

SOLAR PANEL DEVELOPMENT FOR HIGH
ALTITUDE AND LOW EARTH ORBIT APPLICATION

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**SOLAR PANEL DEVELOPMENT FOR HIGH ALTITUDE AND LOW EARTH ORBIT
APPLICATION**

By

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Thesis submitted in partial fulfillment of the requirements for the degree

Master of Technology: Electrical Engineering

in the Faculty of engineering

at the Cape Peninsula University of Technology

Supervisor: Professor MTE Kahn

**Bellville
DECEMBER 2010**

DECLARATION

I, Salim Rashid Bakari, declare that the contents of this thesis represent my own unaided work, and that the thesis has not previously been submitted for academic examination towards any qualification. Furthermore, it represents my own opinions and not necessarily those of the Cape Peninsula University of Technology.

Signed

Date

ABSTRACT

Stable and reliable source of electrical energy is a requirement for efficient operation of satellites. Several sources of electrical power for satellites exist such as fuel cells, nuclear or battery stored Direct Current energy but of late concentration has been on solar cells as the advantages compared to the other sources are many. Solar cells are p-n semiconductor devices which convert light energy into electrical energy by photovoltaic effect. The biggest drawback of solar cell energy system is the low light to electricity conversion efficiency. Apart from powering satellites, solar cells and panels have found other numerous applications such as in water pumping systems, rural electrification, street lighting. Photovoltaic principle of solar cells started way back in 1839 when Alexandre Edmund Becquerel observed that electrical currents arose from certain light induced chemical reactions. A comprehensive understanding of this phenomenon became clear when the science of quantum theory was unveiled in the early parts of the 20th century. Most solar cells and panels available today in the market are silicon based made of single junction technology. The disadvantage with single junction technology is that the p-n junction is made of a single type of solar cell material which absorbs a fraction of light wavelengths from the spectrum of light. The disability of the single p-n junction to convert all the light energy to electricity accounts for the low efficiency for the solar cells.

One way to go around the problem of efficiency is to use multi-junction solar cells. Multi-junction solar cells are designed to absorb a large fraction of the light spectrum and convert them to electrical energy. They are made of multiple p-n junctions made of different solar cell materials which absorb different parts of light spectrum and convert them to electrical energy. In this thesis, a design of a multi-junction solar cell for developing space solar panel is presented. The multi-junction cell has been designed from simulation results of different solar cell materials simulated with space conditions. Ideas and recommendations for future work are also presented.

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DEDICATION

To my entire family, Siti Salim, Juma Salim, Bisauda Salim and, Fatuma Salim under the directorship of Madams Fatuma Mohammed Ali and Elina Nyamvula Jola.

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GLOSSARY OF TERMS

Absorber- Material that readily absorbs photons to generate charge carriers (free electrons or holes).

Acceptor - A dopant material, such as boron, which has fewer outer shell electrons than required in an otherwise balanced crystal structure, providing a hole, which can accept a free electron.

Air mass (sometimes called air mass ratio) — Equal to the cosine of the zenith angle—that angle from directly overhead to a line intersecting the sun. The air mass is an indication of the length of the path solar radiation travels through the atmosphere. An air mass of 1.0 means the sun is directly overhead and the radiation travels through one atmosphere (thickness).

Ambient Temperature -The temperature of the surrounding area.

Amorphous Silicon -A thin-film, silicon photovoltaic cell having no crystalline structure. Manufactured by depositing layers of doped silicon on a substrate.

Ampere (amp) - A unit of electrical current or rate of flow of electrons. One volt across one ohm of resistance causes a current flow of one ampere.

Angle of Incidence -The angle that a ray of sun makes with a line perpendicular to the surface. For example, a surface that directly faces the sun has a solar angle of incidence of zero, but if the surface is parallel to the sun (for example, sunrise striking a horizontal rooftop), the angle of incidence is 90°.

Anode -The positive electrode in an electrochemical cell (battery). Also, the earth or ground in a cathodic protection system. Also, the positive terminal of a diode.

Antireflection Coating - a thin coating of a material applied to a solar cell surface that reduces the light reflection and increases light transmission.

Array - photovoltaic (PV) array.

Array Current -the electrical current produced by a photovoltaic array when it is exposed to sunlight.

Array Operating Voltage - the voltage produced by a photovoltaic array when exposed to sunlight and connected to a load.

Balance of System - represents all components and costs other than the photovoltaic modules/array. It includes design costs, land, site preparation, system installation, support structures, power conditioning, operation and maintenance costs, indirect storage, and related costs.

BandGap - in a semiconductor, the energy difference between the highest valence band and the lowest conduction band

BandGap Energy (E_g) -the amount of energy (in electron volts) required to free an outer shell electron from its orbit about the nucleus to a free state, and thus promote it from the valence to the conduction level.

Battery -two or more electrochemical cells enclosed in a container and electrically interconnected in an appropriate series/parallel arrangement to provide the required operating voltage and current levels. Under common usage, the term battery also applies to a single cell if it constitutes the entire electrochemical storage system.

BIPV (Building-Integrated Photovoltaics) - a term for the design and integration of photovoltaic (PV) technology into the building envelope, typically replacing conventional building materials. This integration may be in vertical facades, replacing view glass, spandrel glass, or other facade material; into semitransparent skylight systems; into roofing systems, replacing traditional roofing materials; into shading "eyebrows" over windows; or other building envelope systems.

Blocking Diode - a semiconductor connected in series with a solar cell or cells and a storage battery to keep the battery from discharging through the cell when there is no output, or low output, from the solar cell. It can be thought of as a one-way valve that allows electrons to flow forwards, but not backwards.

Bypass Diode - a diode connected across one or more solar cells in a photovoltaic module such that the diode will conduct if the cell(s) become reverse biased. It protects these solar cells from thermal destruction in case of total or partial shading of individual solar cells while other cells are exposed to full light.

Cadmium Telluride (CdTe) - a polycrystalline thin-film photovoltaic material.

Cathodic Protection - a method of preventing oxidation of the exposed metal in structures by imposing a small electrical voltage between the structure and the ground.

Charge Carrier - a free and mobile conduction electron or hole in a semiconductor.

Chemical Vapor Deposition (CVD) - a method of depositing thin semiconductor films used to make certain types of photovoltaic devices. With this method, a substrate is exposed to one or more vaporized compounds, one or more of which contain desirable constituents. A chemical reaction is initiated, at or near the substrate surface, to produce the desired material that will condense on the substrate.

Concentrator - a photovoltaic module, which includes optical components such as lenses (Fresnel lens) to direct and concentrate sunlight onto a solar cell of smaller area. Most concentrator arrays must directly face or track the sun. They can increase the power flux of sunlight hundreds of times.

Conduction Band (or conduction level) - an energy band in a semiconductor in which electrons can move freely in a solid, producing a net transport of charge.

Contact Resistance - the resistance between metallic contacts and the semiconductor.

Conversion Efficiency - See photovoltaic (conversion) efficiency.

Copper Indium Diselenide (CuInSe₂, or CIS) - A polycrystalline thin-film photovoltaic material (sometimes incorporating gallium (CIGS) and/or sulfur).

Crystalline Silicon - a type of photovoltaic cell made from a slice of single-crystal silicon or polycrystalline silicon.

Current at Maximum Power (I_{mp}) - the current at which maximum power is available from a module.

Czochralski Process - a method of growing large size, high quality semiconductor crystal by slowly lifting a seed crystal from a molten bath of the material under careful cooling conditions.

Dangling Bonds - a chemical bond associated with an atom on the surface layer of a crystal. The bond does not join with another atom of the crystal, but extends in the direction of exterior of the surface.

Diffusion Length - The mean distance a free electron or hole moves before recombining with another hole or electron.

Diode - an electronic device that allows current to flow in one direction only. See blocking diode and bypass diode.

Direct Insolation - Sunlight falling directly upon a collector. Opposite of diffuse insolation.

Donor - In a photovoltaic device, an n-type dopant, such as phosphorus, that puts an additional electron into an energy level very near the conduction band; this electron is easily excited into the conduction band where it increases the electrical conductivity over that of an undoped semiconductor.

Dopant - a chemical element (impurity) added in small amounts to an otherwise pure semiconductor material to modify the electrical properties of the material. An n-dopant introduces more electrons. A p-dopant creates electron vacancies (holes).

Doping - the addition of dopants to a semiconductor.

Edge-Defined Film-Fed Growth (EFG) - a method for making sheets of polycrystalline silicon for photovoltaic devices in which molten silicon is drawn upward by capillary action through a mold.

Electrodeposition - Electrolytic process in which a metal is deposited at the cathode from a solution of its ions.

Electron Volt (eV) - the amount of kinetic energy gained by an electron when accelerated through an electric potential difference of 1 Volt; equivalent to 1.603×10^{-19} ; a unit of energy or work.

Epitaxial Growth - the growth of one crystal on the surface of another crystal. The growth of the deposited crystal is oriented by the lattice structure of the original crystal.

Fermi Level - Energy level at which the probability of finding an electron is one-half. In a metal, the Fermi level is very near the top of the filled levels in the partially filled valence band. In a semiconductor, the Fermi level is in the band gap.

Fill Factor - the ratio of a photovoltaic cell's actual power to its power if both current and voltage were at their maxima. A key characteristic in evaluating cell performance.

Flat-Plate Module - An arrangement of photovoltaic cells or material mounted on a rigid flat surface with the cells exposed freely to incoming sunlight.

Flat-Plate Photovoltaics (PV) - A PV array or module that consists of nonconcentrating elements. Flat-plate arrays and modules use direct and diffuse sunlight, but if the array is fixed in position, some portion of the direct sunlight is lost because of oblique sun-angles in relation to the array

Fresnel Lens - An optical device that focuses light like a magnifying glass; concentric rings are faced at slightly different angles so that light falling on any ring is focused to the same point.

Full Sun - The amount of power density in sunlight received at the earth's surface at noon on a clear day (about 1,000 Watts/square meter).

Gallium Arsenide (GaAs) - a crystalline, high-efficiency compound used to make certain types of solar cells and semiconductor material.

Heterojunction - a region of electrical contact between two different materials.

Hole - the vacancy where an electron would normally exist in a solid; behaves cell.

Hydrogenated Amorphous Silicon - amorphous silicon with a small amount of incorporated hydrogen. The hydrogen neutralizes dangling bonds in the amorphous silicon, like a positively charged particle.

Homojunction - the region between an n-layer and a p-layer in a single material, photovoltaic allowing charge carriers to flow more freely.

Incident Light - light that shines onto the face of a solar cell or module.

Infrared Radiation - Electromagnetic radiation whose wavelengths lie in the range from 0.75 micrometer to 1000 micrometers; invisible long wavelength radiation (heat) capable of producing a thermal or photovoltaic effect, though less effective than visible light.

Insolation - the solar power density incident on a surface of stated area and orientation, usually expressed as Watts per square meter or Btu per square foot per hour. See diffuse insolation and direct insolation.

Intrinsic Semiconductor - an undoped semiconductor.

Irradiance - the direct, diffuse, and reflected solar radiation that strikes a surface. Usually expressed in kilowatts per square meter. Irradiance multiplied by time equals insolation.

I-V Curve - a graphical presentation of the current versus the voltage from a photovoltaic device as the load is increased from the short circuit (no load) condition to the open circuit (maximum voltage) condition. The shape of the curve characterizes cell performance.

Light-Induced Defects - defects, such as dangling bonds, induced in an amorphous silicon semiconductor upon initial exposure to light.

Light Trapping - the trapping of light inside a semiconductor material by refracting and reflecting the light at critical angles; trapped light will travel further in the material, greatly increasing the probability of absorption and hence of producing charge carriers.

Majority Carrier - Current carriers (either free electrons or holes) that are in excess in a specific layer of a semiconductor material (electrons in the n-layer, holes in the p-layer) of a cell.

Maximum Power Point (MPP) - The point on the current-voltage (I-V) curve of a module under illumination, where the product of current and voltage is maximum. For a typical silicon cell, this is at about 0.45 volts.

Minority Carrier Lifetime - the average time a minority carrier exists before recombination.

Multicrystalline - a semiconductor (photovoltaic) material composed of variously oriented, small, individual crystals. Sometimes referred to as polycrystalline or semi crystalline.

Multijunction Device - a high-efficiency photovoltaic device containing two or more cell junctions, each of which is optimized for a particular part of the solar spectrum.

Normal Operating Cell Temperature (NOCT) - the estimated temperature of a photovoltaic module when operating under 800 w/m² irradiance, 20°C ambient temperature and wind speed of 1 meter per second. NOCT is used to estimate the nominal operating temperature of a module in its working environment.

N-Type Semiconductor - a semiconductor produced by doping an intrinsic semiconductor with an electron-donor impurity (e.g., phosphorus in silicon).

Open-Circuit Voltage (Voc) - the maximum possible voltage across a photovoltaic cell; the voltage across the cell in sunlight when no current is flowing.

Panel - photovoltaic (PV) panel.

Parallel Connection - a way of joining solar cells or photovoltaic modules by connecting positive leads together and negative leads together; such a configuration increases the current, but not the voltage.

Passivation - A chemical reaction that eliminates the detrimental effect of electrically reactive atoms on a solar cell's surface.

Peak Power Point - operating point of the I-V (current-voltage) curve for a solar cell or photovoltaic module where the product of the current value times the voltage value is a maximum.

Phosphorous (P) - a chemical element used as a dopant in making n-type semiconductor layers.

Photocurrent - an electric current induced by radiant energy.

Photoelectric Cell - A device for measuring light intensity that works by converting light falling on, or reach it, to electricity, and then measuring the current; used in photometers.

Photon - a particle of light that acts as an individual unit of energy

Photovoltaic (PV) Cell - the smallest semiconductor element within a PV module to perform the immediate conversion of light into electrical energy (direct current voltage and current). Also called a solar cell.

Photovoltaic (PV) Conversion Efficiency - the ratio of the electric power produced by a photovoltaic device to the power of the sunlight incident on the device.

Photovoltaic (PV) Effect - the phenomenon that occurs when photons, the "particles" in a beam of light, knock electrons loose from the atoms they strike. When this property of light is combined with the properties of semiconductors, electrons flow in one direction across a junction, setting up a voltage. With the addition of circuitry, current will flow and electric power will be available.

Photovoltaic (PV) Panel - often used interchangeably with PV module (especially in one-module systems), but more accurately used to refer to a physically connected collection of modules (i.e., a laminate string of modules used to achieve a required voltage and current).

Photovoltaic (PV) System - a complete set of components for converting sunlight into electricity by the photovoltaic process, including the array and balance of system components.

Physical Vapor Deposition - a method of depositing thin semiconductor photovoltaic films. With this method, physical processes, such as thermal evaporation or bombardment of ions, are used to deposit elemental semiconductor material on a substrate.

P-I-N - a semiconductor photovoltaic (PV) device structure that layers an intrinsic semiconductor between a p-type semiconductor and an n-type semiconductor; this structure is most often used with amorphous silicon PV devices.

Polycrystalline Silicon - a material used to make photovoltaic cells, which consist of many crystals unlike single-crystal silicon.

P-Type Semiconductor - a semiconductor in which holes carry the current; produced by doping an intrinsic semiconductor with an electron acceptor impurity (e.g., boron in silicon).

Pyranometer - an instrument used for measuring global solar irradiance.

Recombination - the action of a free electron falling back into a hole. Recombination processes are either radiative, where the energy of recombination results in the emission of a photon, or nonradiative, where the energy of recombination is given to a second electron which then relaxes back to its original energy by emitting phonons. Recombination can take place in the bulk of the semiconductor, at the surfaces, in the junction region, at defects, or between interfaces.

Resistance (R) - the property of a conductor, which opposes the flow of an electric current resulting in the generation of heat in the conducting material. The measure of the resistance of a given conductor is the electromotive force needed for a unit current flow. The unit of resistance is ohms.

Ribbon (Photovoltaic) Cells - a type of photovoltaic device made in a continuous process of pulling material from a molten bath of photovoltaic material, such as silicon, to form a thin sheet of material.

Schottky Barrier - a cell barrier established as the interface between a semiconductor, such as silicon, and a sheet of metal.

Semiconductor - any material that has a limited capacity for conducting an electric current. Certain semiconductors, including silicon, gallium arsenide, copper indium diselenide, and cadmium telluride, are uniquely suited to the photovoltaic conversion process.

Semicrystalline - Multicrystalline.

Series Connection - a way of joining photovoltaic cells by connecting positive leads to negative leads; such a configuration increases the voltage.

Series Resistance - Parasitic resistance to current flow in a cell due to mechanisms such as resistance from the bulk of the semiconductor material, metallic contacts, and interconnections.

Short-Circuit Current (I_{sc}) - the current flowing freely through an external circuit that has no load or resistance; the maximum current possible.

Silicon (Si) - a semi-metallic chemical element that makes an excellent semiconductor material for photovoltaic devices. It crystallizes in face-centered cubic lattice like a diamond. It's commonly found in sand and quartz (as the oxide).

Solar Cell - photovoltaic (PV) cell.

Solar Constant - the average amount of solar radiation that reaches the earth's upper atmosphere on a surface perpendicular to the sun's rays; equal to 1353 Watts per square meter or 492 Btu per square foot.

Solar Spectrum - the total distribution of electromagnetic radiation emanating from the sun. The different regions of the solar spectrum are described by their wavelength range. The visible region extends from about 390 to 780 nanometers (a nanometer is one billionth of one meter). About 99 percent of solar radiation is contained in a wavelength region from 300 nm (ultraviolet) to 3,000 nm (near-infrared). The combined radiation in the wavelength region from 280 nm to 4,000 nm is called the broadband, or total, solar radiation.

Staebler-Wronski Effect - the tendency of the sunlight to electricity conversion efficiency of amorphous silicon photovoltaic devices to degrade (drop) upon initial exposure to light.

Stand-Alone System - an autonomous or hybrid photovoltaic system not connected to a grid. May or may not have storage, but most stand-alone systems require batteries or some other form of storage.

Standard Test Conditions (STC) - conditions under which a module is typically tested in a laboratory.

Storage Battery - a device capable of transforming energy from electric to chemical form and vice versa. The reactions are almost completely reversible. During discharge, chemical energy is converted to electric energy and is consumed in an external circuit or apparatus.

String - a number of photovoltaic modules or panels interconnected electrically in series to produce the operating voltage required by the load.

Substrate - The physical material upon which a photovoltaic cell is applied.

Thin Film - a layer of semiconductor material, such as copper indium diselenide or gallium arsenide, a few microns or less in thickness, used to make photovoltaic cells.

Thin Film Photovoltaic Module - a photovoltaic module constructed with sequential layers of thin film semiconductor materials. See amorphous silicon.

Total Internal Reflection - the trapping of light by refraction and reflection at critical angles inside a semiconductor device so that it cannot escape the device and must be eventually absorbed by the semiconductor.

Ultraviolet - Electromagnetic radiation in the wavelength range of 4 to 400 nanometers.

Vacuum Evaporation - the deposition of thin films of semiconductor material by the evaporation of elemental sources in a vacuum.

Valence Band - the highest energy band in a semiconductor that can be filled with atomic nucleus. Also called bound state.

Volt (V) - a unit of electrical force equal to that amount of electromotive force that will cause a steady current of one ampere to flow through a resistance of one ohm.

Voltage at Maximum Power (Vmp) - the voltage at which maximum power is available from a photovoltaic module.

Wafer - a thin sheet of semiconductor (photovoltaic material) made by cutting it from a single crystal or ingot.

Watt - the rate of energy transfer equivalent to one ampere under an electrical pressure of one volt. One watt equals 1/746 horsepower, or one joule per second. It is the product of voltage and current (amperage).

CHAPTER ONE INTRODUCTION

1.1 Background information

Communication satellites have become part of our lives and are involved in many applications such as providing entertainment, weather reports, security and even intercontinental mobile phone communication. For communication to exist between the satellites and ground stations, antennas driving circuits, radio receivers, transmitters and other electronic control circuits associated with the satellite must be electrically powered, hence providing reliable power source over the anticipated mission life is critical to all satellites (Brandhorst, & Rodiek, 2008, p.1233). Several sources of electrical power for satellites exist such as fuel cells, nuclear or battery stored Direct Current (DC) energy but of late concentration has been on solar cells as the advantages compared to the other sources are many. Many types of solar panels for electrical generation exist but most of them are made of single type of solar cell materials which is the reason for their limited efficiency.

Photovoltaic principle of solar cells started way back in 1839 when Alexandre Edmund Becquerel observed that electrical currents arose from certain light induced chemical reactions. A comprehensive understanding of this phenomenon became clear when the science of quantum theory was unveiled in the early parts of the 20th century (Markvart, 2000, p.1). The development of the first solid state device in the late 1940s paved the way to the realization and announcement of a silicon cell. In the year 1954, three American researchers, G.L. Pearson, Daryl Chapin, and Calvin Fuller, demonstrated a silicon solar cell that can convert sun energy to electrical energy at 6-percent efficiency when used in direct sunlight. The development of solar cells has been so rapid that by the late 1980s, the conversion efficiency of silicon cells had gone above 20%.

Solar or photovoltaic cells in solar panels on board the satellites convert sunlight energy to electrical energy to provide the required power. Space solar cells should have both radiation tolerance and suitable thermal properties to enable them to function properly. It is important to understand the thermal radiation properties of solar cells as their conversion efficiency reduces with increase in temperature (Shimazaki, Imaizumi & Kibe, 2007, p.2218). There are several types of solar cells, but proper selection of the type to be used in space must be done to ensure long and reliable operational life time service. In order to decrease both size and cost of solar arrays, high efficiency solar cells are needed. In the last ten years, 117 satellites were recorded with solar array anomalies

and 12 among them completely failed. The solar cell array anomalies and failures were caused by the harsh space environmental condition (Henry, W .B & Julie, A.R. 2008, p1233-1238).

Low earth orbit (Leo) and high altitude space where a number of spacecrafts, including Space Shuttle and where the CPUT-F'SATIE cube satellite will be orbiting has unique environmental characteristics. The space environment consists of high vacuum, and ultraviolet (UV) radiation, extreme thermal cycles, atomic oxygen (AO), charged particles, electromagnetic radiation, micrometeoroids, and other man-made debris which affect solar cell operation in one way or another(Reitz, 2008,p.233). The main focus of this thesis entails the development of a high efficiency solar panel that will be used as a reliable source of electrical energy to power satellites operating in high altitude and low earth orbits. The building block for this panel is a multi-junction solar cell made of different semiconductor materials in parallel. Multi-junction solar cells are design to have high efficiency by absorbing a large portion of the visible light spectrum which is approximately from 350nm to 800 nm (Young, Freedman, & Sandin, 2000, p.1045).

1.2 Statement of research problem

Satellite electronics and communication systems require a stable and reliable source of electrical power for effective and reliable operation. Solar cells as the source of this power are highly affected by space environment. The aim of this research is to develop an efficient solar panel from multi-junction solar cells made of existing terrestrial solar cell technology. The advantage of this solar panel is that it will generate a much higher power compared to the power that will be generated by a silicon solar panel of the same size.

1.3 Research questions

Can an efficient multi-junction solar cell be developed from various existing terrestrial solar cells?

Can the multi-junction solar cell be used to develop solar panels for high altitude and low earth orbit applications?

Can the multi-junction cell be used to develop a 9 volt, 6 watt solar panel to power the CPUT-F'SATIE cube satellite project?

What are the current techniques for developing multi-junction solar cells for space applications?

What are the main requirements for developing such multi-junction cells and solar panel?

1.4 Aims and objectives of research

The research will consider the various solar panel development techniques available today. The main aim of the research is to employ the same available techniques to design an efficient multi-junction cell that will be used to develop a solar panel for space applications. The solar panel will be used to power satellites operating in low earth orbit and high altitude space. The outcome of the research will go a long way to cut down space solar panel production expenses as the technology that will be used is already known and highly developed.

1.5 Objectives

The objectives that need to be accomplished in order to fulfill the main aim are as follows:-

- To develop an equivalent low earth orbit mathematical solar cell model and use it with Mat Lab^(R) simulation software.
- To identify different types of solar cells among the terrestrial ones whose materials can withstand and operate in the low earth orbit and high altitude environmental conditions.
- To simulate different operating conditions with Mat Lab^(R) for different types of solar cells, observe and record their parameters.
- To use simulation results to design an efficient multi-junction solar cell and use it to develop a solar panel with the required specifications.

1.6 Research methodology

In order to reach the research goal, the following methods and tasks were performed.

- Extensive literature survey on the subject of solar cell was performed.
- Equivalent solar cell mathematical model was developed and used with computer simulations to compare operational difference between space & terrestrial environment for different solar cells.
- A number of different types of solar cells were listed and simulated with different environmental conditions.

- Simulation results were used to determine and calculate figures of merits for each solar cell such as open circuit voltage, short circuit current, fill factor, cell efficiency, and etcetera for space environment.
- From the list of simulated solar cells, a number of them were selected according to light spectrum absorption (bandgap) to design a multi-junction solar cell.
- The multi-junction solar cell is then used to develop a solar panel as per power and voltage requirement.

1.7 Research delineation

Solar panels for powering satellites are required to overcome the various strains existing in the space environment which affect and degrade their operations. As explained earlier, the space consists of a number of detrimental factors but, to reduce the complexity of modeling and computational burdening, only two of them, that is light intensity and temperature effects will be considered in this panel development and the others will be assumed constant. The two factors have been selected because, solar cells as opto-electronics and semiconductor devices are more adversely affected by temperature and light intensity in their operations than by the other factors.

1.8 Significance of the research

Most countries rely on satellites for information exchange, communication, entertainments and research work. Reliability of such satellites is of prime importance not only for the power supply but with the entire satellite subsystems. Development of solar panels that will endure severe space conditions and efficiently generate the required electrical power will save a lot of money at the same time extend the satellite operational life time.

1.9 Thesis organization

This thesis is divided into seven chapters. Chapter one is the introduction part and briefly explains the history of solar cells, significance and objectives of the research. Chapter two is the literature review on the subject of solar cells and panels. Basic mathematical modeling of the solar cell will be dealt with in chapter three together with the adaptation of the model to the selected space environment factors. Chapter four explains the methods used in the research while chapter five deals with simulation, measurements and results analysis. Design and development of the solar panel is explained in chapter six.

Conclusion and recommendation on the research is the final part of the thesis and comes in chapter seven.

1.10 Conclusion

The successful completion and development of the solar panel for high altitude and low earth orbit applications is a major contribution to the satellite industry. Stable and improved electrical power source solar panels have an advantage of extending satellite operational life time which is one of the requirements for reducing cost and increasing profit. This chapter presented and discussed the importance of satellites in our daily lives, the main aim and objectives of the thesis. The chapter completes with the explanation of chapter arrangement of the thesis.

CHAPTER TWO LITERATURE REVIEW

2.1 Introduction

Solar cells work in a similar manner to the way plants absorb light energy and convert it to food energy by photosynthesis. Both systems utilize energy from the sun which comes in photon packages with energy content expressed as, $E = h\nu$ where E is energy, h is the Planck constant, and ν is the frequency of the photon (Markvart, 2000, p.30). Solar cells produce quite and clean electricity from sun, a renewable and non-depletable source of energy and also support green peace movement which aims to reduce global warming and its effects. The main challenge for engineers and scientists around the world is to find ways of lowering the costs of solar cell production, increase their energy conversion efficiency, and create innovative and efficient new products and applications based on photovoltaic technology. Apart from domestic and industrial applications, solar cells are extensively used in satellites.

As the technology and applications of satellites is becoming broader, their reliability presents a major concern to satellite designers and end users. One of the required systems to ensure effective functioning of the satellite is a reliable source of electrical power supply. Several sources of electrical power for satellite operation exist today but this research concentrates on photovoltaic or solar cells as their advantages compared to other types of electrical sources are abundant.

2.2 Literature review

The literature review for this research and its documentation required an extensive search of information from several sources. The major sources of information were books, magazines, online sources, past researches and papers on related fields. As explained earlier in chapter one, this research looks into developing a solar panel for high altitude and low earth applications. The solar panel will be developed from a multi-junction solar cell which itself is made from a combination of different single junction solar cells (solar cell materials) that presently exist in the market. The literature review focuses on solar cell information and topics that form the basis of multi-junction solar cell device which is the building block of the solar panel. The topics that have been covered in the review are as follows:-

1. History of solar cells
2. Solar cell energy system

3. Solar cell structure
4. Solar cell operation
5. Basic solar cell model
6. Solar cell parameters.
7. Factors determining solar cell operation
8. Solar cell materials
9. Multi-junction solar cell
10. Low earth orbit definition and its effect on solar cell operations
11. Solar cells applications

2.3 History of solar cells

Solar cells as a source of electrical energy were discovered in 1839 by French physicist A. E. Becquerel. Becquerel observed that electric current flows when light falls on a silver coated platinum electrode immersed in an electrolyte and developed a voltage (Nelson, 2004, p.2). In 1883 the first solar cell was built, by Charles Fritts, who coated a selenium semiconductor with an extremely thin layer of gold to form a junction. The device was only around 1% efficient. Solar cells did not have to wait for long to find applications in space. The first artificial satellite to be powered electrically from solar cells was the Vanguard 1 which was launched and successfully placed in earth orbit by the united states in the year 1958 .The solar cells continued to supply power to the satellite for its operation till late 1964 when communication was lost after its last solar cell died (Naval Research Laboratory, 2008). Several types of solar cell technologies have so far been developed to provide electrical power with different efficiencies.

2.4 Solar cell energy system

Solar energy from solar cells in conjunction with batteries provides most of the electrical power requirements in spacecraft nowadays. Many developments have been made for various types of solar panels and their efficiencies have recently been improved substantially. By definition, a solar cell or photovoltaic cell is a device that converts sunlight directly into electricity by photovoltaic effect. Compared to other sources of electricity, solar cells have many advantages. Solar cells use free renewable energy from the sun to silently produce electricity without polluting the environment. They also have an advantage of requiring little maintenance since they have no moving parts.

