a method to grow single crystals of metal and decades later, the single-crystal silicon has been produced. In early 1932, Cadmium Seleride (CdSe), which is the photovoltaic material has been investigated by Audobert and Stora and it is still being used today.

In 1941, the silicon solar cell was invented by Russell Ohl. and the next 13 years, which was in 1954, three American researchers, Gerald Pearson, Calvin Fuller and Daryl Chapin (Algamdi A, 2007), designed a silicon solar cell which capable to convert energy with 6% efficiency under a direct sunlight. Gerard Pearson et. al creates an array of several strips of silicon (each about the size of a razor-blade), placed them under the sunlight, captured the free electrons and turned them into electrical current. Four years after that, T. Mandelkorn from U.S. Signal Corps Laboratories, makes n-p silicon solar cells for the space application used. About 9% of efficient solar cells has been created by Hoffman Electronics and a year later, the use of grid contact was introduced to the commercial solar cell with the efficiency of 10 %. In 1985, Centre for Photovoltaic Engineering, University of New South Wales was created a 20 % efficient solar cells and this trend has been challenged by University of South Florida in 1992 that fabricates about 15.89 % of efficiency for thin-film solar cell.

The multilayer solar cell was proposed by Jackson in 1955 (Masafumi, 2013). The idea is that, each individual solar cell in the solar cell system will only correspond and absorb a small range of the solar spectrum resulting more efficient for absorption. It is possible to improve on a single-junction cell by stacking thin layers of material with varying band gaps on top of each other commonly known as tandem cell or multi-junction. In 1993, the National Renewable Energy Laboratories (NREL) was established and GaInP/GaAs two-terminal concentrator cell has been delevoped which becomes the first solar cell to exceed 30 % conversion efficiency. There is reporting that three-layer GaAs cells achieved 41.6 % efficiency for experimental examples (David Biello, 2009). In September 2013, a four layer cell reached 44.7 % efficiency (Megan Treacy, 2013).

In 2006, the new solar cell with 40 % of the efficiency has been recorded (Badger R., 2006). Two years after that, new record achieved in solar cell efficiency when the researchers at the U.S. Department of Energy's National Renewable Energy Laboratory (NREL) achieves about 40.8 % of the efficiency (Gruener W., 2008). The inverted metamorphic triple-junction solar cell was designed, fabricated and independently measured at NREL (NREL Public Relations, 2008). The previous conventional silicon solar cells have efficiencies only around 25 % (Martin L., 2011), while lab examples of multilayer cells have the performance over 43 % efficiency (Zachary S., 2012). The GaAs solar cell produced about 46 %, according to the latest record in December 2, 2014 by Cities and CEA-Leti, France, together with the Fraunhofer Institute for Solar Energy Systems ISE, Germany (Paul Bauckley, 2014).

This efficiency was obtained from the improvement of four-junction solar cell, which is the latest trend of solar cell so far. The efficiency record was measured at a concentration of 508 suns and has been confirmed by the Japanese AIST (National Institute of Advanced Industrial Science and Technology), which is one of the leading centers for independent verification of solar cell performance result under standard-testing conditions. This record had a challenge that had to be met. One of the problems of this cell is the exact distribution of the photons among the four sub-cells. This has been achieved by precise tuning of the composition and thicknesses of each layer inside the cell structure. Another solar cell material, Gallium Phosphide (GaP) was reported of having the efficiency of 1.17 % from Allen et al (Allen, Jeon, & Woodall, 2010). In 2010, the efficiency improved by Xuesong Lu et al with the value of 1.98 %, which increase about 0.81 % from previous studies. After a year, the same researchers team, Xuesong Lu et al reports that the best GaP solar cell result has an efficiency of 2.42 %. (Xuesong Lu et al, 2012). However, all of reported papers have their own method for analyzing the GaP single layer cells and most of them are using experimental Liquid Phase Epitaxy (LPE) to grow epitaxial layers described by X. Lu et al. in 2009. Based on the previous research, GaP solar cell is designed and analyzed by fabrication process which involve a lot of procedure and chemical usage to determine their performance in term of efficiency.

Previously, a conversion efficiency greater than 30 % InGaP on a Germanium (Ge) substrate, which is the same group with silicon material was reported by T.Takamoto et.al (Masafumi Yamaguchi, 2012). However, due to the cost factor, Ge-based bottom cells should be replaced with Si-based since silicon is cheap and most widely used in semiconductor material in the solar cell industry. Thus, group III-Arsenide or Phosphide/Silicon junctions are likely to be the ideal structure for multilayer cell.

The growth of compound semiconductor-based cells on Si substrates or on Si-based bottom cell was reported by D.C Law et.al (Law et al., 2010). The paper reported that it is difficult to prepare multilayer cell with a larger number of subcells on Si substrates because of the lattice constant and thermal coefficients of semiconductor materials for the respective subcells are likely to be different from each other. Hence, two-layer cells or tandem cell of Si-based substrate is preferable to be investigated to prevent lattice constant mismatch among materials. Tandem layer InGaP/Si solar cell previously achieve the efficiency about 9.9 %-10.4 % (Shigekawa, Morimoto, Nishida, & Liang, 2014). This range is determined by fabrication process step using different wafer orientation, which is <100> and <111> types.

Based on the literature studies, the researchers found that this InGaP/GaAs can achieve about 27 %. However, this 27 % of efficiency is produced by introducing InAlGaP as a window layer on top cell and about 13% efficiency achieved when having AlGaAs as a window layer (Jolson, Subir, & Sarkar, 2012).In solar cell applications, the conversion efficiency of Gallium Arsenide (GaAs) solar cell devices are found to be higher than Silicon. This is because, GaAs can provide physically direct band gap and lattice-match properties, for example, a p+ GaAs solar cell with base layer thickness of 3.3μm can absorb 97% of the solar air mass 1.5 (AM1.5) global illumination spectrum, and the generated carriers with high mobility ensure that they can reach the junction before any recombination process takes place (Tsai et al., 2010). Previously, InGaP/GaAs cells have drawn increased attention because of the possibility of high conversion efficiency of over 30% (M Yamaguchi, 2001).

By introducing InGaP as a top cell on GaAs, the InGaP top cell must absorb the minimum amount of light with maximum conversion efficiency. To achieve this, the technique is thinning the top cell base layer. This make this layer more sensitive to the quality of its interface with the layer underneath (Garcia, Rey-Stolle, Algora, Stolz, & Volz, 2008). InGaP/GaAs is a proven structure of high-efficiency cells in space