2.5 Solar cell structure

The starting point for all solar cells is a semiconductor. Semiconductors are crystalline solids, which in their pure state are very good insulators especially at low temperatures. At higher temperatures they start to demonstrate electronic conductivity due to the disruption of the ideal lattice structure. (Berger, Knobloch, & Bernhard, 1998, p.9). Like all semiconductor devices, solar cells work with a semiconductor that has been doped to produce two different regions separated by a p-n junction. The important feature of all p-n junctions is that they contain a strong electric field that pulls and cause holes and electrons to flow in opposite directions. In conventional solar cells, the electrical field is created at the junction between two regions of a crystalline semiconductor having contrasting types of conductivity. Doping refers to the addition of impurities to an intrinsic semiconductor for example by ion implantation, diffusion of dopants, or by epitaxy (growing a layer of crystal doped with one type of dopant on top of a layer of crystal doped with another type of dopant). For example if one side of a silicon semiconductor is doped with phosphorous, a group V element, a n-semiconductor is formed which has excess electrons freely flowing. The other side of the silicon semiconductor can be doped with boron; a group III element to results in a p-semiconductor, with excess holes. The region between the n and p is what is referred as p-n junction (Lorenzo, Araujo, & Zilles, 1994, p.80). Semiconductors can be found in elemental or compound form. Silicon (Si) and Germanium (Ge) are examples of elemental semiconductors. Both of these semiconductors belong to group IV of the periodic table. Majority of the photovoltaic cells are silicon based. Compound photovoltaic cells are made from a combination of elements from groups III and V or elements from groups II and VI. Figure 2.1 shows a section of a periodic table derived from dynamic periodic table. Examples of group III-V semiconductors include Aluminum Phosphide, Gallium Nitride, Indium Phosphide, and Gallium Arsenide while those from group II and VI are Zinc Oxide, Cadmium Telluride, and Mercury Sulfide (Whitaker, 2005, p.124). Majority of solar cells in the market today are silicon based but other technologies based on compound semiconductors are also pushing their way into the market.

3A		13	4A	14	5A	15	6A	16	
5		B	6	C	7	N	8	O	
10.811 Boron			12.0107 Carbon		14.0067 Nitrogen		15.9994 Oxygen		
13		Al	14	Si	15	P	16	S	
26.9815 Aluminum			28.0855 Silicon		30.9738 Phosphorus		32.065 Sulfur		
2B	12								
30	Zn	31	Ga	32	Ge	33	As	34	Se
65.409 Zinc		69.723 Gallium		72.64 Germanium		74.9216 Arsenic		78.96 Selenium	
48	Cd	49	In	50	Sn	51	Sb	52	Te
112.411 Cadmium		114.818 Indium		118.710 Tin		121.760 Antimony		127.60 Tellurium	
80	Hg	81	Tl	82	Pb	83	Bi	84	Po
200.59 Mercury		204.383 Thallium		207.2 Lead		208.9804 Bismuth		[209] Polonium	

Figure 2.1 Partial periodic table (Dynamic periodic table, 2010)

Basically, a solar cell is made of three layers for its operation. The first layer is usually a highly doped N-type semiconductor called emitter. The next layer is the core of the device; this is the absorber layer or the P-N junction. The third layer is the base made of P-type semiconductor which is less highly doped than the emitter. The top structure of the cell is made to allow light to pass through and has a widely-spaced thin metal strips (*fingers*) that collect and supply light generated current to a larger bus bar (Markvart, 2000, p.33). The back electrical contact which must be a good electrical conductor is usually made of metal case which also serves as a base for the solar cells and provides rigidity.

2.6 Solar cell operation

Solar cells convert light energy into electrical energy by photovoltaic process. When a package of light energy called a photon hits the p-n part of a silicon solar cell or any other type of solar cell material, one of the three things can happen:

- The photon may pass freely through the material as usually happens if it has a low energy or
- The photon may be reflected off the surface or

- The photon may be absorbed if it has energy is a higher than the material bandgap value. This will cause an electron-hole pair to be released and sometimes heat, depending on the bandgap value.

Solar cells generate electricity in three steps. The first step is the absorption of light by the material, followed by generation and separation of the light generated charge carriers (electrons and holes), and finally transporting of these carriers to the electrodes. The separation and transportation of charges is a function of the electric field across the p-n junction which is also responsible for directing the electrons and holes in opposite directions (Archer & Hill, 2005, p.15).

Once a photon of light with enough energy hits the p-n junction of a solar cell, it will be absorbed and break apart an electron-hole pair from a covalent bond. The electrons will be excited to the conduction band as shown in figure 2.2. Normally, when a light photon with enough energy is absorbed by a material, it will free only one electron-pair (Wufel, 2009, p.71). If these electron-hole pairs are released close enough to the electric field, or if they happen to wander into its range of influence, the electrons will be attracted and sent to the N side and the holes to the P side. When the cell is connected to an external load, electrons will pass through that load and back to the P side to unite with the hole, and in doing so, work is done. The flow of electrons produces electrical current and the cell's electric field causes a voltage. The product of these two parameters gives the cell power. Figure 2.3 shows a basic layout of a solar cell connected to a load.

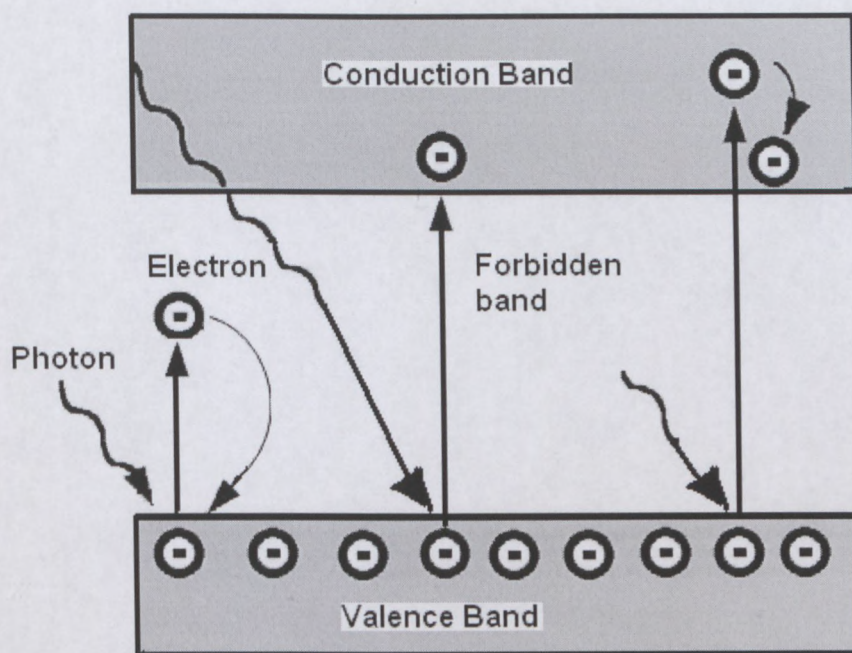


Figure 2.2 Electron transition from valence to conduction state (Solannski, 2009, p.37)

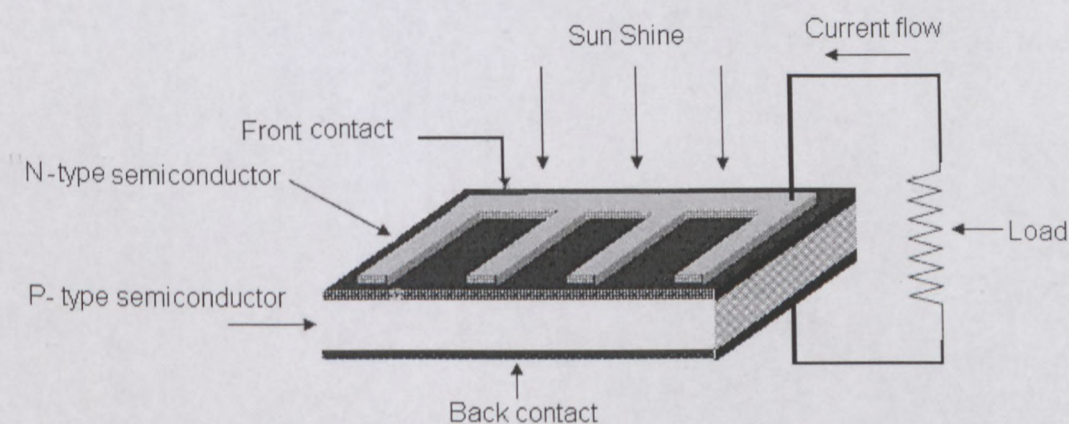


Figure 2.3 Basic solar cell layout (Knier, 2002, p.1)

The performance of a solar cell is usually described using power conversion efficiency (η) and fill factor (FF) parameters. These parameters can be determined from the current-voltage (I - V) characteristics of the cell (Desilvestro, 2008, p.1). Energy content in a photon depends on light wavelength and is expressed as $E = h\nu = hc/\lambda$, where h is Planck's constant (6.63×10^{-34}), ν is the frequency of light, c is speed of light (2.998×10^8 m/sec) and λ is the wavelength of light. The energy in a photon must exceed the

semiconductor energy band gap, E_g to be absorbed and generate electrons from covalence bonds.

The basic operation of a solar cell can be explained using its equivalent electrical model which is based on discrete electrical components. An ideal solar cell can be represented by a simple model having a current source in parallel with a diode, D. In practice all solar cells have losses, hence resistance component are added in the model to represent these losses. The common losses associated with solar cell operation are leakage current losses represented by shunt resistance (R_{SH}) and contact losses represented by series resistance (R_S) (Lorenzo *et al*, 1994, p.80). Figure 2.4 shows an electrical equivalent model of a solar cell.

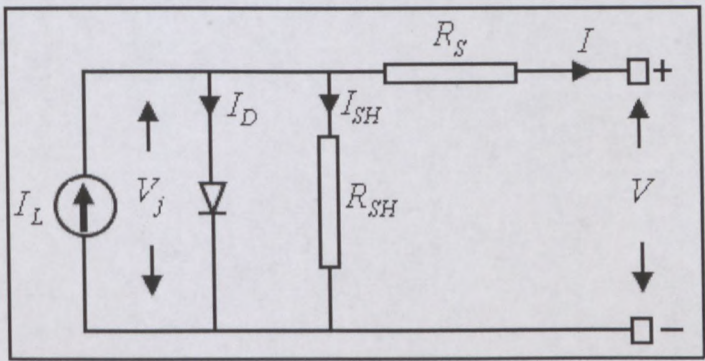


Figure 2.4 Solar cell model (Carson, 2008, p.26)

As seen from the diagram of figure 2.4, the output current I from the cell is the difference of the light generated current I_L and the diode current I_D . Hence,

$$I = I_L - I_D - I_{SH} \tag{2.1}$$

Where,

I = Output current in amperes.

I_L = Photo generated current in amperes.

I_D = Current passing through diode, D.

I_{SH} = Current passing through shunt resistance R_{SH} .

V = Output voltage across solar cell terminals.

$V_j = V + IR_s$ = Voltage across the diode.

R_s = Series resistance of the cell

R_{SH} = Shunt resistance of the cell.

The current I_D is given by Shockley diode equation (Markvart, 1996, p.34), as

$$I_D = I_0 \left\{ \exp \left[\frac{qV_j}{nKT} \right] - 1 \right\} \quad (2.2)$$

In this equation, the constants stand as;

I_0 = Reverse saturation current in amperes.

n = diode ideality factor, 1 for ideal diode.

q = elementary charge = 1.602×10^{-19} Coulomb.

k = Boltzmann's constant = 1.38×10^{-23} J K⁻¹.

T = Absolute temperature.

At 25°C, $\frac{kT}{q} = 0.0259$ volts.

By ohm's law, the current through shunt resistance is expressed as

$$I_{SH} = \frac{V + IR_s}{R_{SH}} \quad (2.3)$$

Using equation 2.2 and 2.3, equation 2.1 can be re-written as;

$$I = I_L - I_0 \left\{ \exp \left[\frac{q(V + IR_s)}{nKT} \right] - 1 \right\} - \frac{(V + IR_s)}{R_{SH}} \quad (2.4)$$

Equation 2.4 is referred to as solar cell I-V characteristic equation and is sometimes written in terms of current densities as;

$$J = J_L - J_0 \left\{ \exp \left[\frac{q(V + Jr_s)}{nkT} \right] - 1 \right\} - \frac{(V + Jr_s)}{r_{SH}} \quad (2.5)$$

Where

- J = Current density in amperes per cm^2 .
- J_L = Photo generated current density in amperes per cm^2 .
- J_0 = Reverse saturation current density in amperes per cm^2 .
- r_s = Specific series resistance ($\Omega - cm^2$).
- r_{SH} = Specific shunt resistance ($\Omega - cm^2$).

The current density expression has several advantages. One is that since cell characteristics are referenced to a common cross-sectional area they may be compared for cells of different physical dimensions. While this is of limited benefit in a manufacturing setting, where all cells tend to be the same size, it is useful in research and in comparing cells between manufacturers. Another advantage is that the density equation naturally scales the parameter values to similar orders of magnitude, which can make numerical extraction of them simpler and more accurate even with naive solution methods.

There are practical limitations of this formulation. For instance, certain parasitic effects grow in importance as cell sizes shrink and can affect the extracted parameter values. Recombination and contamination of the junction tend to be greatest at the perimeter of the cell, so very small cells may exhibit higher values of J_0 or lower values of R_{SH} than larger cells that are otherwise identical. In such cases, comparisons between cells must be made cautiously and with these effects in mind.

This approach should only be used for comparing solar cells with comparable layout. For instance, a comparison between primarily quadratical solar cells like typical crystalline silicon solar cells and narrow but long solar cells like typical thin film solar cells can lead to wrong assumptions caused by the different kinds of current paths and therefore the influence of for instance a distributed series resistance r_s (Aberle & Wenham, 1993, p.114).

2.7 Solar cell parameters

The external characteristic of a solar cell is a property of its operating current versus voltage known as solar cell characteristic curve. Practical derivation of any solar cell

characteristic curve can be drawn and approximated from equation 2.6, which is a simplification of equation 2.4.

$$I = I_L - I_o \left(\exp \left[\frac{qV + IR_s}{nkT} \right] - 1 \right). \tag{2.6}$$

Figure 2.5 shows a typical current/voltage solar cell characteristic curve. Practically, this curve is used to determine various solar cell parameters such as open circuit voltages, short circuit current etc.

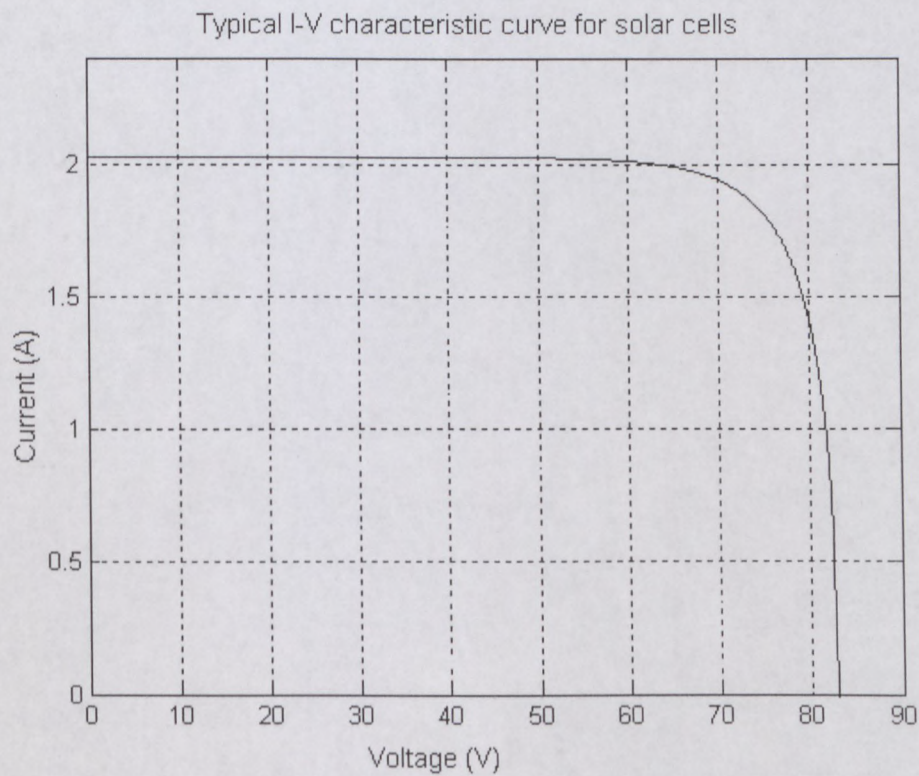


Figure 2.5Typical I-V characteristic curve of a solar panel

2.7.1 Open circuit voltage (V_{oc})

This is defined as the voltage across the output terminals when the output current *I* is equal to zero. From equation 2.4 when output current, *I* is equated to zero, the expression will read;

$$0 = I_L - I_0 \left\{ \exp \left[\frac{qV}{nkT} \right] - 1 \right\} - \frac{V}{r_{SH}}.$$

For an ideal or high efficiency solar cell, shunt resistance r_{SH} is supposed to be very high representing very low losses (Shen, Ding, Choo, Wang, Loh, & Tan, 2009, p.3334). By assuming a very high shunt resistance and after rearrangement, the expression becomes ;

$$\left(\frac{I_L}{I_0} + 1 \right) = \exp \left[\frac{qV}{nkT} \right] \quad (2.7)$$

By multiplying both sides with natural log_e and making V the subject the result is;

$$V = \frac{nkT}{q} \ln \left[\frac{I_L}{I_0} + 1 \right] = V_{OC} \quad (2.8)$$

This equation can be used to determine open circuit voltage for any given type of solar cell.

2.7.2 Short circuit current (I_{sc})

This is defined as the output current when a short circuit is placed between the output terminals or when the terminal voltage of the cell is equal to zero. For high quality solar cells, R_S and I_0 values are very low while R_{SH} is very high therefore from equation 2.4, it can be seen and concluded that all the light generated current flows out as short circuit current. Figure 2.6 shows the open circuit voltage and short circuit current on solar cell I-V characteristic curve.

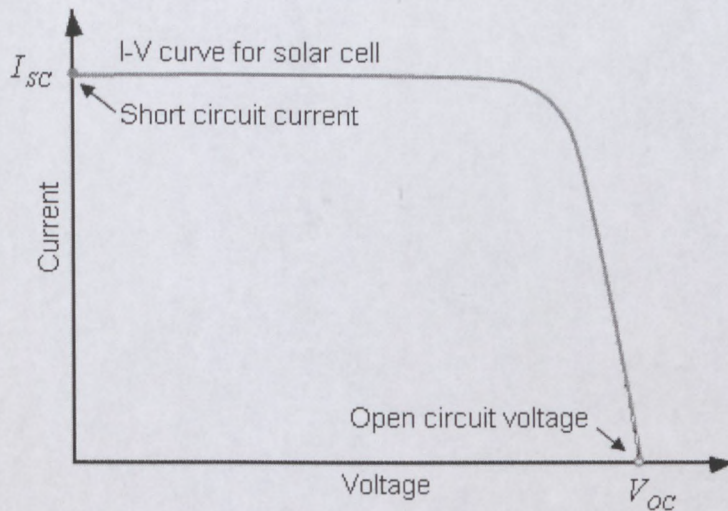


Figure 2.6 Solar cell I-V curve showing voltage and current
(Honsberg & Bowden, 2009, p.72)

2.7.3 Fill factor (ff)

The short-circuit current and the open-circuit voltage are the maximum current and voltage operating points respectively from a solar cell. However, at both of these operating points, the power from the solar cell is zero. The "fill factor" of a cell, more commonly known by its abbreviation "FF", is a parameter which, in conjunction with V_{oc} and I_{sc} , determines the maximum power from a solar cell. The FF is defined as the ratio of the maximum power from the solar cell to the product of V_{oc} and I_{sc} (Jha, 2010, p.94). Graphically, the FF is a measure of the "squareness" of the solar cell IV characteristic and is also the area of the largest rectangle which will fit in the IV curve. Figure 2.7 shows how a solar cell fill factor can be determined graphically.

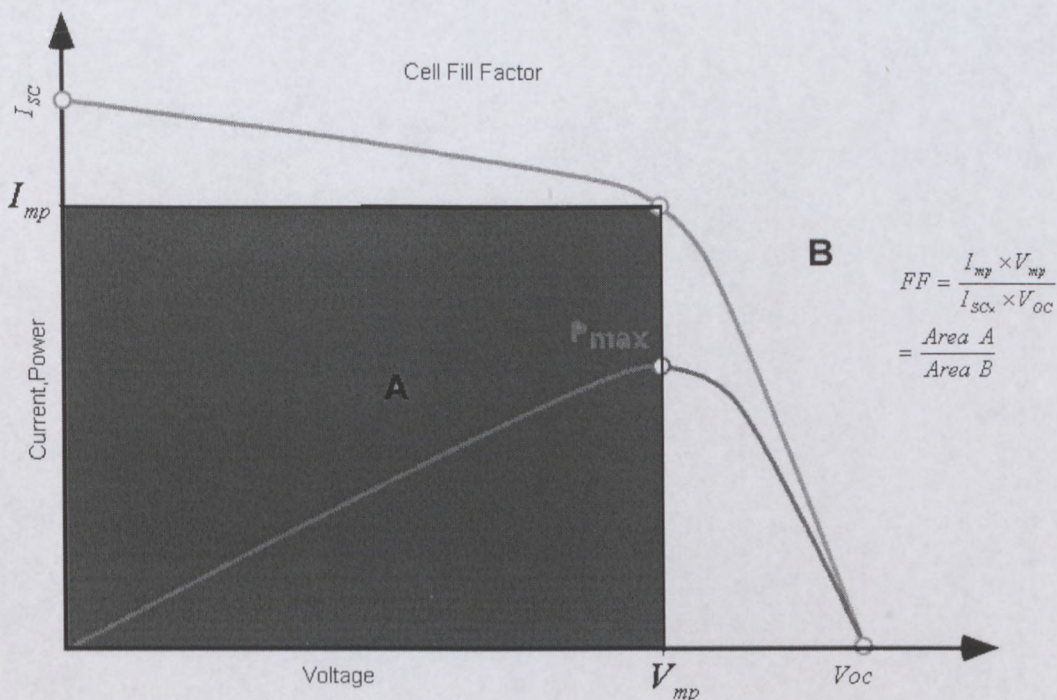


Figure 2.7 Determination of fill factor (Honsberg et al, 2009, p.74)

$$FF = \frac{P_m}{V_{OC} \times I_{SC}} = \frac{\eta \times A_C \times E}{V_{OC} \times I_{SC}}, \text{ Where } A_C \text{ stands for cell area, } E \text{ is light density and } (\eta)$$

is the efficiency of the solar cell. Fill factor is directly affected by the values of the cells series and shunt resistance. Increasing the shunt resistance (R_{SH}) and decreasing the series resistance (R_s) will lead to higher fill factor, thus resulting in greater efficiency, and pushing the cells output power closer towards its theoretical maximum (Nema, Nema, & Agnihotri, 2010, p.493).

2.7.4 Maximum-power point (MPP)

A solar cell may operate over a wide range of voltages (V) and currents (I). By increasing the resistive load on an irradiated cell continuously from zero (a *short circuit*) to a very high value (an *open circuit*) one can determine the maximum-power point, the point where the solar cell delivers maximum power to the load. This power is expressed as $P_m = I_m \times V_m$ where I_m and V_m corresponds to maximum current and voltage points respectively at a given level of irradiation. This corresponds to area labeled, A in figure 2.8.

2.7.5 Efficiency (η)

The efficiency is the most commonly used parameter to compare the performance of one solar cell to another. Efficiency is defined as the ratio of energy output from the solar cell to input energy from the sun.

In addition to reflecting the performance of the solar cell itself, the efficiency depends on the spectrum and intensity of the incident sunlight and the temperature of the solar cell. Therefore, conditions under which efficiency is measured must be carefully controlled in order to compare the performance of one device to another. Terrestrial solar cells are measured under AM1.5 conditions and at a temperature of 25°C. Solar cells intended for space use are measured under AM0 conditions.

Solar cell efficiency η is expressed as

$$\eta = \left[\frac{P_m}{E \times A_c} \right] \text{ .Where } P_m \text{ is the maximum power point, } E \text{ is input light irradiance in}$$

W/m² and A_c is the solar cell surface area in m² under standard test conditions (STC). The standard test conditions (STC) for solar cells operating in terrestrial environment is the Air Mass 1.5 spectrum, an incident light power density of 1000 W m⁻², and a temperature of 25°C (Nelson, 2004, p.12). Other test standards exist for different environments such as space. In this environment the standard is air mass zero (AM0) with light intensity condition of 1367Wm⁻²(Luque & Hegedus, 2003, p703.).

2.8 Factors determining solar cell operation

2.8.1 Temperature

Solar cells are equally affected by temperature as any other semiconductor devices do. An increase in temperature reduces the band gap of a semiconductor, thereby effecting most of the semiconductor material parameters. Decreasing the band gap of a solar cell device due to increase in temperature can be viewed as increasing the kinetic energy of the electrons in the cell material thereby reducing the energy required to break them from their covalence bonds.

Temperature rise affects solar cell characteristic equation in two ways: directly, via T in its exponential term, and indirectly via the way it affects its reverse saturation current, I_o (Strictly speaking, temperature affects all of the terms in the characteristic equation, but these two are significantly more affected than the others). The exponential component of the equation will reduce with increase in temperature while the value of reverse current

will increase. The net effect is to linearly reduce the open circuit voltage V_{OC} of the solar cell (Green, Wenham, Watt, 2007, p.50)

The impact of increasing temperature is shown in figure 2.8.

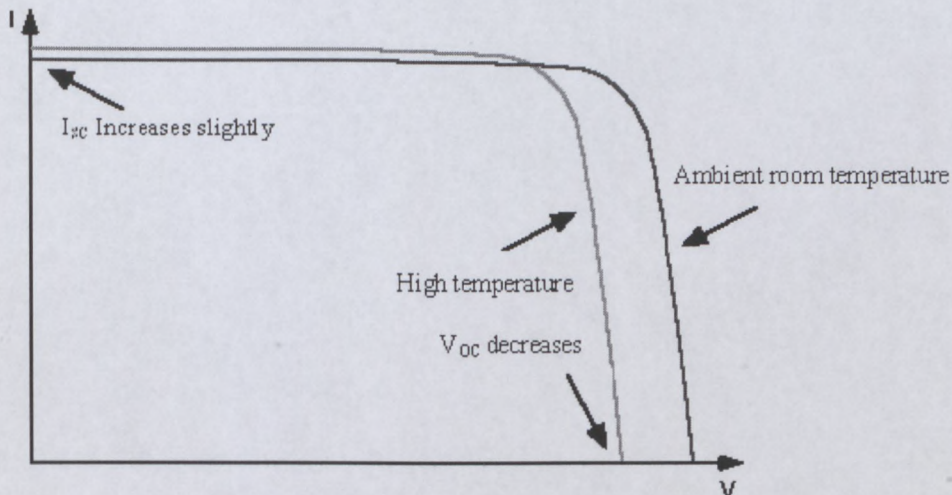


Figure 2.8 Effect of temperature on solar cell open circuit voltage
(Green, Wenham, & Watt, 2007, p.50)

2.8.2 Irradiance

In this context, irradiance refers to the amount of light incident to a solar cell surface.

Light-generated current is proportional to the flux of photons with energy band gap above that of the solar cell material. Increasing the sun irradiance will proportionally increase the photon flux which, in turn, generates a proportionately higher current. Therefore, the short-circuit current of a solar cell is directly proportional to the irradiance (Markvart, 2000, p.45). Solar cell characteristics under different levels of light illumination is shown in figure 2.9.

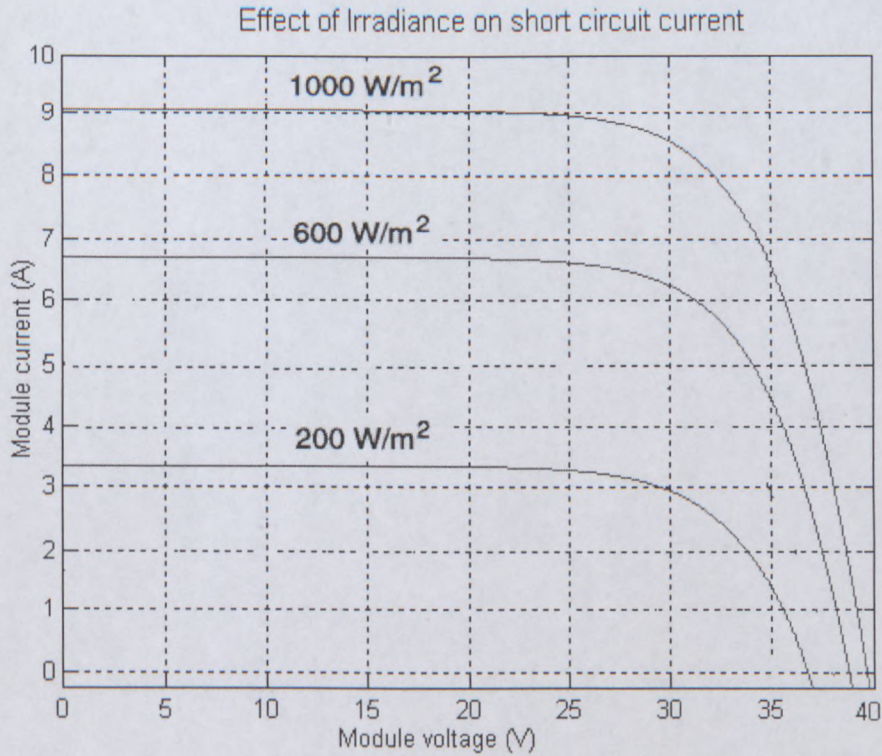


Figure 2.9 Effect of irradiance on short circuit current (Solar Server, 2010)

Changing of light intensity incident on a solar cell has a bigger effect on short circuit current than on open circuit voltage. The light intensity on a solar cell is sometimes expressed in terms of number of suns which is a ratio of the actual light intensity on the cell to the light magnitude of 1000 W/m^2 .

2.8.3 Characteristic resistance

The characteristic resistance of a solar cell is the output resistance of the solar cell at its maximum power point. If the resistance of the load is equal to the characteristic resistance of the solar cell, then the maximum power is transferred to the load and the solar cell operates at its maximum power point. It is a useful parameter in solar cell analysis, particularly when examining the impact of parasitic loss mechanisms. The characteristic resistance can be determined with the help of a characteristic curve as shown in figure 2.10.

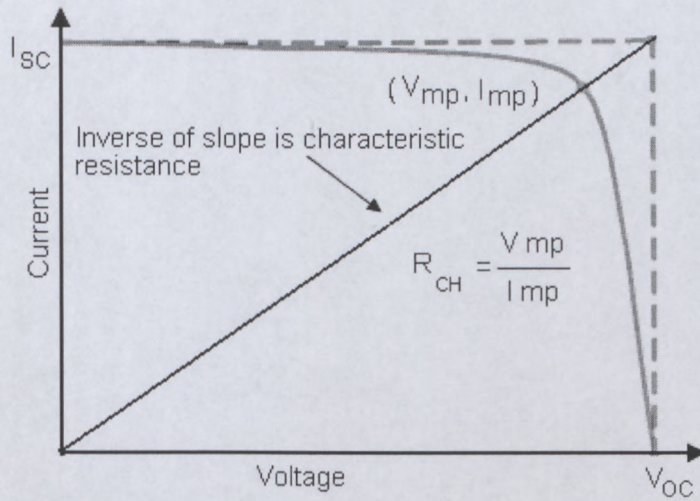


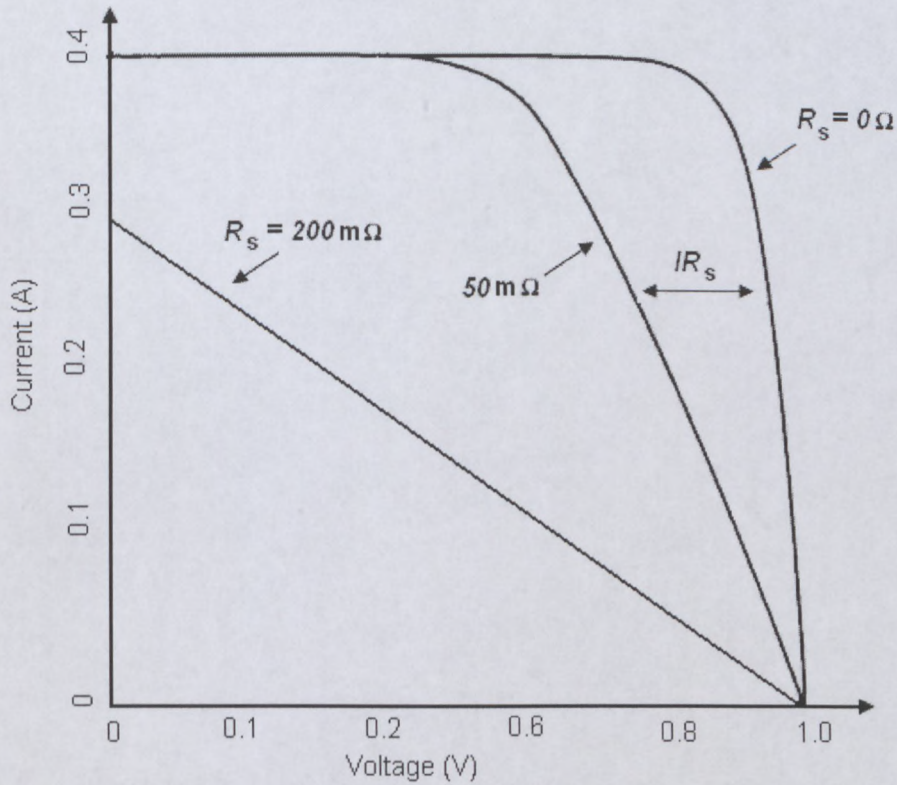
Figure 2.10 Characteristic resistance of a solar cell (Green, 1982)

Characteristic resistance of a solar cell is the inverse of the slope of the line, and is expressed as:

$$R_{CH} = \frac{V_{MP}}{I_{MP}} \quad \text{Or can be approximated as } R_{CH} = \frac{V_{OC}}{I_{SC}} \quad (\text{green et al, 1982 p.113}).$$

2.8.4 Parasitic resistance

Resistive effects in solar cells reduce the efficiency of the solar cell by dissipating power in the resistances. The most common parasitic resistances are series and shunt resistances. The series resistance is detrimental to solar cell performance because it reduces the device power output by reducing its fill factor and short circuit current value if it is in excessively high value. The series resistance arises from the resistance of the cell material to current flow, particularly through the front surface to the contacts and from resistive contacts (Nelson, 2004, p.14). As the series resistance increases, the voltage drop across it becomes greater for a given flow of current. The result is that the current-controlled portion of the I-V curve begins to sag toward the origin, producing a significant decrease in the terminal voltage V and a slight reduction in I_{SC} , the short-circuit current. The effect of series resistance on the shape of characteristic curve is shown in figure 2.11.



**Figure 2.11 Effect of series resistance on current-voltage characteristic of a solar cell
(Nelson, 2004)**

In photovoltaic (PV) modules, series resistance R_s represents the resistances in cell solder bonds, emitter and base region, cell metallization, cell-interconnect busbars, and resistances in junction-box terminals. As a practical matter it is generally found that the series resistance in a cell should be no more than a few tenths of an Ohm for each square centimeter of illuminated cell area under one sun conditions. If this is exceeded the cell loads itself down with internal resistance. The series resistance becomes more effective at high generated photocurrents (Mohammed & Shehathan, 2000, p.142).

Power losses in cells due to shunt resistance, R_{SH} are typically due to manufacturing defects, rather than poor solar cell design. Low shunt resistance causes power losses in solar cells by providing an alternate current path for the light-generated current. Such a diversion reduces the amount of current flowing through the solar cell junction and reduces the voltage from the solar cell. As shunt resistance decreases, the current diverted through it increases resulting in the voltage-controlled portion of the I-V curve to sag towards the origin, producing a significant decrease in the terminal current and a

slight reduction in V_{OC} . Very low values of R_{SH} will produce a significant reduction in V_{OC} . Much as in the case of a high series resistance, a badly shunted solar cell will take on operating characteristics similar to those of a resistor (Guo, Cousins & Cotter, 2005, p.96). Figure 2.12 shows how shunt resistance affect the I-V curve of a solar cell.

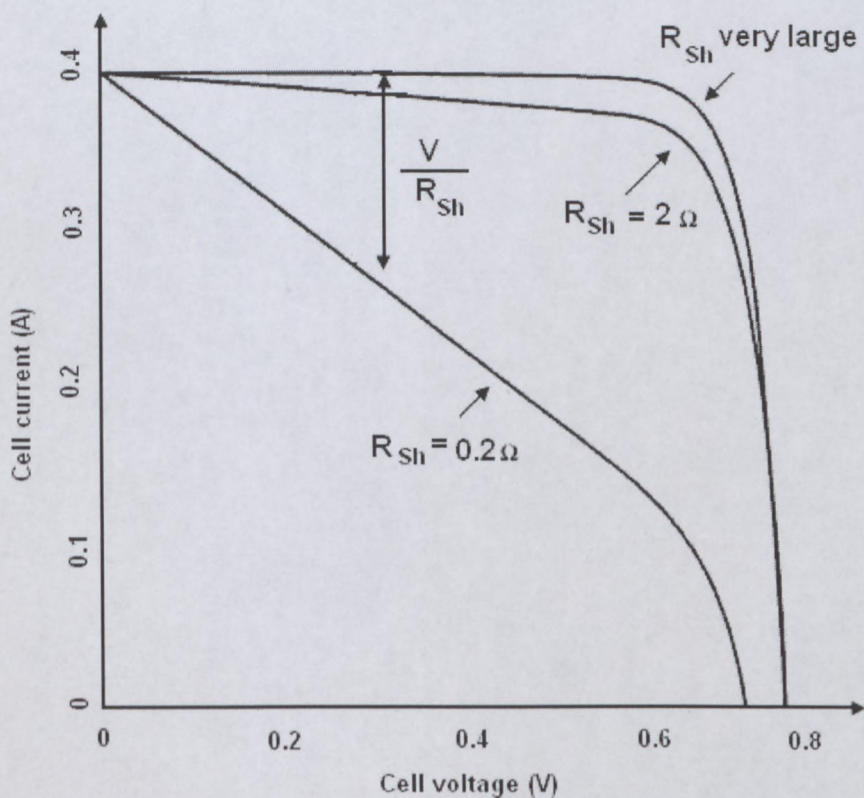


Figure 2.12 Effect of shunt resistance solar cell I-V characteristic curve (Guo, Cousin, & Cotter, 2005, p.96)

2.9 Solar cell materials

There are a number of different technologies that can be used to produce devices which convert light into electricity. In coming up with solar cells, a balance has to be struck between how well the solar cell work and how much it costs to make it work. Solar cells can be made from different types of semiconductor materials. The major type of material has been silicon. Silicon has been the source of solar cell material for a long time and it is also the material found inside integrated circuits and transistors. There are good reasons for using silicon; it is the next most abundant element on earth after oxygen. Sand which is silicon dioxide (SiO_2) is found everywhere on earth (Harper, 2007, p.82).

There are three types of silicon solar cells or silicon cell technology. The first one is amorphous (a-Si) or thin-film solar cells. The second one is polycrystalline cells which are cut from ingots made up of many smaller crystals. The third type is mono-crystalline cells, which are cut from silicon ingots grown from single large crystals of silicon.

2.9.1 Amorphous crystalline cells

Amorphous is the cheapest and most recently developed solar technology for making solar cells and panels. Some companies have already started with the production of these solar cells and have achieved efficiency of between 6 and 8%. Amorphous solar panels are good at generating power even on overcast days and some can generate small amounts of power on bright moonlit nights. Because of their lower efficiency, amorphous solar panels have to be very large and as a result the panels can only be used either where there is no size restriction on the solar panel array or the overall power requirements is low. Amorphous technology is most often seen in small solar panels, such as those in calculators or garden lamps, although amorphous panels are increasingly used in larger applications. They are made by depositing a thin film of silicon onto a sheet of another material such as steel and over large areas by plasma enhanced chemical vapor deposition (PECVD). The design of the PECVD system has great impact on the production cost, focusing on a design that has a higher throughput leads to a lower production cost (Shah, Meier, Buechel, Kroll, Steinhauser, Meillaud, Shade & Domine, 2006, p298). More recently, improvements in a-Si construction techniques have made them more attractive for large-area solar cell use as well. Here their lower inherent efficiency is made up, at least partially, by their thinness - higher efficiencies can be reached by stacking several thin-film cells on top of each other, each one tuned to work well at a specific frequency of light. This approach is not applicable to c-Si cells, which are thick as a result of their construction technique and are therefore largely opaque, blocking light from reaching other layers in a stack. The main advantage of a-Si in large scale production is not efficiency, but cost. a-Si cells use approximately 1% of the silicon needed for typical c-Si cells, and the cost of the silicon is by far the largest factor in cell cost. However, the higher costs of manufacture due to the multi-layer construction have, to date, make a-Si unattractive except in roles where their thinness or flexibility is an advantage. Amorphous silicon thin-film solar cells typically use a p-i-n structure (lightly doped diode nearly intrinsic). solar panel structure includes front

side glass, transparent conducting oxide (TCO), thin film silicon, back contact, polyvinyl butyral (PVB) and back side glass (Frederiksen, Energimidt, & Stephansen, 2009, p.20).

2.9.2 Mono-crystalline cells

Mono-crystalline solar cells are made from single wafers of silicon crystal and are the most efficient solar technology. To produce mono-crystalline silicon cells, absolutely pure silicon material is melted and formed into ingots or rods which are then sawed into thin plates. This production process guarantees a relatively high level of efficiency. The most commonly used process for creating the silicon ingot is called the Czochralski method. In this process, a seed crystal of silicon is dipped into melted polycrystalline silicon. As the seed crystal is withdrawn and rotated, a cylindrical ingot or "boule" of silicon is formed. The ingot withdrawn is unusually pure, because impurities tend to remain in the liquid. Mono-crystalline solar panels have efficiency levels of between 14-22% and because of this; they form the smallest solar panels per watt. As the material for the cells is a single crystal, it has a very regular structure and no boundaries between crystal grains. This high uniformity in the structure results in higher energy conversion efficiency, which is the ratio of electric power produced by the cell to the amount of available sunlight power i.e. power-out divided by power-in. The higher the cell's conversion efficiency, the more electricity it generates for a given area of exposure to the sunlight. The price average for mono-crystalline solar modules was about \$ 3.97 per peak watt in 1996 but at the moment the price has drastically reduced to about 1.07/watt according to information obtained from, solarbuzz, a company for manufacturing solar cells and solar panels.

Mono-crystalline solar cells can easily be recognized as they appear to be round or square with rounded corners.

2.9.3 Polycrystalline cells

The third type of silicon based solar cells is the polycrystalline or multi-crystalline solar cells. These cells are made from small grains of silicon. Polycrystalline PV cells are less energy efficient than single-crystalline silicon PV cells. The grain boundaries in polycrystalline silicon hinder the flow of electrons and reduce the power output of the cell. The energy conversion efficiency for a commercial module made of polycrystalline silicon ranges between 10 to 14%.

A common approach to produce polycrystalline silicon PV cells is to slice thin wafers from blocks of cast polycrystalline silicon. Another more advanced approach is the "ribbon growth" method in which silicon is grown directly as thin ribbons or sheets with the approach thickness for making PV cells. Since no sawing is needed, the manufacturing cost is lower. The most commercially developed ribbon growth approach is EFG (edge-defined film-fed growth). Compared to single-crystalline silicon, polycrystalline silicon material is stronger and can be cut into one-third the thickness of single-crystal material. It also has slightly lower wafer cost and less strict growth requirements. However, their lower manufacturing cost is offset by the lower cell efficiency. The average price for a polycrystalline module made from cast and ribbon was \$3.92 per peak watt in 1962, slightly lower than that of a single-crystal module, but has now reduced to \$ 2.25 per peak watt (Solar electric, 2010).

Apart from silicon based solar cells, other materials have been developed for different types of solar cells. The following section explains the construction and operation of some of these cells.

2.9.4 Gallium arsenide solar cells

This is a compound semiconductor solar cell made of two elements: gallium (Ga) and arsenic (As). GaAs has a crystal structure similar to that of silicon. An advantage of GaAs is that it has high level of light absorptivity. To absorb the same amount of sunlight, GaAs requires only a layer of few micrometers thick while crystalline silicon requires a wafer of about 200-300 micrometers thick. The concept of light absorptivity is different from that of energy conversion efficiency. Light absorptivity measures how much usable solar energy is absorbed by a given area of material. The greater number of different wavelengths of the solar spectrum a material can absorb, the higher the light absorptivity. For the sunlight that is absorbed by the material, how much of the sunlight can be successfully converted into electricity is measured by the concept of energy conversion efficiency. Also, GaAs has much higher energy conversion efficiency than crystal silicon, reaching about 25 to 30%. Its high resistance to heat makes it an ideal choice for concentrator systems in which cell temperatures are high. GaAs is also popular in space applications where strong resistance radiation damage and high cell efficiency are required (Kumar, Suresh, Nagaraju, 2000, p.256).

The biggest drawback of GaAs PV cells is the high cost of the single-crystal substrate that GaAs is grown on. Therefore it is most often used in concentrator systems where only a small area of GaAs cells is needed.

2.9.5 Cadmium telluride solar cells

Cadmium telluride or CdTe is another well-known polycrystalline thin-film material. It is a semiconductor compound made of cadmium and tellurium with a very high light absorptivity level; only about a micrometer thick is enough to absorb 90% of the solar spectrum. Cadmium telluride (CdTe) photovoltaics describe a photovoltaic (PV) technology that is based on the use of cadmium telluride thin film, a semiconductor layer designed to absorb and convert sunlight into electricity. Cadmium telluride PV is the first and only thin film photovoltaic technology to surpass crystalline silicon PV in cheapness for a significant portion of the PV market, namely in multi-kilowatt systems(Wikipedia, Cadmium telluride photovoltaics). One advantage of cadmium telluride is that it is relatively easy and cheap to manufacture by processes such as high-rate evaporation, spraying or screen printing. The conversion efficiency for a CdTe commercial module is between 8-9 %. The instability of cell and module performance is one of the major drawbacks of using CdTe for PV cells. Another disadvantage is that cadmium is a toxic substance. Although very little cadmium is used in CdTe modules, extra precautions have to be taken in manufacturing process (Mah, 1998, p.8). There has been much discussion of the toxicity of CdTe-based solar cells. The perception of the toxicity of CdTe is based on the toxicity of elemental cadmium, a heavy metal that is a cumulative poison. While the toxicity of CdTe is presently under debate, it has been shown that the release of cadmium to the atmosphere is impossible during normal operation of the cells and is unlikely during fires in residential roofs. Furthermore, a square meter of CdTe contains approximately the same amount of Cadmium as a single C cell Nickel-cadmium battery, in a more stable and less soluble form .The properties of CdTe can be altered as required by the addition of alloying elements such as mercury and zinc.

2.9.6 Copper indium diselenide solar cells

These solar cells are made from a polycrystalline semiconductor compound of copper, indium and selenium, CIS. CIS has been one of the major research areas in the thin film solar cell industry. The main processes for forming copper indium diselenide solar cells are the co-evaporation of copper, indium and selenide and the selenisation of Copper

and Indium layers in hydrogen selenide atmosphere. The toxicity of Copper, Indium and Selenide is considered mild. Little information exist on toxicity of CIS. Animal studies have shown that CIS has mild to moderate respiratory track toxicity. By comparing CIS with Copper Gallium Selenide and Cadmium Telluride, CIS was found to be less toxic than Cadmium Telluride and somewhat more toxic than Copper Gallium Selenide (Markvart & Castaner, 2003, p.864). The semiconductors used in the fabrication of these solar cells are especially attractive for thin film solar cell application because of their high optical absorption coefficients and versatile optical and electrical characteristics which can in principle be manipulated and tuned for a specific need in a given device. CIS is also one of the most light-absorbent semiconductors; a 0.5 micrometers thickness is enough to absorb 90% of the solar spectrum.

Manufacturing costs of CIS solar cells at present are high when compared with amorphous silicon solar cells but continuing work is leading to more cost-effective production processes. The first large-scale production of CIS modules was started in 2006 by a Germany company known as Würth Solar. Manufacturing techniques used vary and include the use of Ultrasonic Nozzles for material deposition. (Top alternative energy sources, 2008). Typical efficiency for CIS is 10-13 %.

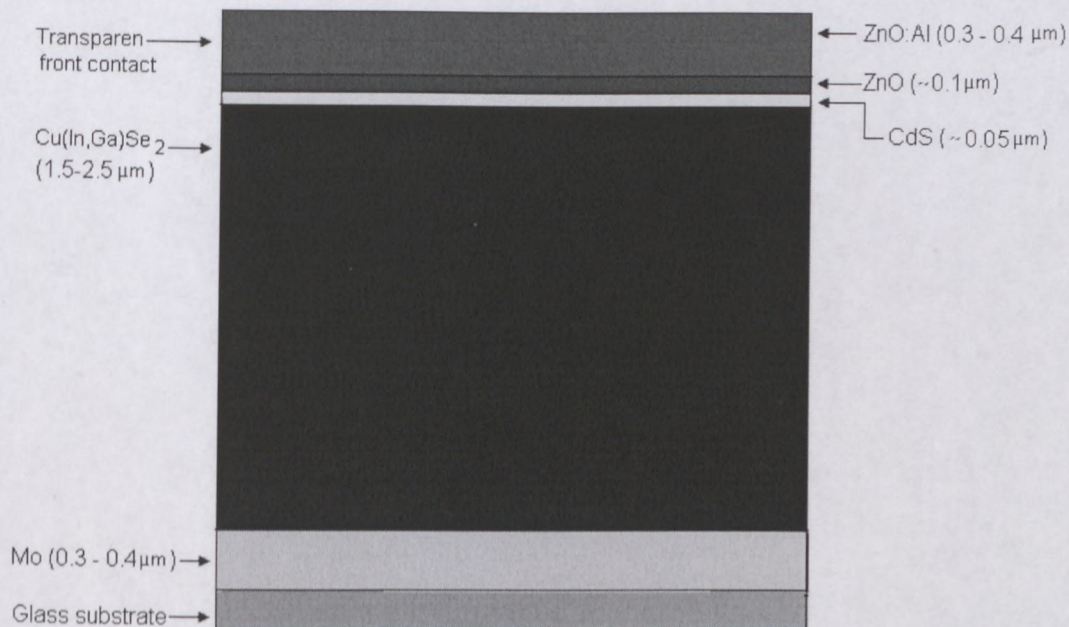
2.9.7 Copper indium gallium selenide solar cells

These solar cells are made from a combination of four different elements forming a light sensitive material. The four element material is a group I-III-VI₂ compound semiconductor composed of copper, indium, gallium, and selenium (CIGS). The material is a solid solution of copper indium selenide (often abbreviated "CIS") and copper gallium selenide, with a chemical formula of CuIn(x)Ga(1-x)Se₂. The value of x can be varied between 0 and 1 which will vary the bandgap between 1.0eV and 1.7eV. Researchers have been trying to improve on the solar cell efficiency and by December 2005, a team from National Renewable Energy Laboratory managed to achieve a new world record of 19.9% by modifying the CIGS surface and made it look like CIS (Zou, Wang, Chu, Lv, Fan, 2010, P.1170).

Several methods can be used to deposit CIGS on substrates to manufacture thin film solar cells. The most common method is the vacuum based process of co-evaporating or co-sputtering copper, gallium and indium, then annealing the resulting film with a selenide vapor to form the final CIGS structure. An alternative method is to directly co-evaporate copper, gallium, indium and selenium onto a heated substrate or to use a

non-vacuum-based process of depositing nanoparticles of the precursor materials on the substrate and then sintering them in situ.

CIGS solar cells are commonly grown on soda-lime glass substrates of thickness of about 1-3 mm and molybdenum serving as metal back contact. Figure 2.13 shows a cross-section of a CIGS solar cell.



2.13 Cross section of CIGS solar cell (Hamakawa, 2004, p.190)

The heterojunction is formed between the semiconductors CIGS and ZnO, buffered by a thin layer of CdS and a layer of intrinsic ZnO. The CIGS is doped p-type from intrinsic defects, while the ZnO is doped n-type to a much larger extent through the incorporation of aluminum (Al). The asymmetric doping causes the developed space-charge region to extend much further into the CIGS than into the ZnO. The CIGS layer serves as a light absorber while the doped ZnO serves as a front contact for current collection. Laboratory scale devices, typically 0.5 cm² large, are provided with a Ni/Al-grid deposited onto the front side to contact the ZnO (Kemell, Ritala, & Leskela, 2005, p.7). For the production of modules, individual cells are divided and monolithically interconnected by a series of scribing steps between the layer depositions. Additionally, susceptibility to dampness makes module encapsulation a requisite for long lifetimes.

2.9.8 Multi-junction and tandem solar cells

Multi-junction solar cells are another class of solar cells or photovoltaic cells developed for high efficiency. The solar cells consist of multiple layers of different semiconductor materials in thin films produced using molecular beam epitaxy and / or metal organic vapour phase epitaxy. Each type of semiconductor has its own characteristic band gap energy which allows it to efficiently absorb at a certain color, or more precisely, a specific wavelength in the electromagnetic spectrum. The semiconductors are carefully chosen and arranged to absorb nearly all of the solar spectrum, thus generating electricity from as much of the solar energy as possible (NREL Network news, 2008). Multi-junction solar cells were initially developed and deployed to generate electrical power for satellite power applications. Although multi-junction solar cell production cost were very high, it was offset by the weight savings offered by the higher efficiency. Multi-junction cells are currently being developed for terrestrial applications in concentrated photovoltaics. The combination of the higher efficiency and concentration has resulted in a price competitive with silicon flat panel arrays. This technology is currently being utilized in the Mars rover missions (Crisp, Pathareb & Ewell, 2004). When the different layers in the multi-junction solar cell are connected in series, the result is a tandem solar cell.

2.9.9 Low earth orbit definition and its effect on solar cell operations

A Low Earth Orbit (LEO) is generally defined as an orbit within the locus extending from the Earth's surface up to an altitude of 2,000 km. Objects in LEO experience different magnitude of atmospheric drag in the form of gases depending on whether they are in the thermosphere or the exosphere. Below approximately 200 km, bodies experience a rapid orbital decay and for this reason the accepted range is from 160-2,000km above the earth's surface. Medium Earth orbit (MEO) is an orbit above LEO which is sometimes called intermediate circular orbit (ICO). This orbit existing at an altitude of between 2000km and 35,786km. Low earth orbit is the space where majority of satellites, as well as the space shuttles and International Space Station operate from. The low earth orbit space is complex and dynamic and its natural environment constituents of vary with position, local time, season and solar activity (Grossman & Gouzman, 2003, p.49). Generally, the environment includes hazards such as atomic oxygen, UV radiation, ionizing radiation (electrons, protons), high vacuum, plasma, micrometeoroids and man-made debris, high light intensities as well as severe temperature cycles. The

temperature of a surface body facing the sun may have its temperature rise to a maximum of $+150^{\circ}\text{C}$ while the shadow facing surface may fall to -150° (Han & Kim, 2006, p. 218). The average temperature on the sun facing side is $+75^{\circ}\text{C}$. The different constituents of the space environment has an effect and plays a crucial role of determining the system function, reliability and operational lifetime. One of the effect is in the changing of organic and inorganic materials characteristics that make up the whole of the satellite body and the solar cells. Exposure of solar cells to the space environment may result in detrimental effects via modification of their chemical, electrical, thermal, optical and mechanical properties as well as surface erosion. The high vacuum induces material outgassing (e.g. low-molecular weight residues, plasticizers and additives) and the products may condense on a nearby colder surface of a satellite such as a camera lens or solar cell surface and obscure them. This is of great concern to space missions as it can ruin an expensive mission. Space debris presents a big danger to both the astronauts and the space craft. Space debris is as a result of broken off pieces of spaceships or equipment, spent stages of rockets, old unusable satellites, and even small flecks of paint or naturally due to space rocks, ice, and dust. Impact of such debris on space craft or solar panels may cause a very big damage due to their high speeds and momentum. The impact effects may be minimal, or can degrade a functional spacecraft component, or can compromise spacecraft functionality, even to the point of mission loss or loss of life. To minimize the damage threat from the meteoroid/orbital debris environment, it is often necessary to install protective shielding around critical spacecraft systems. If a system cannot be shielded, operational constraints may need to be imposed to reduce the damage threat. If the material for solar cells are not carefully selected, the solar arrays will drastically be affected and cause malfunctioning or failure to the power supply subsystem.

2.10 Solar cell applications

Light energy from the sun is plenty and free, all that is needed is to tap and converting it to electrical energy. Solar cells are often electrically connected and encapsulated as a module. Photovoltaic modules often have a sheet of glass on the front (sun up) side, allowing light to pass while protecting the semiconductor wafers from the elements rain, hail, etc. Solar cells can be connected in series in modules, creating an additive voltage or in parallel to yield a higher current. Depending on requirements, modules can be interconnected, in series or parallel, or both, to create an array with the desired peak DC

voltage and current. Once a solar system is installed and except for system maintenance, electricity will always be available without bills to pay. From the time of discovery, solar cells have found numerous energy delivery applications such as the ones explained below.

2.10.1 Satellite and electric power generation in space

Photovoltaic solar generators have been and will remain the best choice for providing electrical power to satellites in an orbit around the Earth. Indeed, the use of solar cells on the U.S. satellite Vanguard I in 1958 demonstrated beyond doubt the first practical application of photovoltaics. The power and the size of a satellite solar panel will depend on the satellite mission and may vary from a few milliwatts to several hundred watts. The solar panels are the most affected by the space environment because of the energetic particles from the sun and cosmic rays from elsewhere in space that hits them. produce physical damage to solar cells and for this reason the cells have to be rugged, radiation tolerant and very reliable. To provide electrical energy for satellite electronic circuits and devices, solar panels are attached to the satellite body. Storage batteries may be required as part of the power system for dark side operation of the satellite.

2.10.2 Rural electrification

All countries, be they industrialized, middle income or low income places a high priority on providing their citizens access to electricity. Despite this policy and the expenditure of billions of dollars, more than 1.5 billion people, mainly in Sub-Saharan Africa and South Asia, remain without access to electricity services today. In general approximately one third of the world's population still lack access to grid electrical supplies and over 2 billion people continue to meet their cooking needs and lighting with traditional fuels or paraffin. The majority of this population lives in rural areas of developing countries (Smith, 2000, p.7).The provision of electricity by photovoltaic systems to rural areas where no grid system is available, derives important social and economic benefits to remote communities throughout the world. Electricity from solar panels is mainly used to power electronic devices such as Small radios, television and to charge mobile phones. The economics of Photovoltaic systems compares favorably with the usual alternative forms of rural electricity supply, grid extension and diesel generators. Many countries are now engaged in solar electricity programs for rural electrification and other areas where extension and subsequent maintenance of transmission lines is difficult and expensive.

India is one example of countries which have succeeded in utilizing solar power for rural electrification. In there 10th National Five Year Plan (2002–2007), a target was to electrify 5000 villages and by 2004 more than 2700 were already connected (Muneer, Asif & Munawar, 2005, p.461). The DC electrical energy from the solar cells may be used directly or may be converted to alternating current to power regular electrical appliances using an inverter. A battery bank is usually installed together with the solar panels for storing energy for use at night.

2.10.3 Domestic supply

Stand-alone Photovoltaic system is an off the grid type of power supply for domestic use small scale farming. Depending on the requirements of the user, the power rating may vary between 50 watt to 5 kilowatt. Stand-alone systems may be designed to power individual houses or for communal use. Communal stand alone systems require a wide open area for solar panels installation, but for individual stand alone systems, the solar panels are usually mounted on roof tops. Maximum power will be available on hot sunny days but other sources will be required at night unless storage batteries are installed with the stand alone system. Japan, USA and several other European countries support the use of rooftop PVs. Japan aims to build 70,000 solar homes, installing 400 MW of PV by the year 2000 and 4,600 MW by 2010. In the USA in 1997 President Clinton announced a Solar Roofs Program, which aimed to install solar energy systems; either PV or solar hot water, on one million roofs in America by 2010 (Creagh, 2004).

2.10.4 Health care

Solar cells and panels are used to power refrigerators and coolers known as solar chill. These coolers which are powered by nature are used for transporting perishable goods, drugs and vaccines to regions of the world without electricity or with inadequate electrical supply in a controlled temperature. Extensive vaccination programs in desert and rural areas to fight against common diseases are now possible due to the use of solar cells with the solar chills. All vaccines have to be kept within a strict temperature range throughout transportation and storage, otherwise they will be destroyed. The provision of refrigeration for this aim is known as the vaccine cold chain (Solar chill, 2005).

2.10.5 Lighting

Remote lighting is often used to power essential systems in locations where the installation of grid systems is very expensive or impossible. Lighting is presently the biggest application of photovoltaic solar cells with tens of thousands of units installed all over the world. Such applications include security lighting, sea navigation aids roads and railway crossing signs etc. lighting is also applied for domestic or community buildings, such as schools, health centers and village lighting. For all these applications, solar cells are the source of the electrical energy. Remote lighting systems usually consist of a PV panel plus a storage battery, power conditioner and a low voltage, high efficiency DC fluorescent lamp (Creagh, 2004). Apart from fluorescent and energy saving bulbs, many companies are now engaged in designing even more efficient street light systems using light emitting diodes (LEDs) which consumes less power and provide light for longer hours. Figure 2.14 shows an energy saving street lamp made of light emitting diodes.

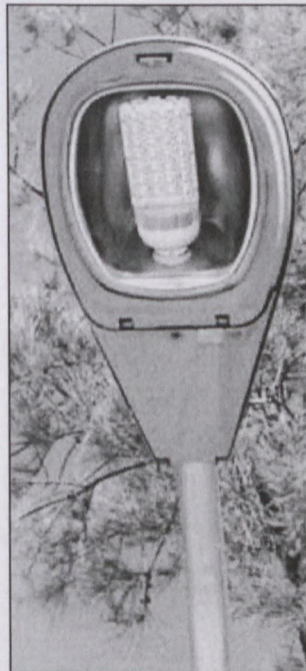


Figure 2.14 LED street lamp (Shenzhen Electronics, 1998)

2.10.6 Professional applications

Stand-alone photovoltaic systems have proved to be a good source of reliable power for remote professional applications in inaccessible locations or where the small amount of power required is not economical to be met from mains electricity. Examples of these applications include: Ocean navigation aids, like lighthouses and buoys which are mostly powered by solar cells. Telecommunication systems like radio transceivers on mountain tops and telephone boxes in the country sides are other examples of professional applications using stand-alone solar cell systems. Scientific research stations, seismic recording, and weather stations are some of the applications which use very little power. A photovoltaic solar panel with a dependable battery will be more economical to use than to construct a grid system. Cathodic protection is an electrical method for shielding metal work like pipelines and other metal structures from corrosion. This protection system also requires very small electrical energy which can suitably be supplied by a PV system. (Applications, 1997).

2.10.7 Grid-connected systems

Two types of grid-connected installations are usually distinguished, centralized PV power stations, and distributed generation units located directly at the customer's premises or building. For a PV power station to feed the generated power instantaneously into the utility distribution network, one or more inverters and transformers are required to convert and transform the dc power to ac power. The first PV power station was built at Hysperia in southern California in 1982 with nominal power rating of 1 MW, using crystalline silicon modules mounted on a 2 axis tracking system. PV power stations have been constructed in some locations where they assist local grid system during periods of peak demand, and obviate the need to construct a new power station. This is known as peak shaving. It can also be cheaper to place small PV plants within the transmission system, "embedded" generation rather than to upgrade it .PV arrays mounted on roof tops or facades offer the possibility of large-scale power generation in decentralized medium-sized grid-connected units. Studies in Germany, Switzerland and the UK have shown that the roof and facade area is technically suitable for PV installations and is large enough to supply the country's electricity demand. The size envisaged for each decentralized residential PV system is typically 1- 5kW, with systems up to a hundred kW or so suitable for commercial and industrial buildings. A solar cell company, Atlantis Solar System AG, have recently introduced solar panels with

the trademark "Sun slates" that can be fitted to existing roofs easily and unobtrusively (Applications, 1997). The main advantages of these distributed systems over large PV plants are as follows:

There is no cost in buying the land and preparing the site.

The transmission losses are much lower because the load is on the same site as the supply.

The value of the PV electricity is also higher because it is equal to the selling price of the grid electricity which has been replaced, rather than to the cost of generating it.

However, it should also be noted that the price paid by utility companies for electricity exported from a decentralized source is a fraction of the utility sale price. The optimum economic benefit is therefore derived by consuming all PV produced electricity, with direct reduction of the energy imported from the utility. Thus grid connected PV systems are ideal for loads which vary in proportion to the irradiation. Typical loads are air-conditioning, refrigeration and pumping. Other significant loads can be timed to operate when PV power is likely to be available. Examples include washing machines and clothes dryers which can operate on timing clocks (Applications, 1997).

2.11 Advantages of using solar cells

- a) The individual energy generators are very small and occupy less space.
- b) The light weight and small surface area features reduces the power weight ratio.
- c) They are silent and a highly efficient in energy conversion.
- d) They are easy to maintenance and do not require skilled maintenance.
- e) They are compact and do not discharge any harmful emission or waste product.

2.12 Disadvantages of using solar cells

- a) Solar cell energy generation systems are still expensive compared to grid systems.
- b) They are not suitable for high power applications unless very many big solar panels are used. This increases the cost of operating solar power system.
- c) Storage batteries are required to be installed with the solar system to provide energy at times when no sun is available. This again increases overall cost of unit.

2.13 Satellite applications

A satellite is any natural or artificial body moving around a celestial body such as planets and stars. Satellites have become essential components in our lives. In this part of chapter, reference is made to artificial satellites orbiting the planet earth. These satellites

are put into the desired orbit and have a payload depending on the intended mission. Satellites have many applications and are categorized according to their use (Maini & Agrawal, 2007, p.10-23). The following are some of the many different satellite applications:

- Communication Satellites, they are the core of communication industry.
- Navigational Satellites, used in global positioning systems.
- Scientific satellites, used in scientific applications such as studying the universe, remote sensing, exploring the earth mineral resources, etc.
- Meteorological satellites, for checking and distributing world weather reports.
- Military satellites, for uses like imaging enemy territory, eavesdropping of enemy components.

2.14 Types of electrical power sources for satellites

Several ways of providing electrical power to satellites systems have been used since its invention. Some of these systems includes: - Battery, Chemical, Nuclear, fuel cells and Solar cell energy systems. Before the discovery of self sustaining power systems like solar cells, batteries were the main sources of power for satellites. Since there was no means of recharging the batteries in space, the satellite missions were short lived. Before 1958 and before the first solar power operated Vanguard 1 satellite, the preceding satellite missions were being run by batteries which usually lost power in a week's time, rendering equipment worth millions of dollars useless (Sun & Sariciftci, 2005, p.5).

The discovery of chemical energy system added to the satellite electrical power list. In this system, chemical energy is converted directly into electricity by electrochemical processes. The fuel cells used produce electrical energy in the same way as batteries do (Fuelcells, 2000, p.1). Compared to a normal battery, fuel cell 'batteries' will not run down or require recharging as long as the fuel is present. Fuel cells are composed of two electrodes sandwiched around an electrolyte. The common fuel cell uses hydrogen and oxygen to produce electricity and some byproducts of water and heat. Fuel cells have been used for decades as an alternative source of energy to power space probes, satellites and even manned spacecraft. Big fuel cell systems have also been installed in

utility power plants, hospitals, schools, hotels, and office buildings for both primary and backup power (Hosch, 2007).

The disadvantage with fuel cells is that the system is very expensive and has to be designed carefully to avoid explosion from hydrogen gas. Another disadvantage is that when used with satellites, big tanks will have to be fixed to carry the liquid fuel which makes them heavier.

Nuclear energy system provided another source of electrical power to satellites since late 1960s. Compared to other energy sources, nuclear power have enabled or enhanced some of the most challenging and exciting space missions yet conducted, including missions such as the Pioneer flights to Jupiter, Saturn, and beyond; the Voyager flights to Jupiter, and the rest. The development and use of nuclear power in space has enabled the human race to extend its vision into regions that would not have been possible with non-nuclear power sources (Bennett, 2006, p.1). Nuclear power plants run on uranium fuel whose atoms when split by fission process produces a huge amount of heat which can be converted to electricity. The heat energy boils water, creating steam that is used to turn turbines and produce electricity. Nuclear energy sources provide a number of advantages but its usage has been withdrawn because of its hazardous nature, it emits harmful radiations which can penetrate deep inside the human body where they can damage biological cells and thereby initiate a cancer. If they strike sex cells, they can cause genetic diseases in progeny (Cohen, 2007, P.1). Presently, most of the satellites are designed to be powered with solar cells. The advantages of using solar cells for satellite power are many compared to the advantages of other types of power sources. Solar cells are light in weight and therefore have another advantage having a high power to weight ratio.

2.15 Conclusion

This chapter has discussed a number of different types of solar cell materials and explained the difference between single junction and multi-junction solar cell in terms of operation and efficiency. It has also explained the advantages and disadvantages of solar cells and concluded with their applications in different fields

CHAPTER THREE TECHNIQUES FOR ENHANCING SOLAR CELL EFFICIENCY

3.1 Introduction

Photovoltaic cells are semiconductor devices for converting solar energy to electrical energy. Solar is one of the major sources of renewable energy; however the major problem of utilizing the energy is associated with the poor conversion efficiency. Solar energy on earth is estimated at 1000 Watts per square meter. The most commonly used solar cells are silicon based and have an efficiency of about 23%. This means that most of the energy available from the sun is wasted as heat. This chapter focuses on various potential techniques for enhancing the conversion efficiencies of solar cells. The increased efficiency will simultaneously reduce the input cost and has a potential to lead the world's most cost efficient solar energy technology with a cost price of lower than 50 cent per Watt, which is roughly one-third of present production cost of 1.5 Euro per Watt. The information discussed in this chapter is based on silicon solar cell but it applies equally well to other types of solar cells.

3.2 Anti-reflection surface coating

One of the factors that contribute to the reduction in solar cell efficiency is light reflection. Photovoltaic modules suffer from reduced conversion efficiency even before the sun's light reaches the solar cell. This is because the usually shiny solar cell itself or the solar cell module's protective glass cover reflects some of the incident sunlight. In order to suppress reflections from a solar absorber surface an anti-reflection (AR) layer is usually deposited on top of the solar absorbing coating. For the AR coating to function well it should be made of a material with a lower refractive index than the underlying surface. Provided that the AR coating is sufficiently thin, it will not increase the thermal emittance value. Besides increasing the solar absorption it is equally important that the AR layer has long term stability in order to create a successful solar selective coating. (Bostrom, Wackelgard & Westin, 2004, p.183). Anti-reflection coatings on solar cells are similar to those used on other optical equipment such as camera lenses. They consist of a thin layer of dielectric material, with a specially chosen thickness so that interference effects in the coating cause the wave reflected from the anti-reflection coating top surface to be out of phase with the wave reflected from the semiconductor surfaces.

These out-of-phase reflected waves destructively interfere with one another, resulting in zero net reflected energy. The thickness of the anti-reflective coating must be carefully calculated so that the wavelength in the dielectric material is one quarter the wavelength of the incoming wave otherwise it will not be effective (Honsberg & Bowden, 2010).

Figure 3.1 shows how AR coatings transmit and reflects incident light.

To calculate the correct thickness, d_1 , for a quarter wavelength anti-reflection coating of a transparent material with a refractive index n_1 and light incident on the coating with a free-space wavelength λ_0 , the formula below is used.

$$d_1 = \frac{\lambda_0}{4n_1} \quad 3.1$$

For example if we choose the wavelength, λ to be $0.6 \mu\text{m}$ and the refractive index of the anti-reflection layer n_1 to be 2, the optimal anti-reflection coating thickness, d_1 will be equal to $0.075 \mu\text{m}$.

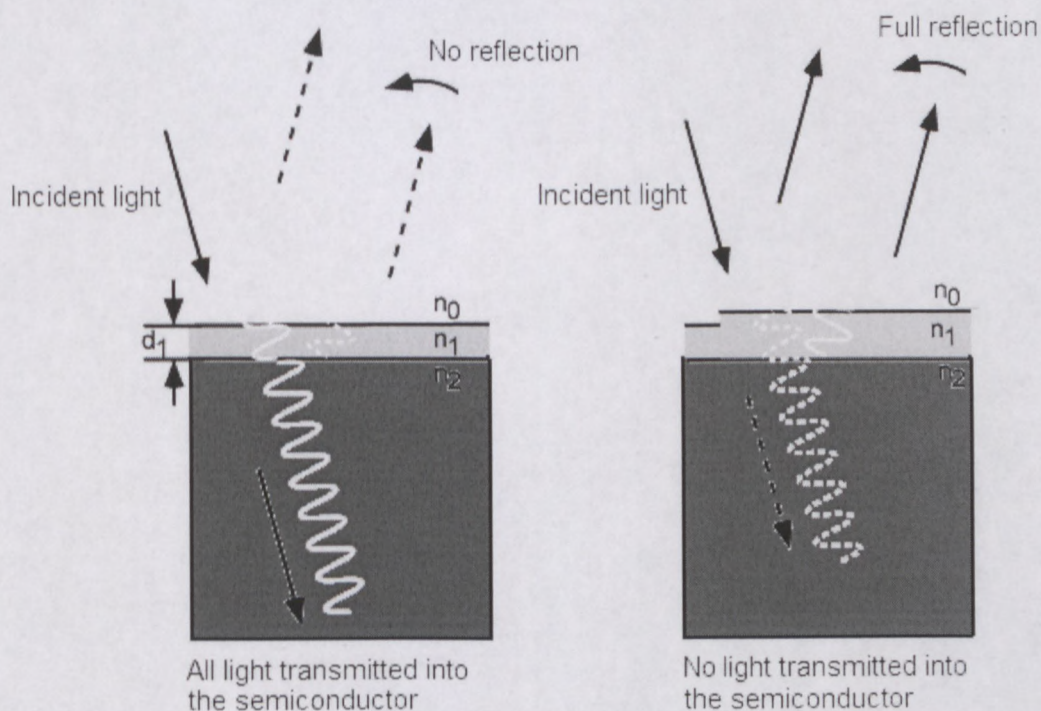


Figure 3.1 Transmission and reflection of light by solar cell surfaces
(Hosberg et al, 2010)

3.3 Surface texturing

Some solar cell material such as silicon have a poor light absorptivity. Texturing the surfaces of silicon wafer or other solar material surfaces is one of the ways of increasing their efficiencies. The texturing process reduces the surface reflection loss through photon trapping, thereby increasing the short circuit current of the solar cell. This increase arises from three distinct mechanisms, all of which are related to the fact that the incident photons strike the cell surface at an angle. Firstly, some light rays will be reflected from one angled surface merely to strike another, resulting in an improved probability of absorption, and therefore reduced reflection. Secondly, photons refracted into the silicon will propagate at an angle, causing them to be absorbed closer to the junction than would occur with a planar surface. This is especially relevant in material with diffusion lengths comparable to or less than the cell thickness, such as many multi-crystalline silicon wafers. Thirdly, long-wavelength photons which are reflected from the rear surface back to the front will encounter an angled silicon surface, improving the chance of being internally reflected, either at the silicon interface or at the glass surface, and providing another chance for absorption. This final process is referred to as light-trapping, and gives an improved response to infrared light (Macdonald, Cuevas, Kerr Samundsett, Ruby, Winderbaum & Leo, 2004, pg.1)

Surface texturing can be accomplished in a number of ways. A single crystalline substrate can be textured by etching along the faces of the crystal planes. The crystalline structure of silicon results in a surface made up of pyramids if the surface is appropriately aligned with respect to the internal atoms. Single-crystal silicon solar cells are generally textured with random pyramids, which are produced by etching in an alkaline solution such as potassium hydroxide or sodium hydroxide (Green, Wenham, Watt & Corkish, 2007, p.60). Figure 3.2 shows an electron microscope photograph of a pyramid textured silicon surface.

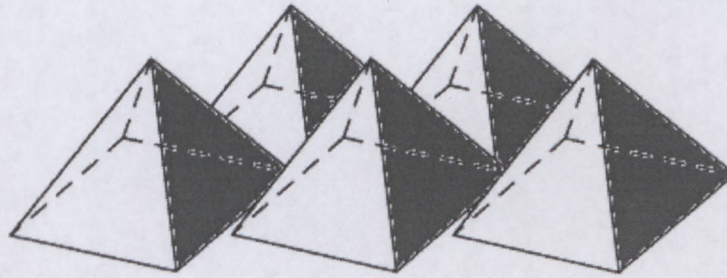


Figure 3.2 Appearance of a pyramid textured solar cell surface
(Green, et al, 2007)

3.4 Series and shunt resistances

Another aspect to consider for increasing cell efficiency is to reduce parasitic resistance losses. Both shunt and series resistance losses decrease the fill factor and efficiency of a solar cell. A good solar cell is required to have a low series and a high shunt resistance. Series resistance is determined by top contact design and emitter resistance. The series resistance is a sum of fingers, bus bars, emitter, base and contact wires resistances as shown in figure 3.3. Of these resistances, the emitter, fingers and bus bars dominate the overall series resistance and are therefore most heavily optimised in solar cell design (Honsberg & Bowden, 2010, p.99).

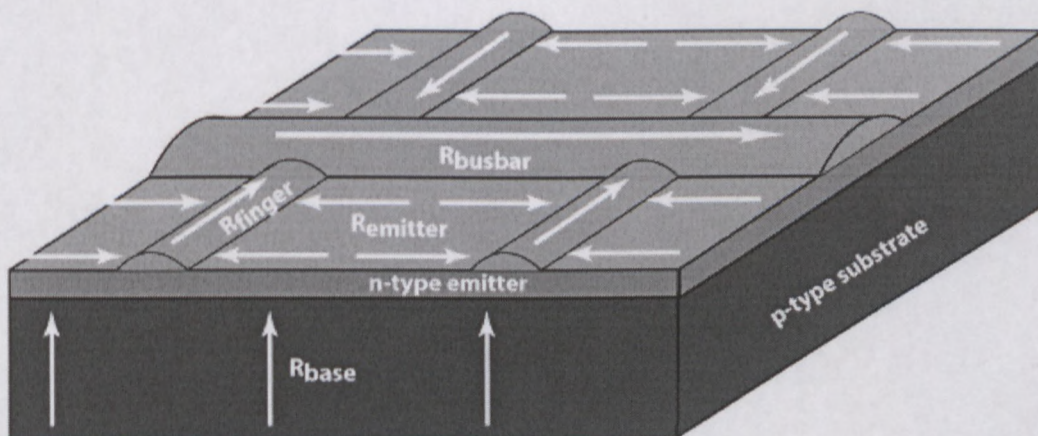


Figure 3.3 Top contact resistance components of a solar cell
(Honsberg, 2010)

3.5 Fingers and bus bars resistances

Fingers and bus bars on top of the cell collect generated currents to the external connected load but at the same time reduce material light absorption due to shading and reflection. The remedy for this is to make the fingers and the bus bars as thin as possible and as widely spaced as possible. This remedy also has a disadvantage in that it increases fingers and bus bars resistance losses. The key design trade-off in top contact design is the balance between the increased resistive losses and the increased reflection caused by a high fraction of metal coverage of the top surface.

3.6 Base resistance

Light generated current typically flows perpendicularly from the bulk of the cell to the cell surface and then laterally through the top doped layer until it is collected at a top surface contact. The material making up the entire solar cell presents some resistance to the flow of current and may also cause heating. The resistance to the current of the bulk component of the cell, or the "bulk resistance", R_b , taking into account the thickness of the material is defined as:

$$R_b = \frac{\rho L}{A} = \frac{\rho_b L}{A} \quad 3.2$$

Where:

L is the length of the conduction path, ρ_b is the "bulk resistivity" of the conducting material and A is the cell cross-sectional area. Typical bulk resistivity values for silicon lies between (0.5 – 5.0Ω/cm) As can be seen from the expression resistance is directly proportional to the bulk resistivity and inversely proportional to cell area, hence to minimize cell losses due to base resistances, the cell area has to be made big while the conducting length is made small (Honsberg *et al* 2010, p.100).

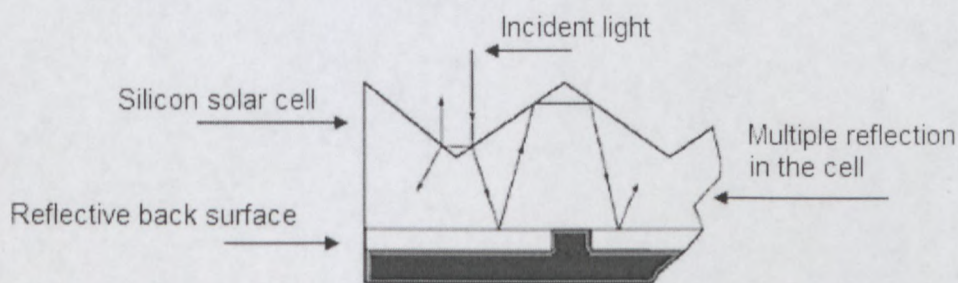
3.7 Emitter resistance

Power loss due to the emitter resistance is a function of finger spacing in the top contact. The distance that current flows in the emitter is not constant. Current can be collected from the base close to the finger and therefore has only a short distance to flow to the finger or, alternatively, if the current enters the emitter between the fingers, then the length of the resistive path seen by such a carrier is half the grid spacing. The resistance

seen by the current is proportional to the distance it has to travel to reach the fingers. These losses can be reduced by reducing the width of the emitter and by employing a highly n-doped emitter.

3.8 Light trapping technique

Optimum solar cell structure will typically have "light trapping" in which the optical path length is several times the actual device thickness, where the optical path length of a device refers to the distance that an unabsorbed photon may travel within the device before it escapes out of the device. Apart from reducing reflection, surface texturing introduces light trapping which increases the chances of light absorption and conversion to electricity (Schropp & Zeman, 1998, p.160). The utilization of textured substrates leads to a large suppression of the reflection optical loss at the front of the cell and the implementation of back reflectors minimizes the transmission loss into the back contact of the cell. Figure 3.4 shows how a textured surface traps light.



3.4 Light trapping mechanism using textured surface

(Schropp & Zeman, 1998, p.160)

3.9 Back contact

The back contact, made out of a metal, covers the entire back surface of the solar cell and acts as a conductor. To increase light absorption efficiency, and hence solar efficiency, the inner side of the plate is silver coated to reflect light back into the cell. Reduction in the loss of electrons by surface recombination at the back contact, strong p-doping is used in front of the back contact to establish a hole membrane. The reduction of the recombination at the rear contact is commonly attributed to the so-called back surface field originating from the negative charge of the p^+ -doped region (Wufel, 2009, p.172). In design, the rear contact itself is much less important than the front contact since it is much further away from the junction and does not need to be

transparent. The metal plate may be used for inter cell connection or for connection to the external load.

3.10 Solar cell front covers

Covers for solar cell modules must be transparent to the solar spectrum, should provide hermetic sealing, and should not degrade under exposure to ultra-violet component of the solar spectrum. Cover glasses are mostly used to cover solar cells and prevent them from degradation which reduces efficiency. Since glass is reflective, it reduces the efficiency of the cells by reducing the amount of light absorbed. This drawback is reduced by coating anti-reflective coatings on the glass surface. Efficiency is further improved by using a glass type with a high transmission in the wavelength used by the cells, i.e. in 350-1200 nm range. Tempered, low-iron glass is the material of choice. The glass also serves the purpose of keeping out water and rigidifying the module, protecting the cells from damage from hail impact and bending and impact during manufacture, transport and installation (Chopra & Das, 1983, p.555).

3.11 Light concentrators for solar cells

The efficiency of solar cells increases and produces more power under high light intensity. Concentrator systems use large mirrors or lenses to concentrate intensify and focus sunlight onto a string of solar cells or panels. Compared to flat-plate system, concentrator solar cell system has a number of advantages. Concentrator systems increase the power output while reducing the size or number of cells needed, that is to say, for concentrated radiation, the same power is delivered by a solar cell with smaller area than for non concentrated radiation. In areas with much more direct, unscattered solar radiation, the additional expense for concentration is rewarded by a better efficiency from a smaller solar cell. When the radiation is concentrated with lenses or mirrors, the solar cell sees only a part of the hemisphere and, in the limiting case of maximum concentration, only the sun. Concentrators can be made of small individual cells which has an advantage of price reduction. It is harder and more expensive to produce large-area, high-efficiency solar cells than it is to produce small-area cells. Photo-voltaic (PV) cells are the most expensive components of a PV system, on a per-area basis, but the use of concentrators allows using less cell material. A concentrator makes use of relatively inexpensive materials such as plastic lenses and metal housings to capture the solar energy shining on a fairly large area and focus that energy onto a

smaller area, where the solar cell is. One measure of the effectiveness of this approach is the concentration ratio, in other words, how much concentration the cell is receiving (Energy basics, 2010).

Concentrators systems have a number of disadvantages. The system requires concentrating optics which is expensive compared to simple covers for flat-plate systems. Unlike conventional flat plate PV arrays, concentrator systems require direct sunlight and will not operate under cloudy conditions which mean that sun tracking system must be fixed. To simply follow the sun's path through the sky during the day, a single-axis tracking system can be used but to be able to adjust to the sun's varying height in the sky through the seasons, two-axis tracking system must be used.

Another disadvantage is that light concentration produces heat. Cell efficiencies decrease as temperatures increase, and higher temperatures also threaten the long-term stability of solar cells. Light concentration in solar cells results in the generation of very high currents. These high currents in turn reduces efficiency by causing large voltage losses across the series resistance of the cell and in the leads. Therefore, the solar cells must be kept cool in a concentrator system by using heat sinks, which again add expenses (Wufel, 2009, p.193). Figure 3.5 shows the principles of light concentration using Fresnel lens.

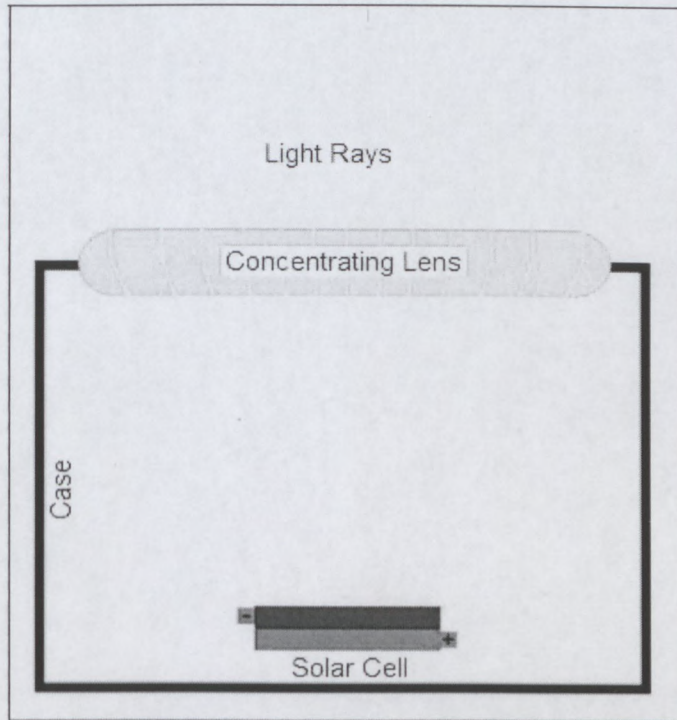


Figure 3.5 Light concentration using Fresnel lens (Wufel, 2009, p.139)

3.12 Single versus multi-junction solar cell efficiency

Most commercial solar cells like silicon are single junction type and are limited in efficiency because they are made of one particular material. In a single junction solar cell, efficiency is limited due to the inability to efficiently convert the broad range of energy that photons possess in the solar spectrum. Photons below the band gap of the cell material are lost; they either pass through the cell or are converted to only heat within the material. Energy in the photons above the band gap energy is also lost, since only the energy necessary to generate the hole-electron pair is utilized, and the remaining energy is converted into heat. Up to date, the highest practical efficiency for silicon solar cell is about 23% while the maximum laboratory theoretical efficiency is about 30 % (Luque *et al*, 2003, p.100).

The ability of a given solar cell material to convert light energy to electrical energy is governed by the bandgap of that material. Different solar cell materials have different Band gaps which determine which portion of the light spectrum is to be absorbed by the solar cell material. Light is composed of all colors of the visible spectrum and ranges in spectrum from about 400 nanometers to about 780 nanometers. The energy contained in a photon of light which is absorbed and converted to electricity is dependent on light

wavelength according to Planck's energy equation, $E = h\nu = hc/\lambda$. Where h is Planck's constant, ν is the frequency of light, c is the speed of light and λ is the light wavelength. This means that if a solar cell material is capable of absorbing the high frequency part of the solar spectrum, it will have a high efficiency.

Since a single junction cell cannot absorb all the energy in the light spectrum, an alternative way to enhance solar cell efficiency is to use multi-junction solar cells.

These multi-junction cells consist of multiple thin films produced using molecular beam epitaxy and / or metal organic vapor phase epitaxy. Each type of semiconductor have its own characteristic band gap energy which, loosely speaking, causes it to absorb light most efficiently at a certain color, or more precisely, to absorb electromagnetic radiation over a portion of the spectrum. The semiconductors are carefully chosen to absorb nearly the entire solar spectrum, thus generating electricity from as much of the solar energy as possible (Gevorkian, 2010, p.40).

3.13 Multi -junction solar cell

The development of high-performance solar cells offers a promising pathway toward achieving high power per unit cost for many applications. Substantial increases in conversion efficiency can be realized by multi-junction solar cells in comparison with single-junction cells. Multi-junction solar cells belong to a class known as High-efficiency solar cells. In this class, a number of different solar cell materials are used and connected together either in series or parallel to produce electricity at high operating efficiencies. The solar cell operate under the concept known as splitting of solar cell concept. Under this concept, the multi-junction solar cell utilizes the solar spectrum more effectively as each split part of the spectrum is absorbed by a different junction. Typically a multi-junction solar cell would consist of an III-V semi conductor for each layer. Every different layer of the solar cell is absorbing a different part of the solar spectrum (Solanski, 2009.p.279).

The different layers are arranged according to their bandgaps, and are optically in series. The top layer is made of a higher bandgap material; the second layer takes the material of lower bandgap than the first one and so on till the final one which is made of the lowest bandgap material. The energy packet that is absorbed and converted to electricity by each material layer is of higher or equal bandgap to that of materials' bandgap. The first layer receives the full spectrum, absorbs its high energy content and transmits the rest to the lower layer. Photons below the band gap of the first layer but of

higher bandgap than the second layer are now absorbed in this layer and the rest is again transmitted downwards. The process continues till the last layer which absorbs the lowest last bit of energy (Burnett, 2002, p.13). Figure 3.6 shows how a multi-junction solar cell absorbs different light waves of the light spectrum.

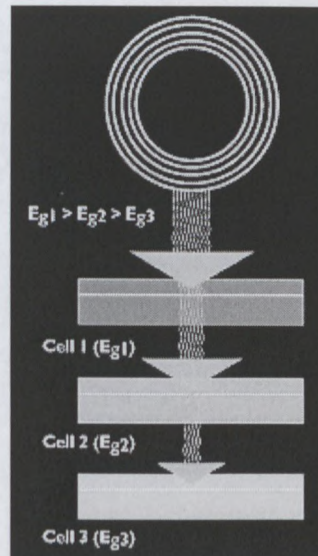


Figure 3.6 Light absorption by multi-junction solar cell (Burnett, 2002)

The number of layers used in the construction of the cell structure determines the name of the multi-junction solar cell. For example if two different layers are used to construct the structure, the multi-junction cell would be termed dual junction solar cell or if the layers are three, then the solar cell would be called triple junction solar cell. The development of multi-junction solar cells was initially for powering satellites where weight savings was used to offset the high costs of the cell. Of late, these cells have found terrestrial applications in concentrated photovoltaics. Concentration techniques in conjunction with the cell high efficiency has resulted in a price competitive with silicon flat panel arrays. Commercialized multi-junction solar cells in the market today utilize tandem connection. In tandem connection, the cells are connected in series and the resulting composite cell has two terminals. Tandem solar cells present a problem because the current through each junction is the same. If the maximum power point current of each junction is not the same, then efficiency suffers. Current match of each junction is a very important design consideration for multi-junction cells (Burnett, 2002,p.14). Figure 3.7 shows an example of a triple junction solar cell made of three

different materials, GaInP, GaAs, and Ge layers on Ge substrate while figure 3.8 shows the quantum efficiency of each material. The three main materials together with the associated sub components make a total of 20 layers (Yastrebova, 2007, p.10).

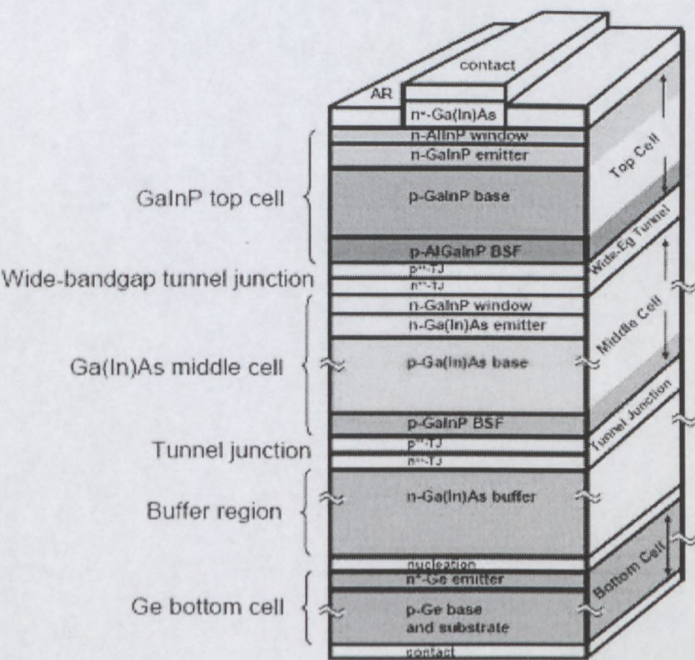


Figure 3.7 Structure of a multi-junction solar cell (Yastrebova, 2007p.10)

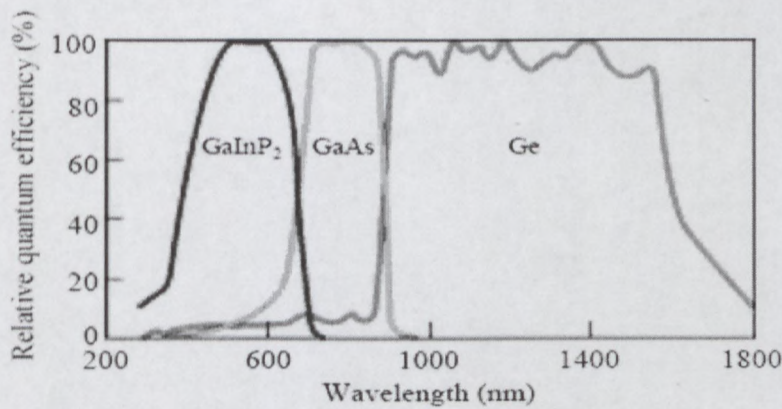


Figure 3.8 Quantum efficiency of each layer of a GaInP/GaAs/Ge triple-junction solar cell (Yastrebova, 2007,p.11)

3.14 Relationship between solar cell efficiency and air mass

One factor that determines solar cell efficiency is irradiance as it determines the number of electron-hole pair generation from solar cells. Irradiance or light intensity is related to atmospheric conditions or what is referred to as AIRMASS and it increases with height from the earth. The path length taken by the light through the atmosphere normalized to the shortest possible path length or when the sun is directly overhead is the Air Mass. The Air Mass quantifies the reduction in the power of light as it passes through the atmosphere and is absorbed by air and dust. The Air Mass is defined as: $AM = \frac{1}{\cos(\theta)}$

Where θ is the angle from the vertical (zenith angle). When the sun is directly above the head, angle θ is zero and the air mass value is 1. The different components of the atmosphere such as water vapor, carbon dioxide, laughing gas, methane, fluorinated hydrocarbons are responsible for the absorption. If the light has to pass through a thickness Y of the atmosphere, then the atmospheric path X of the sun rays at an angle of θ relative to the normal to the earth's surface is given by $Y = X / \cos \theta$. In terms of path lengths, the ratio $Y/X = 1/\cos \theta = \text{Air mass}$. Figure 3.9 shows the relation between direct and inclined light paths defining Air mass.

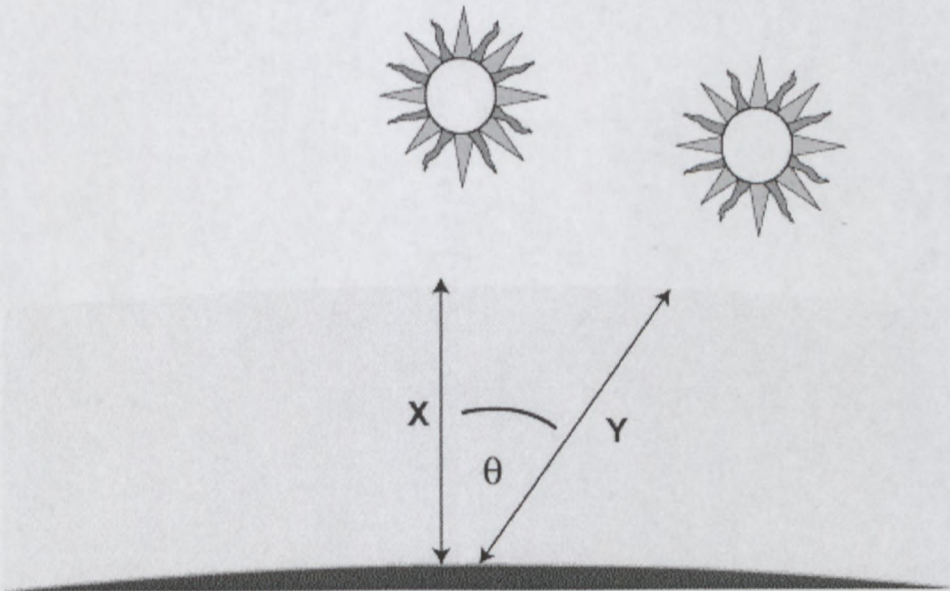


Figure 3.9 Direct and inclined light path defining air mass (Honsberg, et al, 2010,p.16)

The relative light intensity between the face of the earth and space is not constant and is defined in terms of airmass. In space where the atmosphere is almost a vacuum and

clear of any light absorbing matter, the light intensity to be about 1.366kw per square kilometer, while on the face of the earth it is about 1.0kw. The value of 1.366 which has been confirmed by satellite measurements is also known as solar constant (Solar power is the future.com, 2010). Environmental air mass is specified by abbreviations and a number or air mass coefficient. In space the air mass is indicated as Air mass zero (AM0) while on earth the value may be indicated as AM1.5G or AM 1.5D. Air mass 1.5 is a standard earth light spectrum which is used to study the behavior of solar cells. The initial G stands for global and refers to the direct and diffused light radiation reaching the earth while D refers to the direct radiation only (Edmonton, 2005). The variation in incident light power and spectrum varies the efficiency of a solar cell. For accurately comparing solar cells measured at different times and locations, a standard spectrum and power density must be defined and specified for both radiations outside the Earth's atmosphere and at the Earth's surface.

3.15 Relationship between light wavelength, bandgap and solar cell efficiency

Different solar cell technologies exist with different abilities and efficiencies of converting light to electrical energy. The different technology efficiencies are due to the different materials used to construct solar cells. The amount of electrical energy from a cell material will depend on which part of the visible light spectrum or wavelength it absorbs. Visible light is the portion of the electromagnetic spectrum that can be detected by the human eye. Most solar cells convert this light into electricity but some of them include the infra-red portion of the spectrum. Visible light is made up of different colors which can be distinguished by their wavelengths varying from about 380 to 750nm (Donald, Pavia, & Kriz, 2009, p.412). Figure 3.10 shows the linear visible color spectrum and an approximate range of wavelengths for light colors respectively. It should be noted that there is no clear boundary between one color and the next.

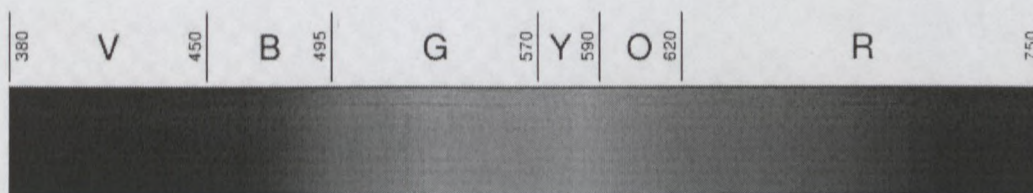


Figure 3.10 Spectrum of visible light (Jones, 2010, p.1)

Light energy (E) which exists in packages called photons is directly proportional to the frequency of that light according to the expression $E = hf = hc / \lambda$, where h is Planck's constant, f is the frequency, c is the speed of light and λ is the wavelength of light (Serway, Vulle & Faughn, 2009, p.873). For a solar cell material to convert light photon to electrical energy, the energy content of that photon must be equal or greater than the bangap of the material. The bandgap of a material is expressed in electron volts and its relationship with light wavelength in nanometer (nm) is as follows.

$$\text{Photon energy } E = hf = hc / \lambda = [6.6261 \times 10^{-34} \times 2.997 \times 10^8] / \lambda = [19.8581 \times 10^{-26}] / \lambda.$$

To convert this energy to electron volts, the photon energy must be divided by the electron charge value, hence $(E/q) = [19.8581 \times 10^{-26}] / [\lambda \times 1.602 \times 10^{-19}] = [1240 \times 10^{-9}] / \lambda = 1240 / [\lambda \text{ (nm)}]$. From this formula, energy of any light wavelength can be calculated. For example, the energy in the green light wavelength of 532 nm is approximately 2.33eV.

Table 3.1 shows energy values of different colors and their wavelengths.

Table 3.1 Relationship between light wavelength and bandgap energy
(Donald et al, 2009, p.412)

Color	Wavelength	Energy (eV)	Mid Wavelength	Average Energy (eV)
Violet	380-450 nm	3.26-2.76	415	2.99
Blue	450-495 nm	2.76-2.51	473	2.62
Green	495-570 nm	2.51-2.18	533	2.33
Yellow	570-590 nm	2.18-2.10	580	2.14
Orange	590-620 nm	2.10-2.00	605	2.05
Red	620-750 nm	2.00-1.65	685	1.81

The efficiency of a solar cell can be improved by increasing the range of light wavelength it absorbs to convert to electrical energy. This can only be achieved by designing a multi-bandgap solar cell or what is referred as multi-junction solar cell.

3.16 Conclusion

The amount electricity from a solar cell by light conversion depends on its efficiency. Researchers and scientists are looking for means and ways of improving solar cells efficiency to reduce costs of manufacture and operations. This chapter has discussed various ways of improving solar cell efficiency by looking at its design improvement. The chapter also discussed relationship between air mass and efficiency and concluded with the explanation of how bandgap and light wavelength relates to efficiency.

CHAPTER FOUR MODELING, SIMULATION CODE DEVELOPMENT AND DATA COLLECTION

4.1 Introduction

The aim of this research is to develop a solar panel for high altitude and low earth orbit applications. This solar panel should have high light to electrical energy conversion efficiency with the ability to tolerate and operate within the harsh environmental space condition. In this chapter, a space solar cell model required for the development of the panel together with its space environment computer simulation code is developed. The type of data required for the research and their collection sources are also presented in this chapter.

4.2 Research Design

Computer simulation method of design is used for this research. As a definition, computer simulation is a substitute for experimentation and intervention on the actual system. It is undertaken when such experimentation is too dangerous, costly, untimely, or inconvenient. Computer simulation is growing in popularity as a methodological approach for researches as it allows a researcher to infer what might happen in the real situation if he/she were to do a real time measurements or experiment (Dooley, 2002, p.3). The reasons for choosing simulation methodology in this research is that the real time experiments require expensive instruments like a sunlight generator with light characteristics almost similar to the one in space and a controlled high heat generator which are not available in the university. This research work can be categorized as secondary data dependant as the tandem solar cell will be developed using secondary data from a selection of solar cell materials already existing in the market. The secondary data is collected from different solar cell manufacturers' data sheets, books, journals, websites and past theses. The following section is necessary to understand why there is a need to develop a solar cell model

4.3 Terrestrial versus low earth orbit and high altitude environments

By definition, terrestrial environment is the region between the earth surface and approximately 90 km above it. Terrestrial environment may also be regarded as natural environment that encompasses all living and non-living things occurring naturally on earth or some region thereof or an environment that encompasses the interaction of all

living species. The atmosphere can be divided into three distinct regions, the lower region being the troposphere, followed by stratosphere and the upper region, mesosphere. The environment is characterised with water vapor, carbon dioxide, oxygen and other inert gases. The temperature varies between -40°C to 40°C except for extreme locations such as deserts and the Polar Regions (NWS Jet stream, 2010). The sun intensity has been measured to have an average intensity of 1000 watts per square meter. In contrast to this environment, the LEO environment is almost a vacuum with a composition of hazardous atomic oxygen, UV radiation, ionizing radiation, etcetera as mentioned in chapter two. The space temperature varies from 0 to $+150^{\circ}\text{C}$ on the side facing the sun and from 0 to -150°C on the eclipse. The average temperature in this environment is about $\pm 75^{\circ}\text{C}$ (Han *et al*, 2006, p.4). Due to the difference in these two atmospheres, same solar cells will behave differently when they are exposed to them. For a terrestrial solar cell to operate in space environment, the effect on the environmental change must be known. If the effect is positive, then it will be advantageous to the research or if it is negative, the researcher must look for a possible way to compensate for the change. To study the behavior of solar cells with changes in operating conditions, the mathematical model discussed in chapter two can be used but must be modified to suit the operating conditions.

4.4 Development of a solar Cell Model for space applications

In a solar panel development or assembly, a solar cell is the basic building block required to be connected either in series mode, or in parallel mode or in both modes to provide a required power at the required voltage. The understanding of the cells' current/voltage characteristics and its electrical behavior with respect to changes with temperature and solar irradiance is crucial for the design and construction of solar panels. With the development of an appropriate solar cell model, the solar cell itself can be studied and evaluated. In this research, the solar model is developed from the basic definition of a solar cell as a large area p-n junction diode, which is formed as a junction between the n-type and p-type regions of a semiconductor. When this solar cell is hit by an incident light ray with photon energy greater than the band gap energy of the material making up the cell, electron-hole pairs will be generated (Lorenzo *et al*, 1994, p.61). The model can be represented by an electrical equivalent circuit as a constant current source in parallel with a diode. In real life when operating a solar cell, losses exists which are represented in the model as shunt and series resistors. A shunt resistor R_{SH} denotes

losses due to the effect of leakage current flowing across the junction between the n and p layers while R_s indicates the losses due to current flowing through the highly resistive emitter and contacts. Figure 4.1 shows the model which is also an equivalent circuit of a solar cell.

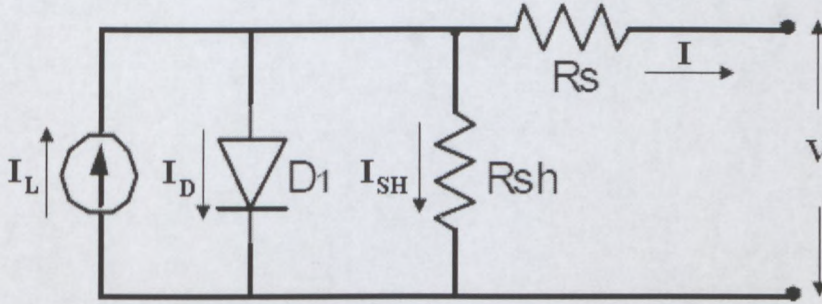


Figure 18.1 Equivalent circuit of a solar cell (Lorenzo, *et al*, 1994)

The conventional technique to model a solar cell is to establish mathematical expressions based on the equivalent circuit of the cell.

From the diagram, it can be seen that the resultant output current, I of the solar cell is given as (Nema *et al*, 2010, p.488):

$$I = I_L - I_D = I_L - I_O \left(e^{\frac{q(V+I.R_s)}{n.kT}} - 1 \right) - \frac{V + I.R_s}{R_{sh}}. \quad (4.1)$$

This equation is referred to as characteristic equation for solar cells. For efficiency of solar cells to be high and to have a better field performance, losses must be low. For these reasons and also to reduce computational complexity, this project will consider a simple model where very a high shunt resistance and a low series resistance. The value for shunt resistance will be assumed to be very high while that of series resistance will be taken to be very low. This leads to ignoring the shunt current as it will be assumed to be negligible small (Walker, 2001, p.1); hence equation (1) reduces to:

$$I = I_L - I_O \left(e^{\frac{q.V}{n.kT}} - 1 \right). \quad (4.2)$$

Equation 2 on its own cannot be used to draw I-V curves for different types of solar cells because: the information on temperature dependence of the photo-current, the

knowledge of open circuit voltage and of the saturation current must be known to complete the model. The following expressions define the individual current components in the characteristic equation forming the model.

The value of light current (I_L) is dependent on temperature (Adamo, Attivissimo, Nisio, Lanzolla & Spadavecchia, 2009.P.964) and at any required temperature, it is given as:

$$I_L(T) = I_L(T_{ref}) + \alpha(T - T_{ref}). \quad (4.3)$$

$$\text{But, } I_L(T_{ref}) = I_{SC}(T_{ref}) \frac{G}{G_{ref}}. \quad (4.4)$$

α , is a factor called temperature coefficient (positive) of short circuit current. It is used to explain how the current of a solar cell changes with temperature. It is defined as;

$$\alpha = \frac{(I_{SC}(T) - I_{SC}(T_{ref}))}{(T - T_{ref})} \quad (4.5)$$

The saturation current I_O is also temperature dependant and at the same time on the bandgap of the material used for the solar cell (Shen et al, 2009.p.338). Taking into consideration these two factors, the current is equated as :

$$I_O = I_{O(ref)} \left(\frac{T}{T_{ref}} \right)^{\frac{3}{n}} \exp \left\{ \left[\frac{(-E_g)}{(N_s nk)} \right] \left(\frac{1}{T} - \frac{1}{T_{ref}} \right) \right\} \quad (4.6)$$

And

$$I_{O(ref)} = \frac{I_{SC}(T_{ref})}{\left[e^{\frac{q V_{OC}(T_{ref})}{nk T_{ref}}} - 1 \right]} \quad (4.7)$$

Finally, the equation used for open circuit voltage is written as:

$$V_{OC}(T) = V_{OC}(T_{ref}) - \beta(T - T_{ref}) \quad (4.8)$$

β , is a factor called temperature coefficient (negative) of open circuit voltage. It is used to explain how the voltage of a solar cell changes with temperature. It is defined as;

$$\beta = \frac{(V_{OC(T_1)} - V_{OC(T_{ref})})}{(T_1 - T_{ref})} \quad (4.9)$$

In all the above equations, the constants and other factors used are explained below as: G is referred to as irradiance and expresses the light intensity in watts per area. K is a constant; the Boltzmann's constant with a value equal to $1.38 \times 10^{-23} JK^{-1}$, q is the electronic charge having a value of $1.6 \times 10^{-19} C$. N_s , is the number of series solar cells in a given solar panel. The subscript *ref* (reference) identifies the Standard Test Conditions (STC) defined in the IEC 61215 international standard. The defined STC conditions stated are $T_{(ref)} = 25^\circ C$ and $G_{ref} = \text{Solar irradiance at } 1000 W/m^2 \text{ at Air Mass, AM } 0$. The short circuit current $I_{SC}(T_{ref})$ and open circuit voltage, V_{OC} at STC are usually stated by manufactures of solar cells in their data sheets. Equations (3) to (9) can be solved and used with equation (2) to plot I-V characteristic curves for any given solar cell material. These characteristic curves are useful in determining the cell parameters ($V_{OC}, I_{SC}, V_{max}, I_{max}, \eta, \& FF$) necessary for designing a solar panel. The advantage with this derived model is that it can be used generally for any solar panel of solar cells made of any material.

4.5 Development of a simulation program

A solar cell that is used to generate energy in terrestrial environment will behave differently when the same cell is to be operated in space environment. To study the effects of changes in environmental conditions on solar cell operation, a general matlab simulation program to simulate various space and terrestrial environment conditions is developed in the following section. The code is general in the sense that it will be used for simulation with any type of solar cell as long as the specifications for that cell are used. The code is developed to use temperature and irradiance as variables.

Table 18.1Electrical parameters for MSX-60 solar module (Solarex, 1998)

Solar panel parameter	Variable	Value
Maximum power	P_m	60W
Maximum voltage	V_m	17.1V
Maximum current	I_m	3.5A
Short-current current	I_{sc}	3.8A
Open-circuit voltage	V_{oc}	21.1V
Open circuit voltage temperature coefficient	β	$-(80 \pm 10)mV/^{\circ}C$
Short circuit current temperature coefficient	α	$+(0.065 \pm 0.015)\%/^{\circ}C$
Power temperature coefficient		$-(0.5 \pm 0.05)\%/^{\circ}C$

4.6 Generalized MATLAB script file for determining solar cell I-V curves

To develop this m-file, data for solar panel model MSX60 shown in table 4.1 was used. The panel provides 60 watts of nominal maximum power, and has 36 polycrystalline silicon cells connected in series (Solarex, 1998). The generalized MATLAB script for determining solar cell I-V curves is given as appendix A.

4.7 Generalized MATLAB script file for determining solar cell voltage-power characteristic curves

This code is developed with specifications for MSX-60 solar panel. The code can still be used for other types of solar panels provided required parameters for that panel are changed accordingly. The developed code is given as appendix B.

4.8 Generalized MATLAB script file for determining maximum voltage and current from solar cell I-V characteristic curves

This code is developed with specifications for MSX-60 solar panel. The code can still be used for other types of solar panels provided required parameters for that panel are changed accordingly. The developed code is given as appendix C.

4.9 Data collection and sources

Searching for data or information sources is an essential aspect of any research work, hence sourcing, collecting and recording of that data or information must be done with great care. The data and information used for this research has been collected from various sources. The sources included Solar cell manufacturer’s data sheets, journals, magazines, websites, and past theses. The data and the information can be regarded as secondary. According to Ghauri and Gronhaug (2005, 91), secondary data can be referred to as any data or information that was previously collected by others for a certain purpose. The same information may be useful for the present researcher who may use it for his intention. The following tables show data and information for different solar cell materials that have been collected for this research. The source of each material is indicated.

Table 18.2Electrical parameters for Copper Indium Gallium Selenide (Global solar,MY-145,CIGS datasheet)

Solar panel parameter	Variable	Value
Maximum power	P_m	145W
Voltage@ P_m	V_m	27.36V
Current@ P_m	I_m	5.3A
Short-circuit current	I_{sc}	6.7A
Open-circuit voltage	V_{oc}	38.8V
Temperature coefficient of open circuit voltage	β	-0.50% / °C
Temperature coefficient of short circuit current	α	+0.01% / °C
Temperature coefficient of power		-0.50% / °C
Cell area	A	210 x 100 mm
Number of cells in series	Ns	72
Operating Temperature	°C	-40/+85

Table 18.3Electrical parameters for Cadmium Telluride (FS-275-datasheet)

Parameter	Variable	Value
Maximum power	P_m	75W
Voltage@ P_m	V_m	68.2V
Current@ P_m	I_m	1.10A
Short-circuit current	I_{sc}	1.23A
Open-circuit voltage	V_{oc}	89.6V
Temperature coefficient of open circuit voltage	β	-0.25% / °C
Temperature coefficient of short circuit current	α	+0.04% / °C
Temperature coefficient of power		-0.25% / °C
Cell area	A	6206 sq.mm
Number of cells in series	N_s	116
Operating Temperature	°C	

Table 18.4Electrical parameters for amorphous silicon (Suntech, STP080Ts-AA)

Parameter	Variable	Value
Maximum power	P_m	80W
Voltage@ P_m	V_m	75.9V
Current@ P_m	I_m	1.10A
Short-circuit current	I_{sc}	1.41A
Open-circuit voltage	V_{oc}	96.2V
Temperature coefficient of open circuit voltage	β	-0.30 %/°C
Temperature coefficient of short circuit current	α	+0.10 %/°C
Temperature coefficient of power		-0.20 %/°C
Cell area	A	13490sq.mm (135sq.cm)
Number of cells in series	N_s	106
Operating Temperature	°C	-40°C to +85°C

Table 18.5Electrical parameters for Gallium arsenide solar panel(Spectrolab,GaAs/ single junction solar cell)

Parameter	Variable	Value
Maximum power	P_m	25.7mW/cm ²
Voltage@ P_m	V_m	0.9V
Current@ P_m	I_m	28.6mA/cm ²
Short-circuit current	I_{SC}	30.5mA/cm ² =1.495
Open-circuit voltage	V_{OC}	1.025V
Temperature coefficient of open circuit voltage	β	-1.8 mV/ °C
Temperature coefficient of short circuit current	α	+20 μ A/cm ² /°C =0.98mA/°C
Temperature coefficient of power		
Cell area	A	7cm X 7cm
Number of cells in series	Ns	1
Operating Temperature	°C	-180 °C to + 95°C

Table 18.6Electrical parameters for multi crystalline silicon nitride (Bp Solar, BP 3125J)

Parameter	Variable	Value
Maximum power	P_m	125W
Voltage@ P_m	V_m	17.4V
Current@ P_m	I_m	7.2A
Short-circuit current	I_{SC}	8.1A
Open-circuit voltage	V_{OC}	22V
Temperature coefficient of open circuit voltage	β	$-(80 \pm 10)mV / ^\circ C$
Temperature coefficient of short circuit current	α	$+(0.065 \pm 0.015)\% / ^\circ C$
Temperature coefficient of power		$-(0.5 \pm 0.05)\% / ^\circ C$
Cell area	A	156mm X156mm
Number of cells in series	Ns	36
Operating Temperature	°C	-40° C to +85°

Table 18.7Electrical parameters for mono crystalline (Sun Power,SPR-205-BLK)

Parameter	Variable	Value
Maximum power	P_m	205W
Voltage@ P_m	V_m	40V
Current@ P_m	I_m	5.13A
Short-circuit current	I_{sc}	5.53A
Open-circuit voltage	V_{oc}	47.8V
Temperature coefficient of open circuit voltage	β	-132.5m V/° C
Temperature coefficient of short circuit current	α	3.5m A/° C
Temperature coefficient of power		-0.38% /° C
Cell area	A	
Number of cells in series	N_s	72
Operating Temperature	°C	-40° C to +90°

4.10 Band gaps for different solar cell materials

A bandgap of a solar cell material is the energy required to excite and free electrons from their covalence to conduction state and also determines which part of a solar spectrum is to be absorbed by the material (NREL, 2008). Bandgap values are required for simulation in this research. Table 4.8 shows energy bandgap values for different types of solar cells and indication of its source.

Table 18.8List of solar cell bandgaps (Bandgap,2010)

Solar cell material	Symbol	Bandgap Value
Silicon amorphous	Si	1.7
Selenium	Se	1.74
Germanium	Ge	0.67
Silicon carbide	SiC	2.86
Aluminium phosphide	AIP	2.45
Aluminium arsenide	$AlAs$	2.16
Aluminium antimonide	$AlSb$	1.6
Aluminium nitride	AlN	6.3

List of solar cell bandgaps (continuation)

Diamond	<i>C</i>	5.5
Gallium(III) phosphide	<i>GaP</i>	2.26
Gallium(III) arsenide	<i>GaAs</i>	1.43
Gallium(III) nitride	<i>GaN</i>	3.4
Gallium(II) sulfide	<i>GaS</i>	2.5
Gallium antimonide	<i>GaSb</i>	0.7
Indium(III) nitride	<i>InN</i>	0.7
Indium(III) phosphide	<i>InP</i>	1.35
Indium(III) arsenide	<i>InAs</i>	0.36
Zinc oxide	<i>ZnO</i>	3.37
Zinc sulfide	<i>ZnS</i>	3.6
Zinc selenide	<i>ZnSe</i>	2.7
Zinc telluride	<i>ZnTe</i>	2.25
Cadmium sulfide	<i>CdS</i>	2.42
Cadmium selenide	<i>CdSe</i>	1.73
Cadmium telluride	<i>CdTe</i>	1.49
Lead(II) sulfide	<i>PbS</i>	0.37
Lead(II) selenide	<i>PbSe</i>	0.27
Lead(II) telluride	<i>PbTe</i>	0.29
Copper(II) oxide	<i>CuO</i>	1.2
Copper(I) oxide	<i>Cu₂O</i>	2.1

4.11 Conclusion

This chapter has discussed the development of space solar cell model and simulation code taking into consideration the selected space conditions affecting solar cell operation. The mathematical expressions used for the development of the model and the code are derived from the basic terrestrial solar cell model. The chapter has also reviewed the source and method of data collection for the research. The information obtained from this section will be used for the solar panel development.

CHAPTER FIVE SIMULATION AND ANALYSIS OF SOLAR CELLS WITH SPACE AND TERRESTRIAL CONDITIONS

5.1 Introduction

This chapter deals with the simulations of both space and terrestrial conditions (irradiance and temperature) for various types of solar panels which will also be referred to as solar cells. The aim is to investigate and analyze the operational behavior of the cells in these two different environments. The results will be used to determine the selection of solar cell material for designing a high efficiency multi-junction solar cell. This multi-junction cell will then be used to develop a suitable solar panel for low earth orbit and high altitude applications. Copper indium gallium selenide (CIGS) solar cell will be the first material to start with and the same process will be repeated for other types of solar cells. Light intensity will be expressed in terms of suns, where 1 sun means 1000 W/m². Seven types of solar cell data were obtained for this research, but only five of them will be used with simulation as the data for the other two types is not suitable for thin solar cells.

5.1.1 Simulation with copper indium gallium selenide (CIGS) solar cells

Copper indium gallium selenide is a solid solution material of copper indium selenide and copper gallium selenide with a chemical formula of $CuIn_xGa_{(1-x)}Se_2$, where x is a value between 1 and zero. The bandgap for this material varies between 1 to 1.7 eV depending on the gallium ratio. CIGS is used as a light absorber material for thin-film solar cells because it has a high light absorption coefficient of more than $10^5/\text{cm}$ for 1.5 eV and higher energy photons (Scofield, Duda, Albin, Ballard & Predecki, 1994, p.26). For this solar cell simulation, the value of 1.5 eV will be used.

5.1.2 Effects of temperature and irradiance on solar cell operation

To analyze the effect of temperature and light intensity (irradiance) on solar cell performance, output power and current-voltage (I-V) characteristic curve behavior for the cell will be studied. For this solar cell and the others to follow, different combinations of temperature and irradiance conditions will be used in their study. MATLAB simulation codes written in section 4.6 to 4.8 will be used as per simulation requirements. The specific parameters for copper indium gallium selenide used in the codes are as follows.

1. Bandgap, $V_g = 1.5\text{eV}$
2. Diode ideality factor, $A = 1.59$
3. Voltage range [0:0.01:40]
4. Number of cell, $N_s = 72$
5. $V_{oc_T1} = 38.8\text{V}$. (Solar panel open circuit voltage at 25°C)
6. $I_{sc_T1} = 6.7\text{A}$. (Solar panel short circuit current at 25°C)
7. $V_{oc_T2} = 29.1\text{V}$. (Calculated panel voltage using equation 8 in section 4.4 at 50°C)
8. $I_{sc_T2} = 6.734\text{A}$. (Calculated panel current using equation 3 in section 4.4 at 50°C)

5.1.3 I-V Characteristic curve for cigs with fixed irradiance and temperature (terrestrial conditions)

The simulation conditions for this section are set at Standard Test Conditions of terrestrial global air mass, AM 1.5G with illumination of 1000W/m^2 and temperature of 25°C . MATLAB code from section 4.6 (Refer to Appendix A) is used with the cigs specific parameters stated above to plot the characteristic as shown in figure 5.1. As can be seen from the results, the solar cell generates an output current of 6.7 amps and voltage of 38.8 volts. These values are similar to the operational values stated by the manufacturer. The characteristic shows the normal behavior of the solar cells under its normal terrestrial operating conditions.

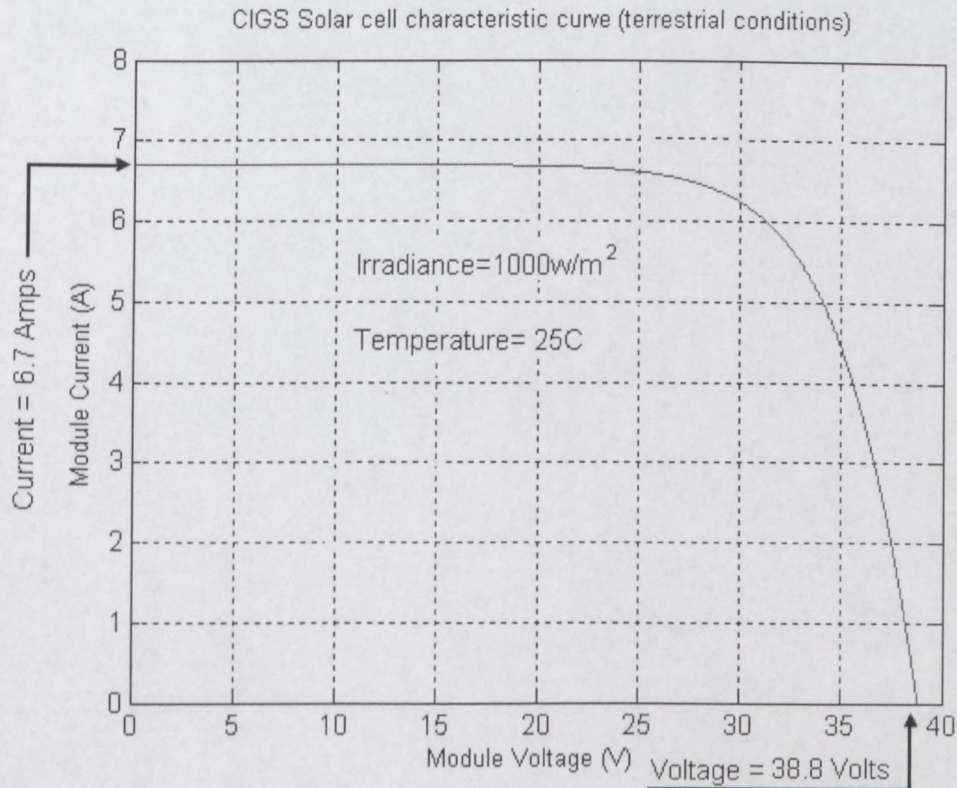


Figure 0.1CIGS I-V curve at 1 sun and temperature of 25C

5.1.4 I-V Characteristic curve for cigs with fixed irradiance and variable temperature

For this simulation, the light irradiance condition is set and fixed at Standard Test Conditions of terrestrial global air mass, 1.5G with illumination of 1 Kw/m² but the temperature is varied in steps of 25 from 0°C to 75 °C. The idea behind this simulation is to investigate how the solar cell will behave in terms of its current and voltage with change in temperature. The simulation code from section 4.6 (Refer to Appendix A) is modified to plot multiple curves for different temperatures on the same graph and the result is as shown in figure 5.2. By comparing these results with the one for figure 5.2, it can be seen that there is a very small change in output current but the change in output is very big. The temperature change has caused the current to increase from 6.68 amps to 6.74 amps (measurements from zoomed in I-V curve) and the voltage to reduce from 45.2 volts to 26.3 volts. The current has changed by only 0.898% and the voltage by 41.8%. This shows that the change in temperature has a higher effect on solar cell output voltage than has on current.

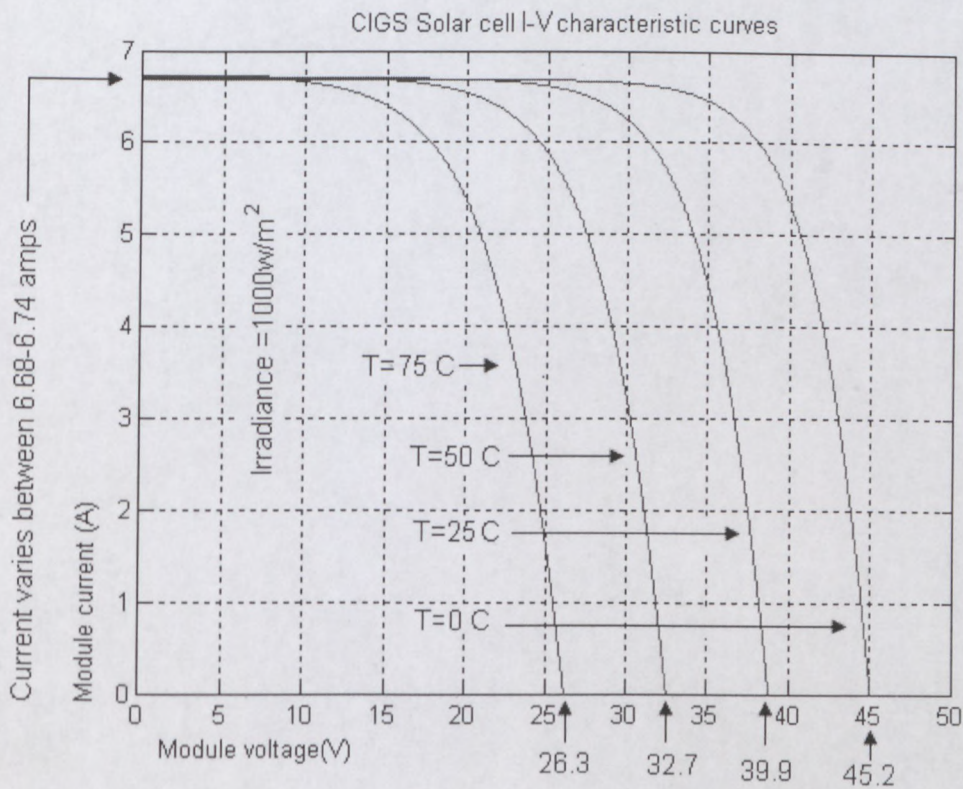


Figure 0.2 CIGS I-V curve at 1 sun and variable temperature

5.1.5 I-V Characteristic curve for cigs with fixed temperature and varied irradiance

For this simulation, the temperature is fixed at 25°C but the irradiance is varied from 0.25 suns to 1.366 suns. Again the idea behind this simulation is to investigate how the solar cell will behave in terms of its current and voltage with change in light intensity. The simulation code is modified to plot multiple curves for different light intensities on the same graph and the result is as shown in figure 5.3. By comparing the I-V characteristics, it can be seen that the output current of the solar cell changes significantly with the change in light intensity but the change in output voltage is slight. The light intensity change from 0.25 suns to 1.367 suns has caused the current to increase from 1.68 amps to 9.15 amps and the voltage to reduce from 38.94 volts to 35.15 volts. The current has changed by 81.64% and the voltage by 9.73 %. This shows that the change in light intensity has a higher effect on solar cell output current than has on voltage.

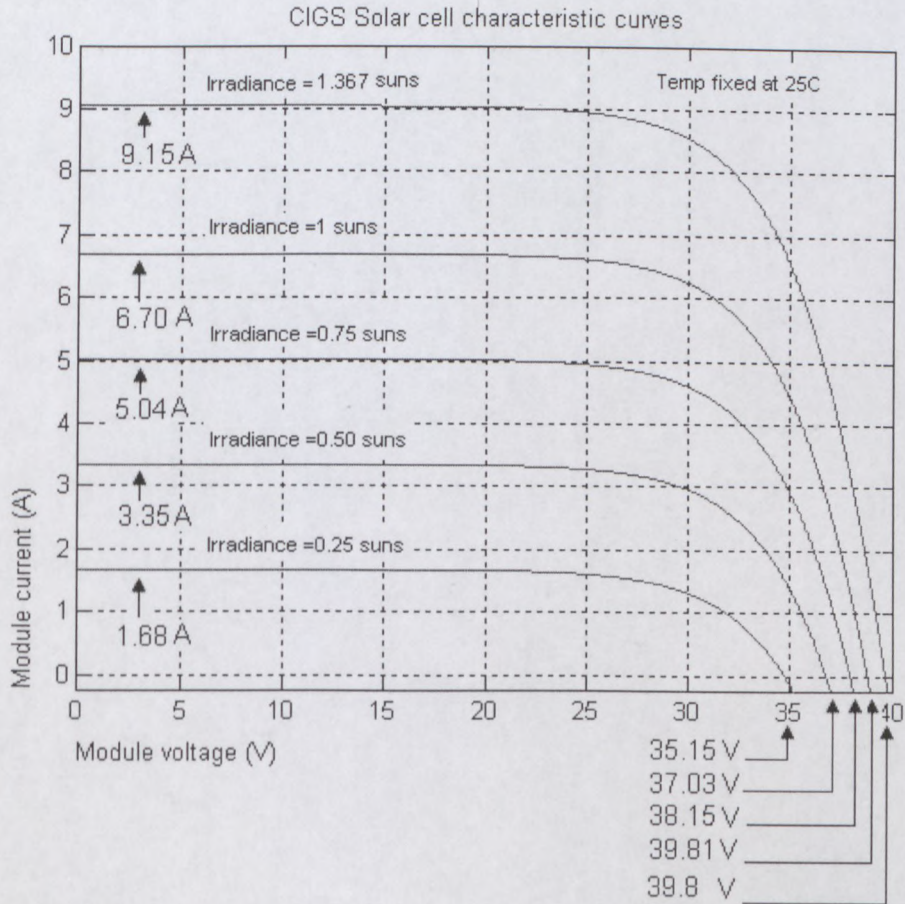


Figure 0.3CIGS I-V curve at 25OC and variable light

5.1.6 I-V Characteristic curve for cigs with space temperatures and irradiance

In this section, the simulation conditions are set and fixed at temperatures of 75°C and light intensity of 1.367 suns. These are the approximate conditions that the solar panels are experiencing in the high altitude and low earth orbit .Here, the researcher is trying to investigate how the solar cells and panels that were originally designed for terrestrial applications will behave in this space environment. The simulation result is as shown in figure 5.4.The output current and voltage for these conditions has changed to 9.2Amps and 27.2Volts respectively. Comparing these results with the ones obtained in section 5.1.2 for terrestrial conditions, it can be seen that the voltage reduces from 38.8 Volts to 27.3 Volts and current increases from 6.7amps to 9.2amps with the increased irradiance and temperature. The voltage has reduced by 29.9% and the current increased by 37.3%.

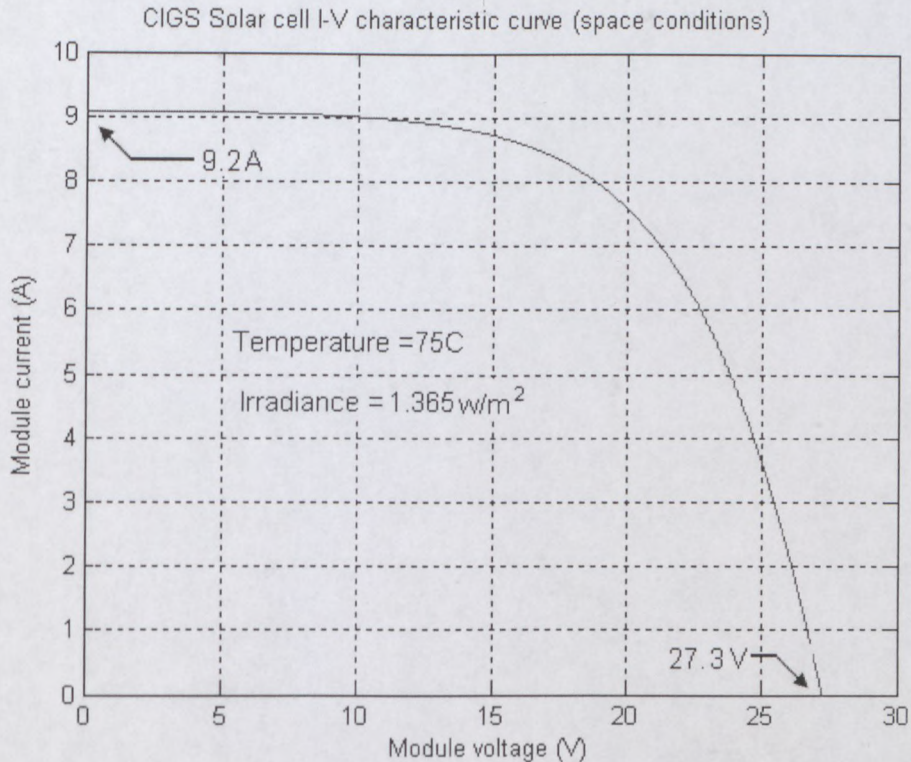


Figure 0.4CIGS I-V Characteristic curve at temperature 75C and 1.367 suns

5.1.7 Effect of irradiance and temperature on solar cell power

In the following sections, effects of fixed and changing temperature and light irradiance on solar cell output power are investigated. Simulations with different combinations of light and temperature conditions will be performed. The results of these investigations will be used in the determination of solar cell efficiency and for developing the multi-junction solar cell.

5.1.8 Effect of fixed temperature and irradiance on cigs solar cell power (terrestrial conditions)

The simulation conditions are set and fixed at Standard Test Conditions illumination of sun and temperature of 25C. The code given in section 4.8 (Refer to Appendix C) is again used for this simulation and the results are shown in figure 5.5. It can be seen from the results that the output voltage is 38.8 volts while the power is 188 watts. This is the nominal panel output power under nominal terrestrial conditions.

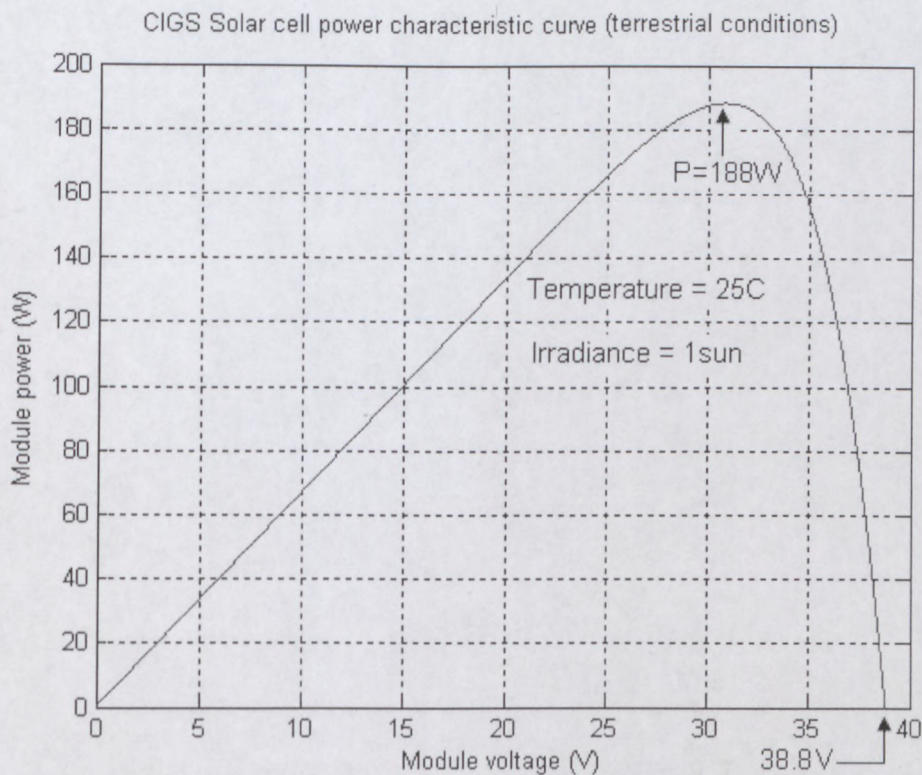


Figure 0.5 CIGS power curve at temperature of 25C and 1sun

5.1.9 Effect of fixed temperature and variable irradiance on cigs solar cell power

The conditions for this simulation are that the temperature is fixed at 25C but the light intensity is varied in steps from 0.25 to 1.366 suns. To analyze the effect of this condition, the code given in section 4.8 (Appendix C) is used and modified to plot multiple power curves for different suns as shown in figure 5.6. Reading from the results it shows that the power changes from 42 watts to 262 watts with changes of light intensity from 0.25 suns to 1.367 suns. The curves are numbered from number 1 for 1.367 suns to number 5 for 0.25 suns. The power has increased by 83.9% between 0.25 and 1.367 suns. It can also be seen that with the same light intensity change, the voltage has increased from 35 volts to 39.7 volts. This represents a voltage change of 11.8%. From the observations, it can be seen that light intensity change has a positive effect on out power which can be explained to be caused by the increase of current with light.

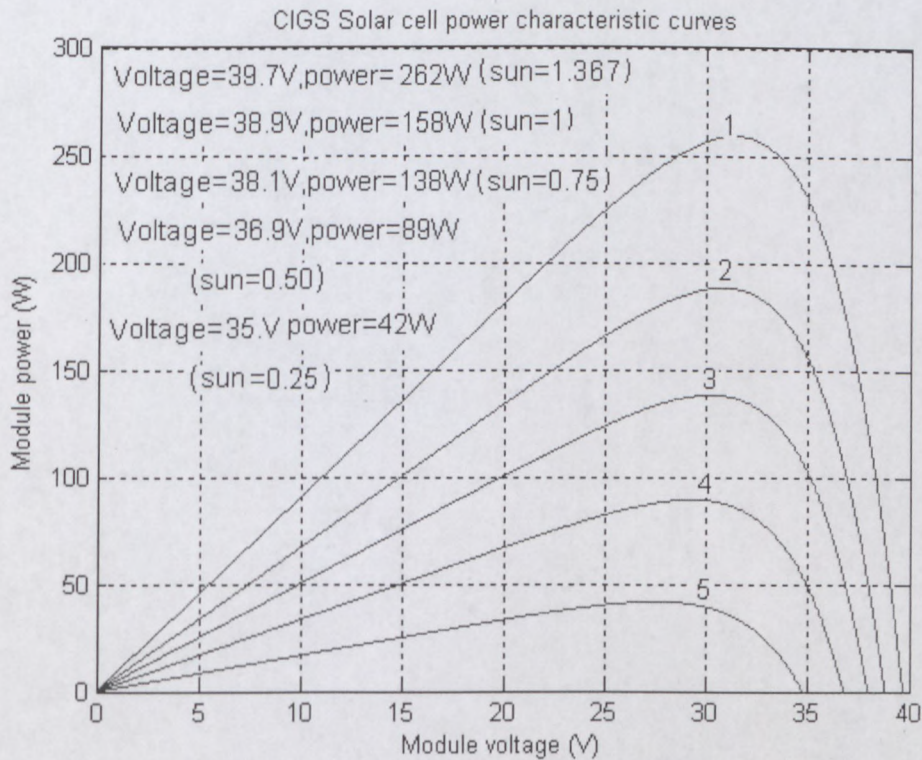


Figure 0.6 Power variation for CIGS with variable light intensity

5.1.10 Effect of fixed temperature and irradiance on cigs solar cell power (space conditions)

For this simulation, the temperature is fixed at 75°C and the irradiance is set at 1.367 suns. Again the code from section 4.8 (Appendix C) is used and the simulation result is as shown in figure 5.7. By comparing the results with those of terrestrial conditions in figure 5.5, it can be seen that the power has reduced from 188 watts to 154 watts while the voltage has reduced to 27.4 volts from 38.8 volts. The power has reduced by 18.1% and voltage by 29.4%. This shows that the combined space conditions of irradiance and temperature reduces the cell power and this can be explained to be caused by the high reduction of cell voltage with the increase in space temperature.

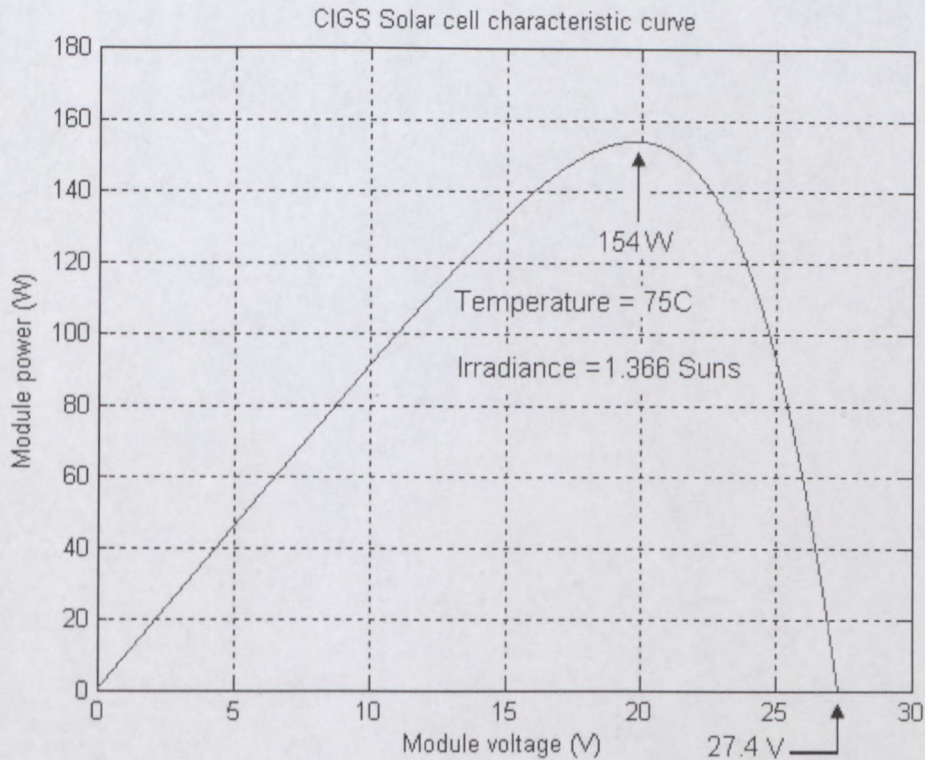


Figure 0.7 CIGS power curve at temperature of 75C and 1.366 suns

5.1.11 Determination of maximum voltage and current for cigs operating at space conditions

Fill factor value is required for solar cell efficiency calculations. A fill factor value for a given solar cell depends on its short circuit current, open circuit voltage, maximum voltage and maximum current which can be determined from I-V characteristic curve. A solar cell will deliver maximum power to a load when its internal resistance matches the external load. Maximum power delivery will correspond to the maximum voltage and current values of the solar cell. The conditions to determine these values are set as for space with light intensity of 1367 watts and a temperature of 75C. Simulation code from section 4.8 (Appendix C) is used and the result is as shown in figure 5.8. From the results, it can be seen that the maximum power delivery occurs at an approximate voltage of about 19.5volts. To determine the maximum current corresponding to this voltage, figure 5.4 is redrawn as shown in figure 5.9. In this figure, a line is drawn upwards from the maximum voltage point to touch the I-V curve and then it is extended to the left and cut the current axis. The point where the line cuts the current axis is the maximum current value and it can be seen to be equal to 7.7 amps.

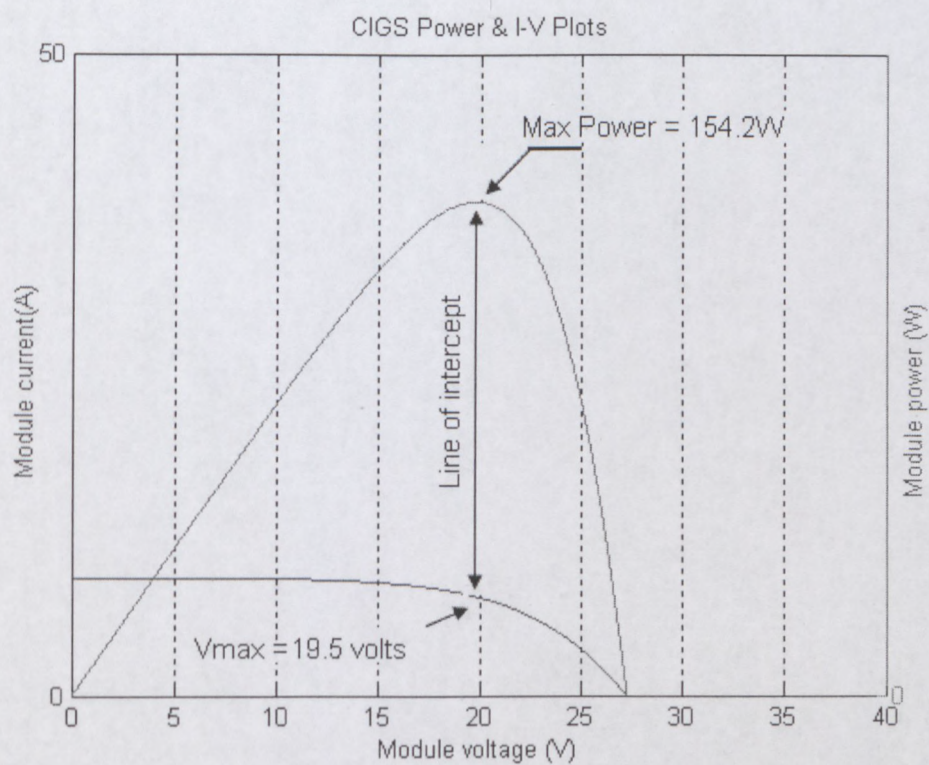


Figure 0.8 I-V & Power curves for CIGS showing power, voltage and current

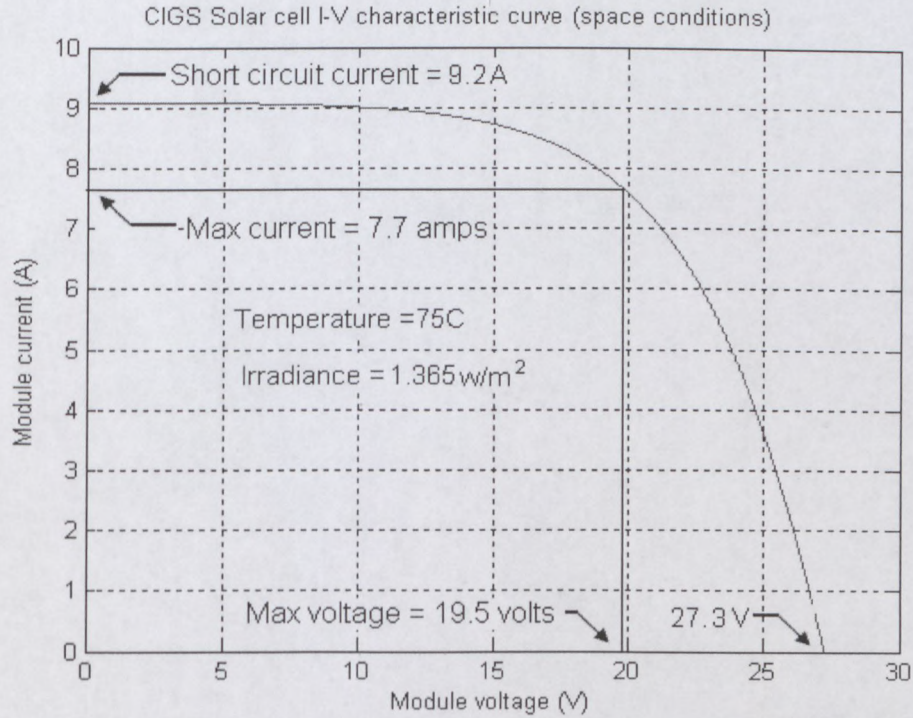


Figure 0.9 Maximum voltage and current values for CIGS solar cell

5.1.12 Calculation of figures of merit for CIGS solar cells (space environment)

(1) Open circuit voltage per cell (V_{OC}) = $\frac{\text{Open circuit voltage}}{\text{Number of solar cells}} = \frac{27.3}{72} = 0.379 \approx 0.4 \text{ volts.}$

(2) Maximum voltage per cell (V_{Max}) = $\frac{\text{Maximu voltage}}{\text{Number of solar cells}} = \frac{19.5}{72} = 0.271 \text{ volts}$

(3) Short circuit current per cell (I_{SC}) = 9.2 amps

(4) Maximum current per cell (I_{Max}) = 7.7 amps

(5) Short circuit current density per cell (J_{SC}) = $\frac{\text{Short circuit current}}{\text{Total surface area of solar cells}}$

$$= \frac{9.2}{72 \times 210 \text{ mm} \times 100 \text{ mm}} = \frac{9.2}{72 \times 21 \text{ cm} \times 10 \text{ cm}} = 0.608 \text{ mA/cm}^2$$

(6) Cell fill factor (FF) = $\frac{\text{Max Voltage} \times \text{Max Current}}{\text{Open circuit voltage} \times \text{Short circuit current}} = \frac{0.271 \times 7.7}{0.4 \times 9.2} =$

$0.567 = 56.7\%$

$$(7) \text{ Cell efficiency } (\eta) = \frac{\text{Max power}}{\text{Irradiance} \times \text{Solar cell area}} \times 100 = \frac{0.271 \times 7.7}{0.1367 \times 21 \times 10} \times 100 = 0.0726 = 7.26\%$$

Table 0.1 Summary of CIGS solar cell simulation results (space conditions)

V_{OC} (volts)	V_{Max} (volts)	I_{SC} (amps)	I_{Max} (amps)	J_{SC} (mA/cm ²)	FF (%)	η (%)	Cell area cm ²
0.4	0.271	9.2	7.7	0.608	59.9	7.26	210

5.2 Simulations with cadmium telluride (CdTe) solar cells

The previous sections discussed a number of simulations with different conditions for copper indium gallium selenide solar cell. In the following sections, cadmium telluride solar cell will be studied and discussed. Cadmium telluride is a well-known candidate material for making thin-film solar cells. It is a semiconductor compound with very high light absorption efficiency having a bandgap of 1.44 eV. Cadmium is a group two element while telluride is a group six element and their combination results in a similar structure like silicon and germanium (Endres, MacFarlane & Abbott, 2008, p.151). Cadmium telluride thin film technology is the first one to surpass crystalline silicon solar cells in terms of cheapness and has also taken a significant market portion of the multi-kilowatt systems (Zweibel, Mason, Fthenakis, 2007, p.66). The information required for the development of the solar panel this thesis is based on space conditions simulations, therefore some of the terrestrial condition simulations will be avoided. The specification used for the cadmium telluride solar cell are as follows.

1. Bandgap, $V_g = 1.44$
2. Diode ideality factor, $A = 1.5$
3. Voltage range [0:0.001:100]
4. Number of cell, $N_s = 116$
5. $V_{oc_T1} = 89.6$ (Solar panel open circuit voltage at 25°C)
6. $I_{sc_T1} = 1.23$ (Solar panel short circuit current at 25°C)
7. $V_{oc_T2} = 78.4$ (Calculated panel voltage using equation 8 in section 4.4 at 50°C)
8. $I_{sc_T2} = 1.255$ (Calculated panel current using equation 3 in section 4.4 at 50°C)

5.2.1 I-V curve for cadmium telluride solar cells (terrestrial conditions)

Simulation conditions are set at Standard Test Conditions with illumination of 1 sun at terrestrial global air mass, AM 1.5G and a fixed temperature of 25C. Matlab code from section 4.7 is used to simulate the terrestrial conditions and the results are as shown in figure 5.10. It can be seen from the results that under these conditions, the solar cells generates an output short circuit current of 1.23 amps and open circuit voltage of 89.6 volts. These are nominal operational values for this solar panel at terrestrial conditions.

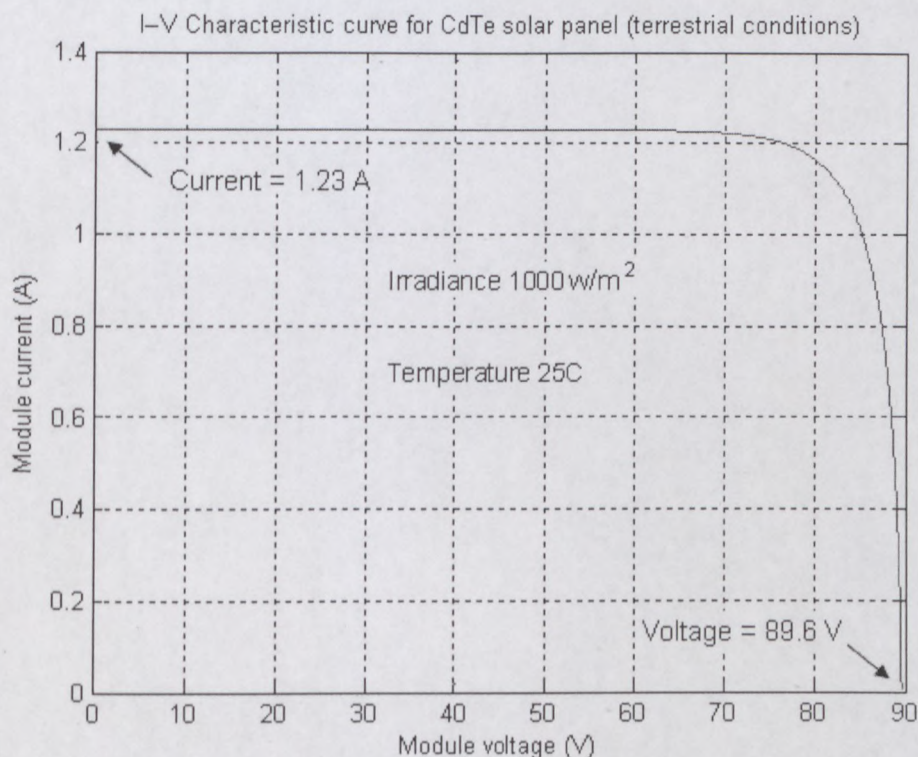


Figure 0.10 I-V curve for CdTe at temperature of 25C and 1sun

5.2.2 I-V Characteristic for cadmium telluride solar cells (space conditions)

This simulation is similar to the one done for section 5.3.1 but the conditions are changed to a temperature of 75C and light irradiance of 1367 watts. Same code is used and the results are as shown in figure 5.11. Comparing the results for space condition with the ones for terrestrial shown in figure 5.10, it can be seen that the open circuit voltage has reduced from 89.6 to 76.5 volts, which represents a drop of 14.62 %. The short circuit current has increased from 1.23 amps to 1.719 amps and this represent an increase of 39.76 %. This means that the combined space conditions of light intensity

and temperature has a positive effect on current by increasing it and a negative effect on voltage by reducing it.

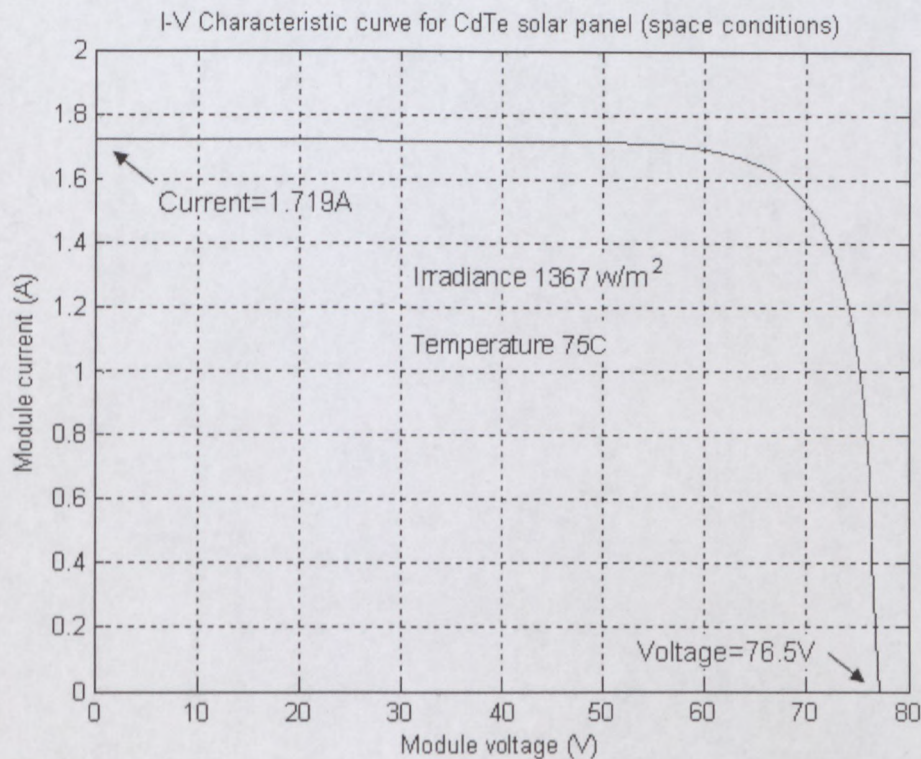


Figure 0.11 I-V curve for CdTe at temperature of 75C and 1.367 suns

5.2.3 Determination of maximum voltage and current for cadmium telluride solar cells (terrestrial conditions)

Maximum power generation simulation to determine maximum current and voltage values is performed as in section 5.2.4 and the results are as shown in figure 5.12. As was mentioned earlier, the maximum current and voltage of a solar cell occurs where the solar cell generates maximum power and from figure 5.13, it can be seen that the solar cell delivers maximum power at a voltage of 80 volts. The double headed arrow shows where the maximum power coincides with the I-V curve. To determine the maximum current from the I-V curve of figure 5.12, a line is drawn vertically from the 80 volt point to the curve and then horizontally to the current axis. The point where the line crosses the current axis is the maximum current and as can be seen it is equal to 1.16 amps.

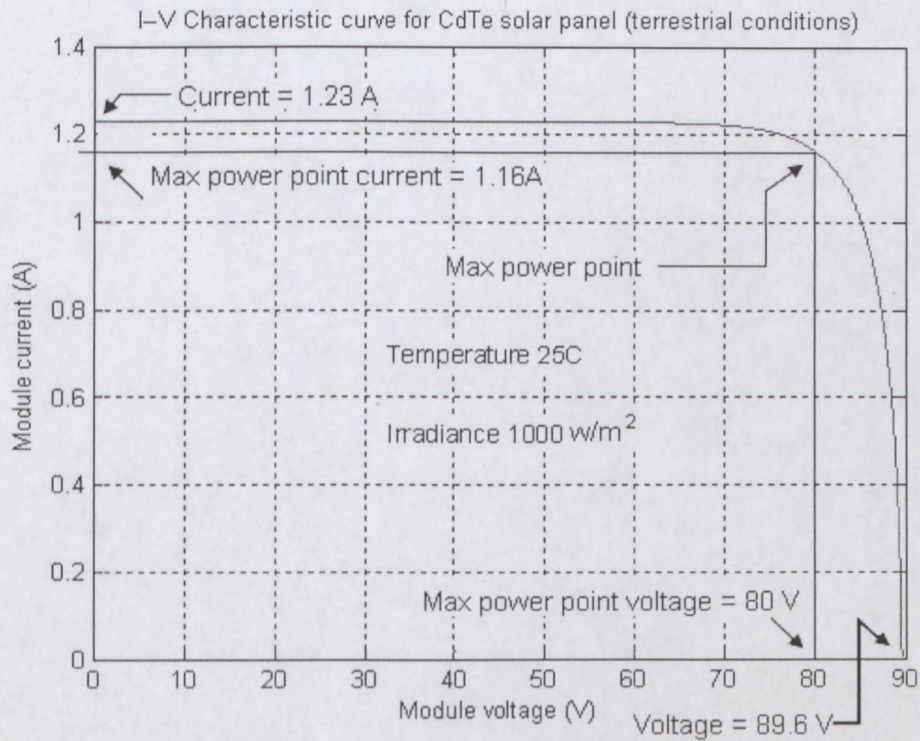


Figure 0.12 Maximum voltage and current for CdTe at temperature of 25C and 1 sun

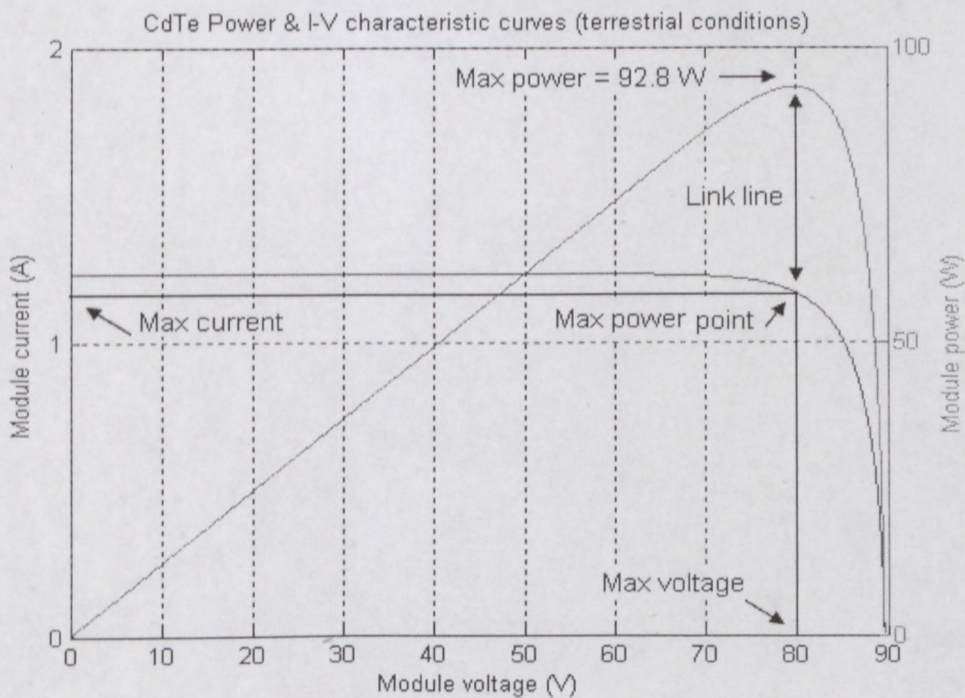


Figure 0.13 I-V & power curves for CdTe at temperature of 25C and 1 sun

5.2.4 Determination of maximum voltage and current for cadmium telluride solar cells (space conditions)

The procedure for determining the values is similar to the one in section 5.3.3 but the conditions are changed to a temperature of 75C and light intensity of 1.367kw. The code in section 4.9 is again used and the simulations repeated as was done for terrestrial conditions. Figures 5.14 and figure 5.15 shows the results of simulations and by repeating the procedure for determining the maximum current and voltage, the values correspond to 1.62 amps and 66.5 volts respectively.

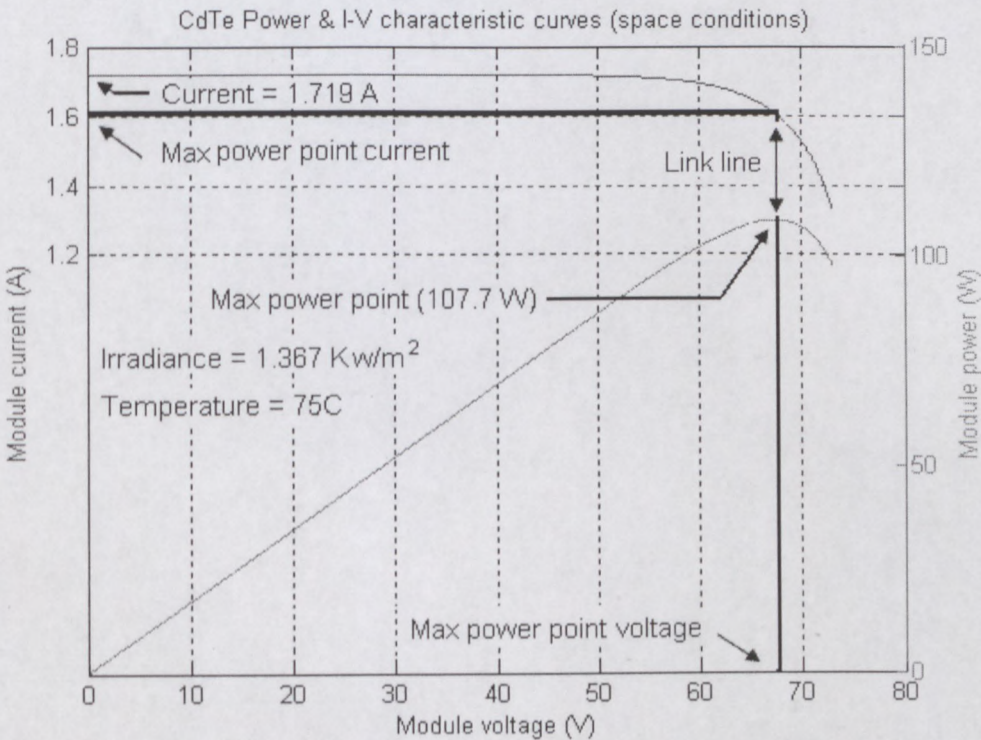


Figure 0.14 I-V & power curves for CdTe at temperature of 75C and 1.367 suns

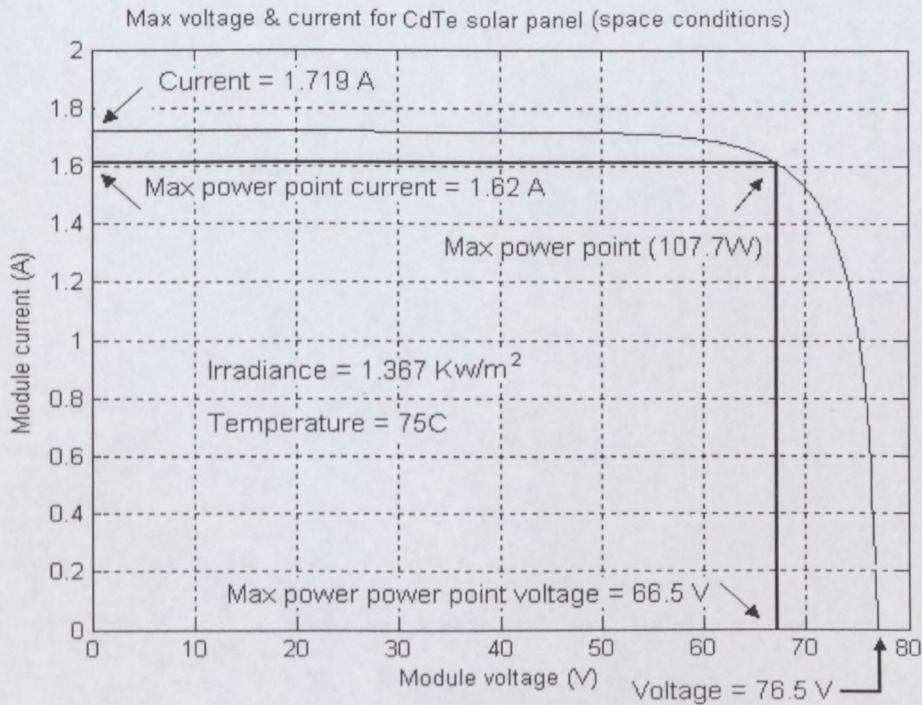


Figure 0.15 Maximum voltage and current for CdTe at temperature of 75C and 1.367 suns

5.2.5 Calculation of figures of merit for cadmium telluride solar cell (space environment)

(1) Open circuit voltage per cell (V_{oc}) = $\frac{\text{Open circuit voltage}}{\text{Number of solar cells}} = \frac{76.5}{116} = 0.659$ volts.

(2) Maximum voltage per cell (V_{Max}) = $\frac{\text{Maximum voltage}}{\text{Number of solar cells}} = \frac{66.5}{116} = 0.573$ volts.

(3) Short circuit current per cell (I_{sc}) = 1.719 amps.

(4) Maximum current per cell (I_{Max}) = 1.62 amps.

(5) Short circuit current density per cell (J_{sc}) = $\frac{\text{Short circuit current}}{\text{Total surface area of solar cells}}$

$$= \frac{1.719}{116 \times 6206 \text{ mm}^2} = \frac{1.719}{116 \times 62.06 \text{ cm}^2} = 0.239 \text{ mA/cm}^2$$

(6) Cell fill factor = $\frac{\text{Max Voltage} \times \text{Max Current}}{\text{Open circuit voltage} \times \text{Short circuit current}} = \frac{0.573 \times 1.62}{0.659 \times 1.719} = 0.819 =$

81.9 %

$$(7) \text{ Cell efficiency} = \frac{\text{Max power}}{\text{Irradiance} \times \text{Solar cell area}} \times 100 = \frac{0.573 \times 1.62}{0.1367 \times 62.06} \times 100 = 11\%$$

Table 0.2 Summary of cadmium telluride solar cell simulation results (space conditions)

V_{OC} (volts)	V_{Max} (volts)	I_{SC} (amps)	I_{Max} (amps)	J_{SC} (mA/cm ²)	FF (%)	η (%)	Cell area cm ²
0.659	0.573	1.719	1.62	0.239	81.9	11	62.06

5.3 Simulations with amorphous silicon solar cells

Prevalent bulk material for solar cells is crystalline silicon which is further divided three subgroups as multicrystalline, monocrystalline and amorphous silicon. Amorphous silicon is a material used for thin film solar cells with a higher light absorption efficiency than crystalline. It has a high bandgap of 1.7eV compared to 1.1eV for crystalline silicon which makes it a good absorber for the visible part of the solar spectrum than for infrared portion (Castellano, 2010, p.15). To simulate the silicon solar cell with the Matlab code, the following parameters are used.

1. Bandgap, Vg = 1.7 eV
2. Diode ideality factor, A =1.8
3. Voltage range [0:0.001:100]
4. Number of cell, Ns =106
5. Voc_T1= 96.2 Volts. (Solar panel open circuit voltage at 25°C)
6. Isc_T1= 1.42 Amps. (Solar panel short circuit current at 25°C)
7. Voc_T2 = 81.77Volts. (Calculated panel voltage using eqn. 8 in section 4.4 at 50°C)
8. Isc_T2 = 1.4805Amps. (Calculated panel current using eqn. 3 in section 4.4 at 50°C)

5.3.1 I-V curve for amorphous silicon solar cells (terrestrial conditions)

Simulation conditions are set at Standard Test Conditions with illumination of 1 Kw/m² at terrestrial global air mass, AM 1.5G and a fixed temperature of 25C.Simulations are done with the general code from section 4.7 and the results are as shown in figure 5.16. It can be seen from the results that under these conditions, the solar panel generates an output short circuit current of 1.41 amps and open circuit voltage of 96.2 volts which are nominal values for the panel at terrestrial operating conditions.

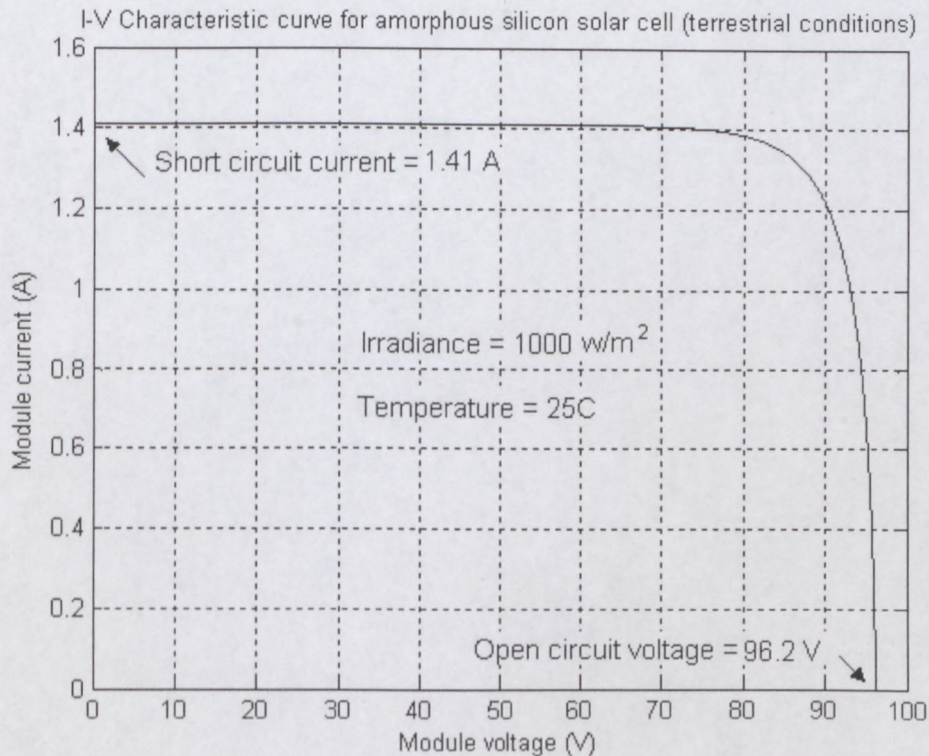


Figure 0.16 I-V curve for amorphous silicon solar cell at temperature of 25 and 1sun

5.3.2 I-V characteristic curve for amorphous silicon solar cells (space conditions)

Simulation conditions are set as for space environment. The temperature is set at 75 degrees and the light intensity at 1367watts. Simulation procedure is the same as for section 5.4.1 and the result is as shown in figure 5.17. Comparing these results with the ones for terrestrial shown in figure 5.16, it can be seen that the open circuit voltage has reduced from 96.2 to 82.5 volts. This represents a drop of 15.3 % while the short circuit current has increased from 1.41 to 2.026 amps which represent an increase of 43.69%. This means that the combined effects of light intensity and temperature has a bigger positive effect on current than on voltage.

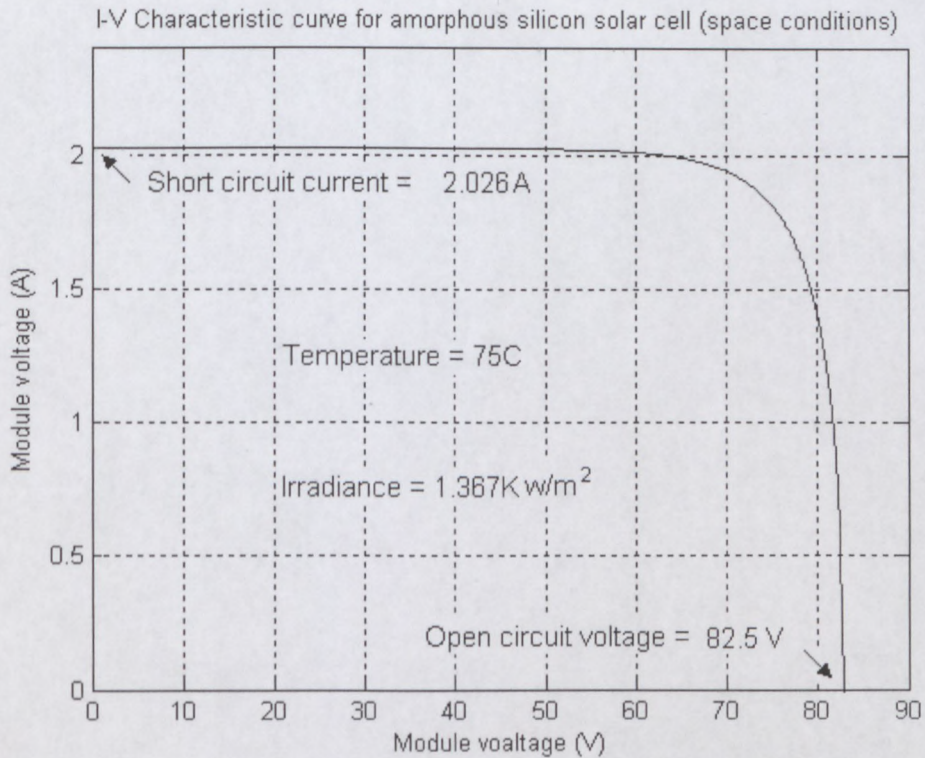


Figure 0.17 I-V curve for amorphous silicon solar cell at temperature of 75C and 1.367suns

5.3.3 Determination of maximum voltage and current for amorphous silicon solar cells (terrestrial conditions)

Simulation procedure is similar as for section 5.3.3 and the results are as shown in figures 5.18, 5.19 & 5.20. From the results it can be seen that the value for maximum power is 114 watts, maximum current is 1.32 amps and maximum voltage is 87 volts.

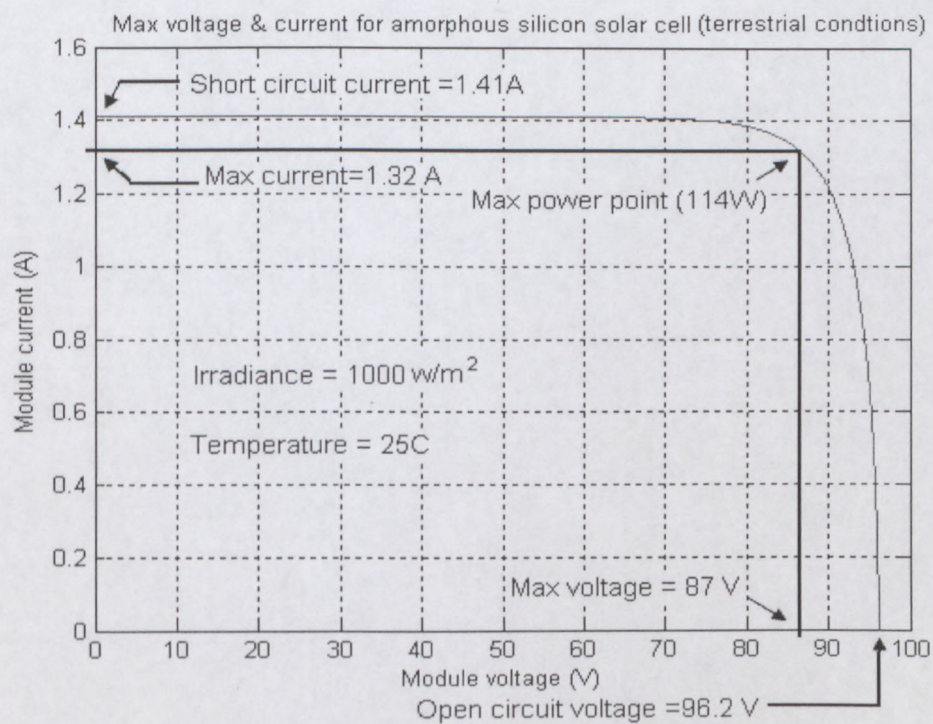


Figure 0.18 Maximum current voltage for amorphous silicon cell (space conditions)

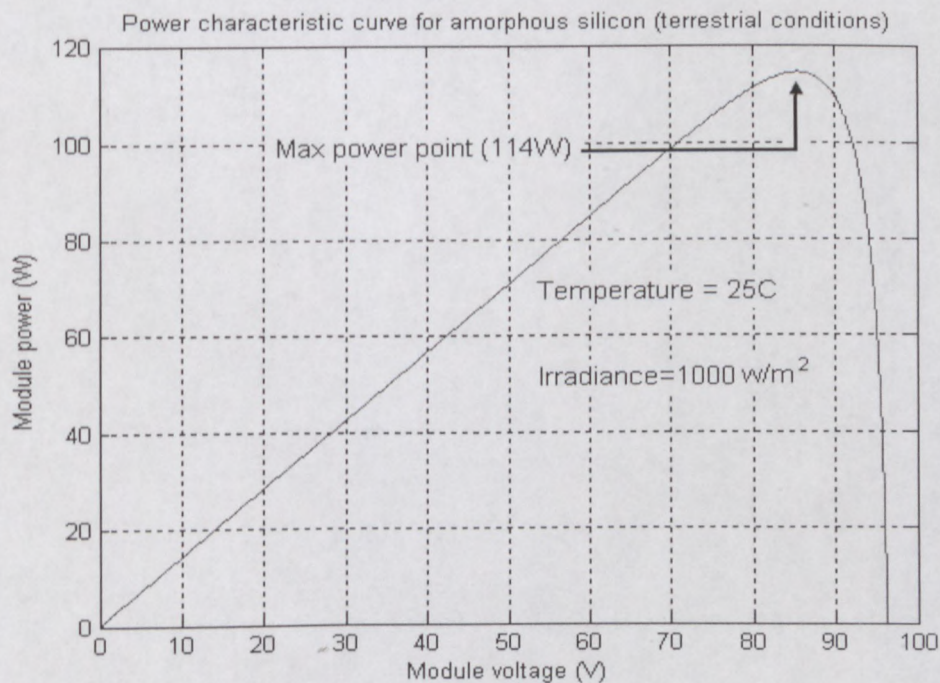


Figure 0.19 Maximum voltage & current for amorphous silicon solar cell at temperature of 25C and 1sun

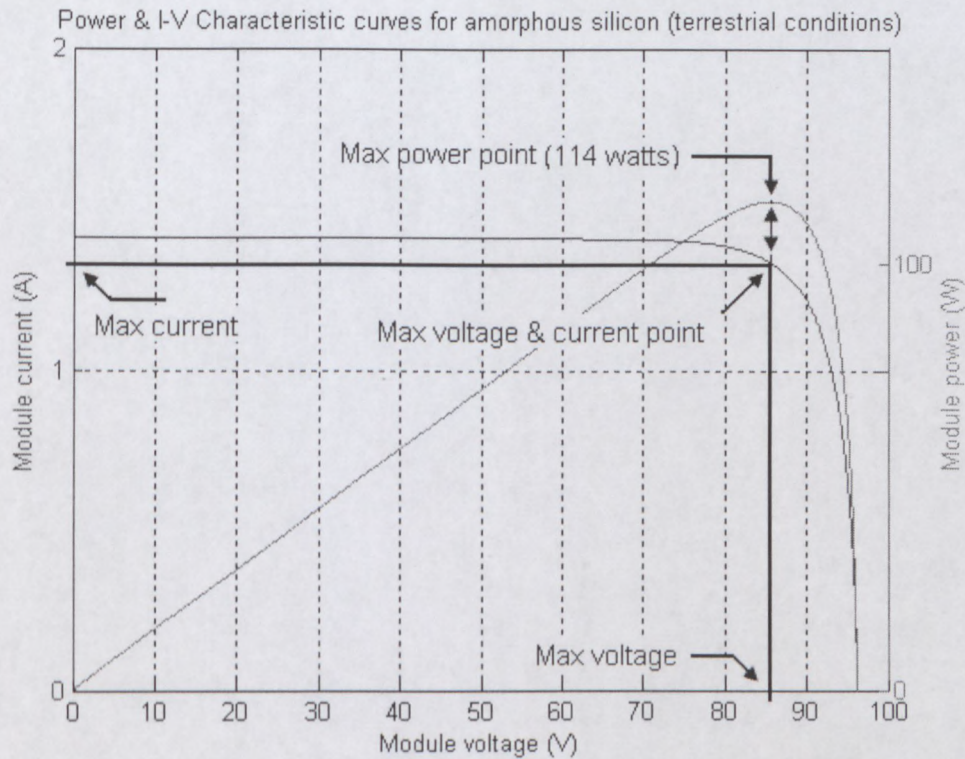


Figure 0.20 Maximum voltage, current & power points for amorphous silicon (terrestrial conditions)

5.3.4 Determination of maximum voltage and current for amorphous silicon solar cells (space conditions)

Simulation procedure is similar as for section 5.4.3 but the temperature is changed to 75C and irradiance to 1367 watts. Figures 5.21, 5.22 & 5.23 show the results of simulations. From the results it can be seen that the value for maximum power is 136 watts, maximum current is 1.88 amps and maximum voltage is 73 volts.

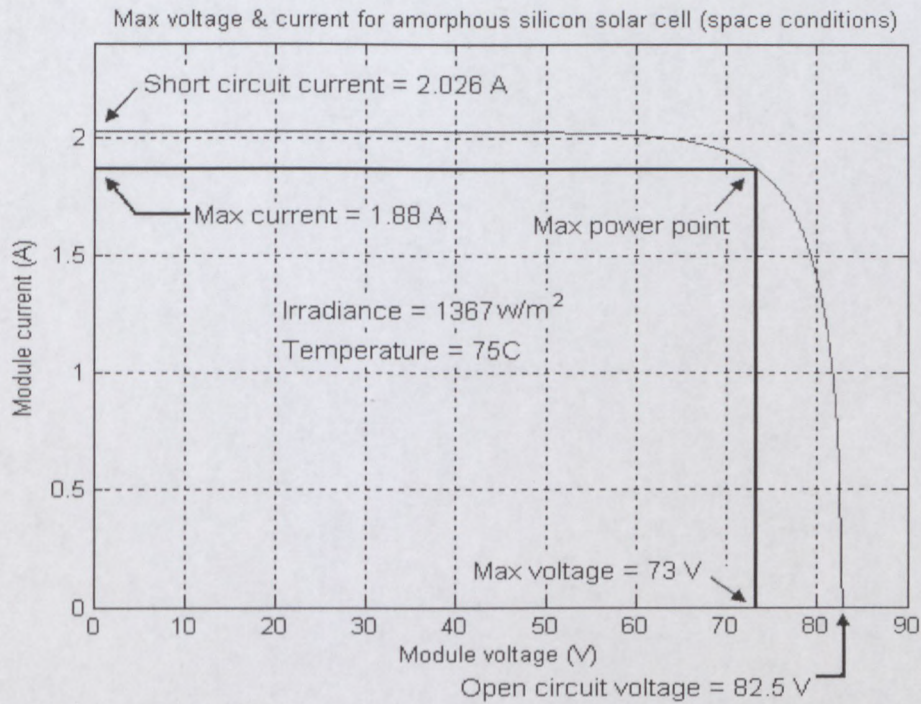


Figure 0.21 Maximum voltage & current for amorphous silicon solar cell at 75°C and 1.367suns

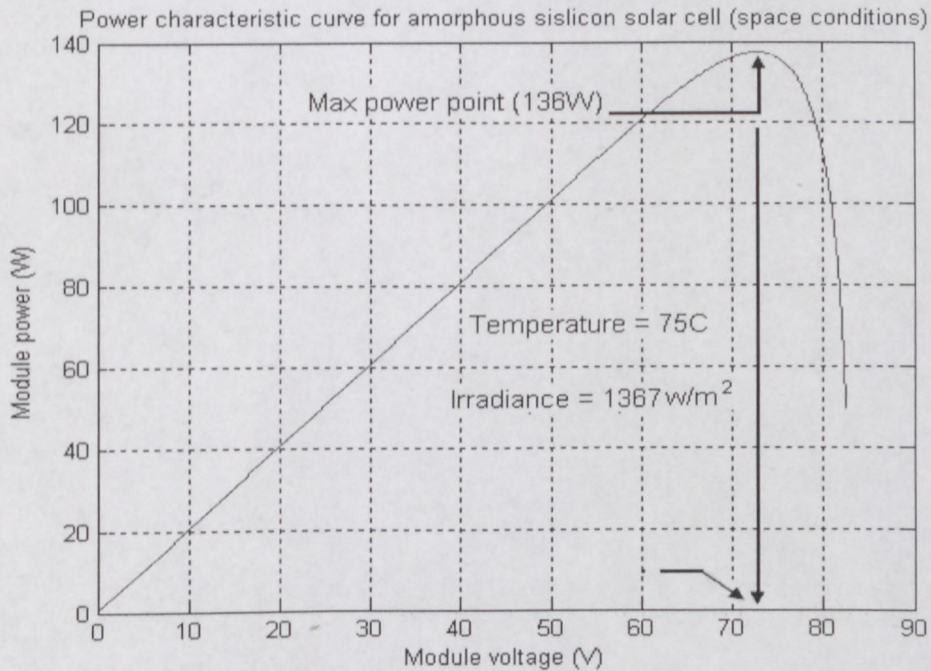


Figure 0.22 Power curve for amorphous silicon solar cell at temperature of 75°C and 1.367suns

Power & I-V Characteristic curves for amorphous silicon solar cells (space conditions)

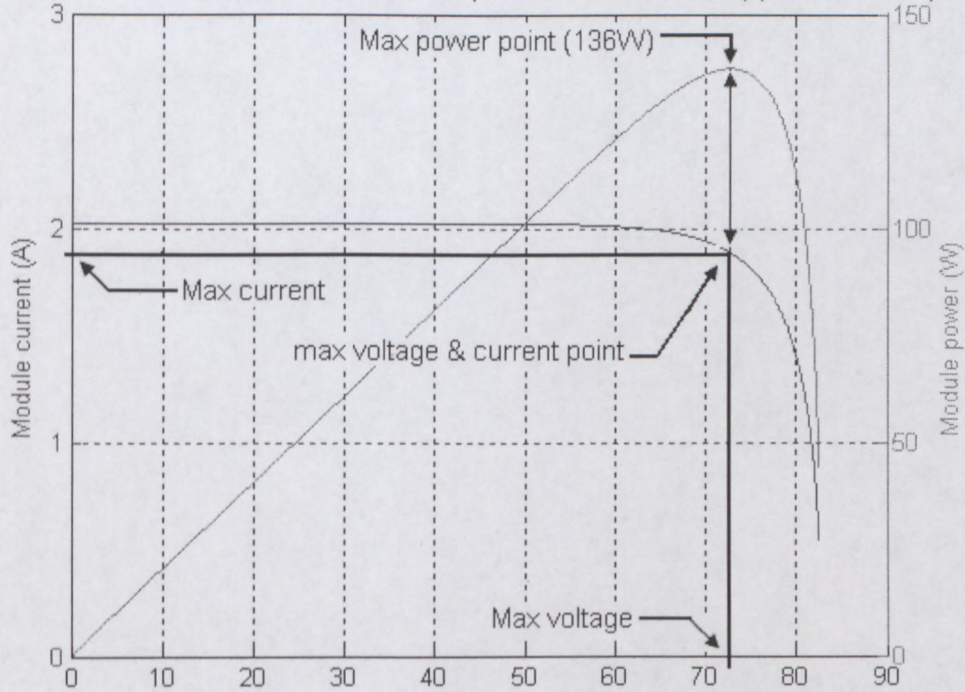


Figure 0.23 Maximum voltage, current & power for amorphous silicon (space conditions)

5.3.5 Calculation of figures of merit for amorphous silicon solar cell (space environment)

(1) Open circuit voltage per cell (V_{oc}) = $\frac{\text{Open circuit voltage}}{\text{Number of solar cells}} = \frac{82.5}{106} = 0.778 \approx 0.8 \text{ volts.}$

(2) Maximum voltage per cell (V_{Max}) = $\frac{\text{Maximum voltage}}{\text{Number of solar cells}} = \frac{73}{106} = 0.689 \text{ volts}$

(3) Short circuit current per cell (I_{sc}) = 2.026 amps

(4) Maximum current per cell (I_{Max}) = 1.88 amps

(5) Short circuit current density per cell (J_{sc}) = $\frac{\text{Short circuit current}}{\text{Total surface area of solar cells}}$

$$= \frac{2.026}{106 \times 13490 \text{ mm}^2} = \frac{2.026}{106 \times 135 \text{ cm}^2} = 0.142 \text{ mA/cm}^2$$

$$(6) \text{Cell fill factor } (FF) = \frac{\text{Max Voltage} \times \text{Max Current}}{\text{Open circuit voltage} \times \text{Short circuit current}} = \frac{0.689 \times 1.88}{0.8 \times 2.026} =$$

$$0.799 \approx 80\%$$

$$(7) \text{Cell efficiency } (\eta) = \frac{\text{Max power}}{\text{Irradiance} \times \text{Solar cell area}} \times 100 =$$

$$\frac{0.689 \times 1.88}{0.1367 \times 135} \times 100 = 7.02\%$$

Table 0.3Summary of amorphous silicon solar cell simulation results (space conditions)

V_{OC} (volts)	V_{Max} (volts)	I_{SC} (amps)	I_{Max} (amps)	J_{SC} (mA/cm ²)	FF (%)	η (%)	Cell area cm ²
0.8	0.689	2.026	1.88	0.142	80	7.02	135

5.4 Simulations with gallium arsenide solar cells

Gallium arsenide is a semiconductor material with many electrical applications. It is made from combination of elements from group 3 and five in the periodic table. Such applications include microwave and integrated circuits, laser diodes, and optical windows. It has a bandgap of 1.4 eV with a good property of absorbing light hence it is listed as one of the materials for thin-film solar cells (Kasturi, Chopra and Das, 1983, p.403). In this section, gallium arsenide cell will be studied. The solar cell parameters to be used with the general code are as follows:

1. Bandgap, $V_g = 1.4$
2. Diode ideality factor, $A = 1.3$
3. Voltage range [0:0.001:3]
4. Number of cell, $N_s = 1$
5. $V_{oc_T1} = 1.025$ Volts. (Solar panel open circuit voltage at 25°C)
6. $I_{sc_T1} = 1.495$ Amps. (Solar panel short circuit current at 25°C)
7. $V_{oc_T2} = 0.933$ Volts. (Calculated panel voltage using eqn. 8 in section 4.4 at 50°C)
8. $I_{sc_T2} = 1.568$ Amps. (Calculated panel current using eqn. 3 in section 4.4 at 50°C)

5.4.1 I-V Characteristic curve for gallium arsenide solar cells (terrestrial conditions)

Simulation conditions are set at Standard Test Conditions with illumination of 1 Kw/m² at terrestrial global air mass, AM 1.5G and a fixed temperature of 25C. Simulation is repeated as in section 5.4.3 with the general code from section 4.7 .Simulation results are as shown in figure 5.24. It can be seen from the results that under these conditions, the solar panel generates an output short circuit current of 1.49 amps and open circuit voltage of 1.025 volts.

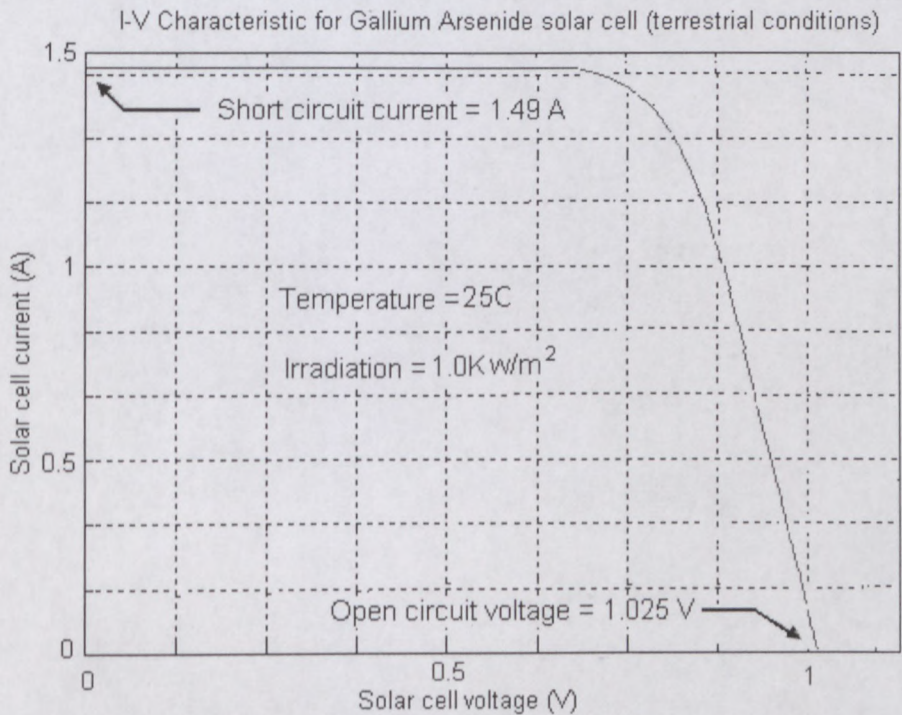


Figure 0.24 I-V curve for gallium arsenide solar cell at temperature of 25C and 1 sun

5.4.2 I-V characteristic curve for gallium arsenide solar cells (space conditions)

Simulation procedure is similar to the ones in section 5.5.1 but the conditions are set as for space environment. The temperature is set at 75 degrees and the light intensity at 1367 watts and the results are shown in figure 5.24. Comparing these results with the ones for terrestrial conditions shown in figure 5.24, it can be seen that the voltage has reduced from 1.025 to 0.87 volts while the current has increased to 1.84 amps from 1.49 amps. The voltage has dropped by 15.12 % and the short circuit current has increased

by 23.49%. This means that the combined effect of light intensity and temperature has a bigger positive effect on current than on voltage.

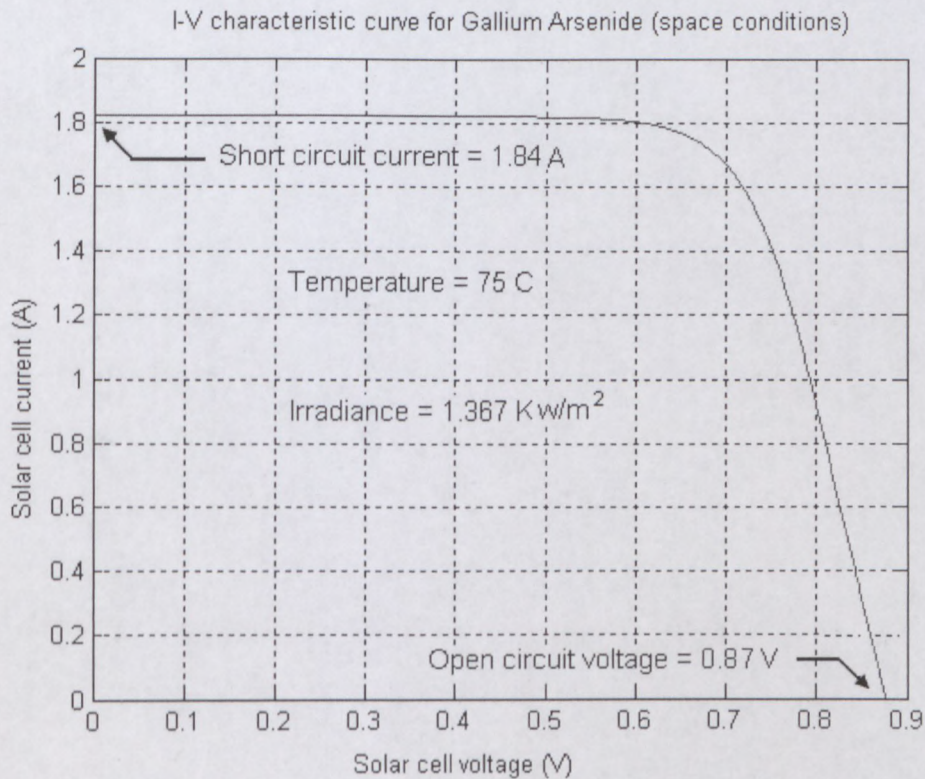


Figure 0.25 I-V curve for Gallium arsenide at temperature of 75C and 1.367 suns

5.4.3 Determination of maximum voltage and current for gallium arsenide solar cells (space conditions)

Simulation procedure is similar as for section 5.4.4 but the temperature is changed to 75C and irradiance to 1367 watts. Figures 5.26, 5.27 & 5.28 show the results of simulations. From the results it can be seen that the value for maximum power is 1.16 watts, maximum current is 1.68 amps and maximum voltage is 0.68 volts.

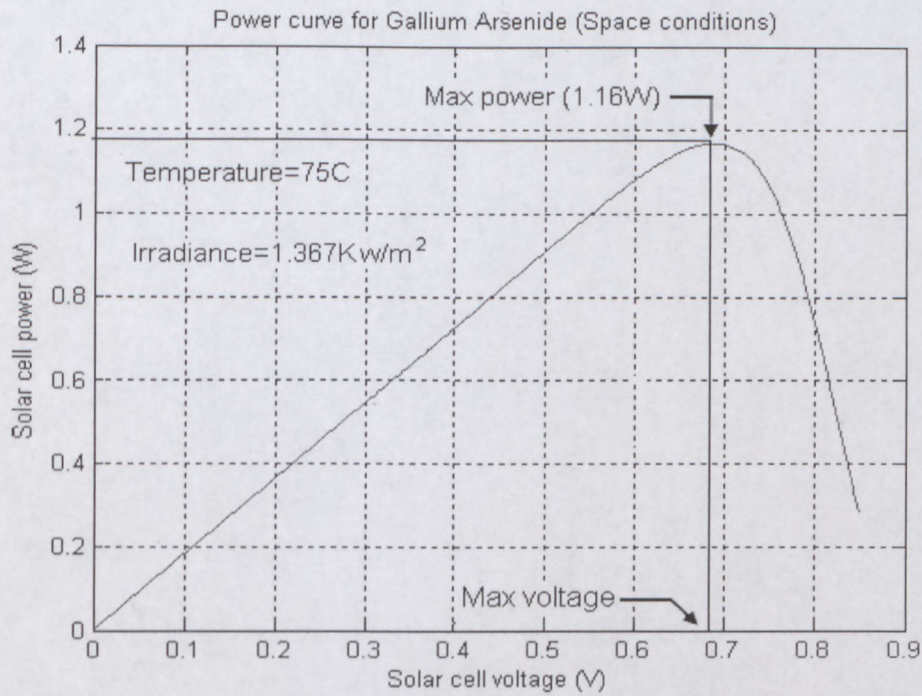


Figure 0.26 Power curve for gallium arsenide solar cell at temperature of 75C and 1.367 sun

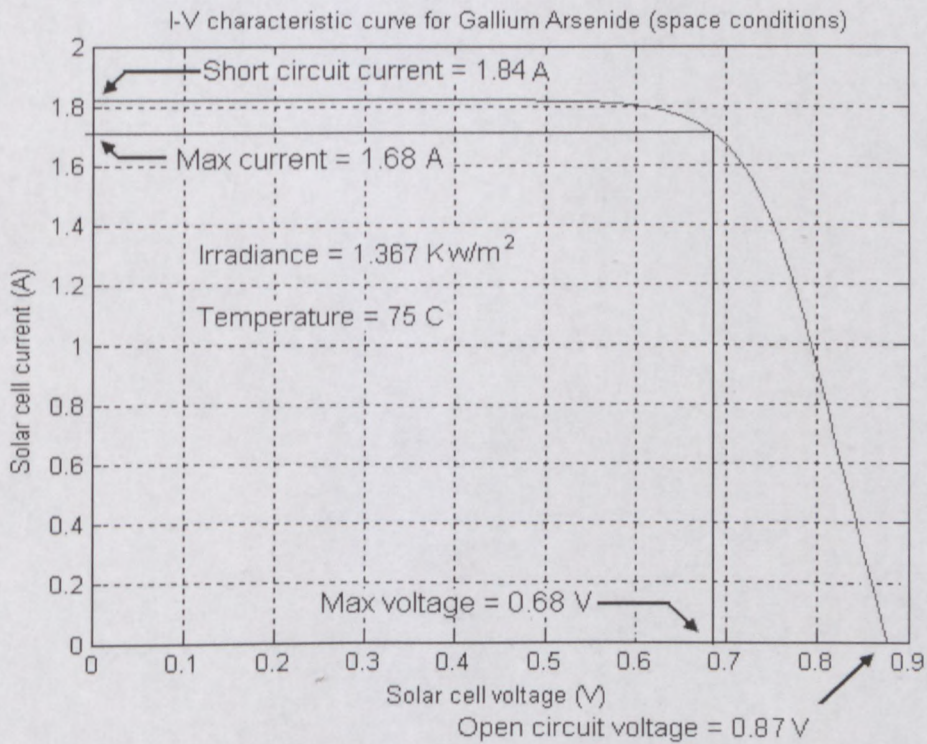


Figure 0.27 Maximum voltage & current for gallium arsenide solar cell at temperature of 75C and 1.367sun

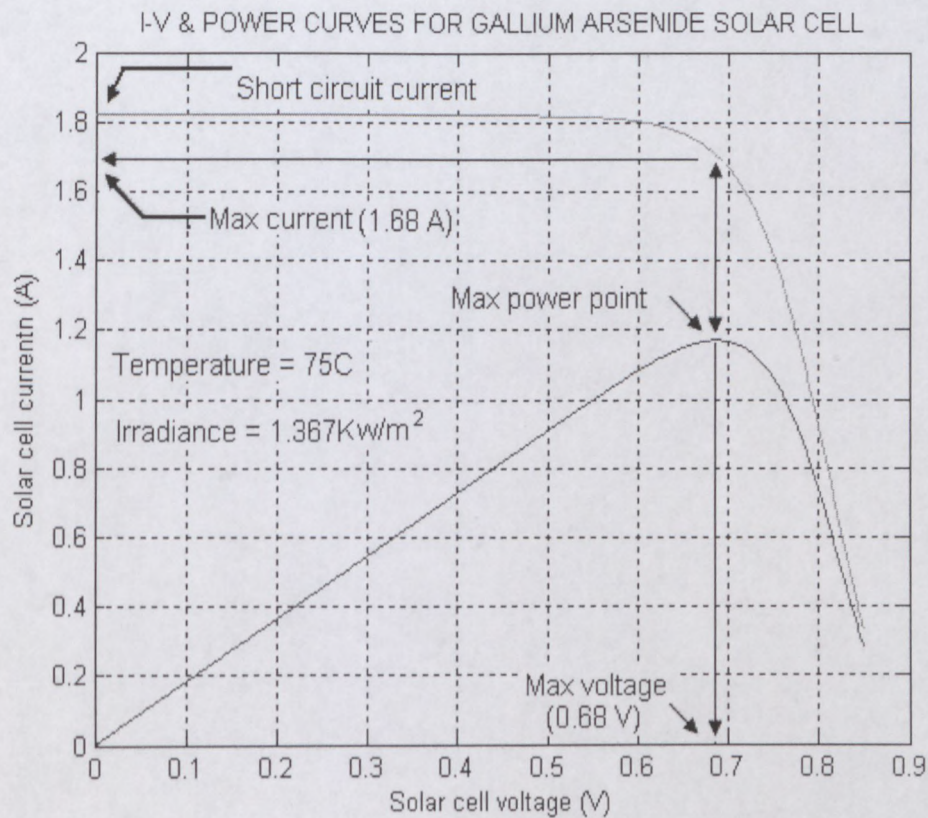


Figure 0.28 Maximum voltage, current & power for gallium arsenide solar cell (space conditions)

5.4.4 Calculation of figures of merit for gallium arsenide solar cell (space environment)

(1) Open circuit voltage per cell (V_{OC}) = $\frac{\text{Open circuit voltage}}{\text{Number of solar cells}} = \frac{0.87}{1} = 0.87 \text{ volts.}$

(2) Maximum voltage per cell (V_{Max}) = $\frac{\text{Maximum voltage}}{\text{Number of solar cells}} = \frac{0.68}{1} = 0.68 \text{ volts.}$

(3) Short circuit current per cell (I_{SC}) = 1.84 amps.

(4) Maximum current per cell (I_{Max}) = 1.68 amps.

(5) Short circuit current density per cell (J_{SC}) = $\frac{\text{Short circuit current}}{\text{Total surface area of solar cells}}$

$$= \frac{1.84}{7 \times 7 \text{ cm}^2} = 37.6 \text{ mA/cm}^2$$

$$(6) \text{ Cell fill factor} = \frac{\text{Max Voltage} \times \text{Max Current}}{\text{Open circuit voltage} \times \text{Short circuit current}} = \frac{0.68 \times 1.68}{0.87 \times 1.84} = 0.714 = 71.4 \%$$

$$(4) \text{ Cell efficiency} = \frac{\text{Max power}}{\text{Irradiance} \times \text{Solar cell area}} \times 100 = \frac{0.68 \times 1.68}{0.1367 \times 49} \times 100 = 17 \%$$

Table 0.4 Summary of gallium arsenide solar cell simulation results (space conditions)

V_{OC} (volts)	V_{Max} (volts)	I_{SC} (amps)	I_{Max} (amps)	J_{SC} (mA/cm ²)	FF (%)	η (%)	Cell area cm ²
0.87	0.68	1.84	1.68	37.6	71.4	17	49

5.5 Simulations with silicon nitride solar cells

Silicon nitride semiconductor is another high efficiency material used in thin film solar cells resulting from using silicon nitride ceramic as a substrate for crystalline silicon thin film solar cells. The material has a band gap of 5.4 eV which means it absorbs wavelengths with higher energy contents (Yu, Zhang, Ding & Fu, 2007, p.53). The solar cell parameters used with this investigation are as follows:

1. Bandgap, $V_g = 5.3 \text{ eV}$
2. Diode ideality factor, $A = 1.5$
3. Voltage range [0:0.01:40]
4. Number of cell, $N_s = 36$
5. $V_{oc_T1} = 22 \text{ V}$. (Solar panel open circuit voltage at 25°C)
6. $I_{sc_T1} = 8.1 \text{ A}$. (Solar panel short circuit current at 25°C)
7. $V_{oc_T2} = 18 \text{ V}$. (Calculated panel voltage using equation 8 in section 4.4 at 50°C)
8. $I_{sc_T2} = 8.363 \text{ A}$. (Calculated panel current using equation 3 in section 4.4 at 50°C)

5.5.1 I-V Characteristic curve for silicon nitride solar cells (terrestrial conditions)

Simulation conditions are set at Standard Test Conditions with irradiance of 1 Kw/m² (1 sun) at terrestrial global air mass, AM 1.5G and a fixed temperature of 25C. Simulation is repeated as for other cell with the general code from section 4.7 and the results are as shown in figure 5.29. It can be seen from the results that under these conditions, the

solar panel generates an output short circuit current of 8.1 amps and open circuit voltage of 22 volts. These values are similar to the ones quoted by the manufacturer when the panel is operating at its normal operating conditions.

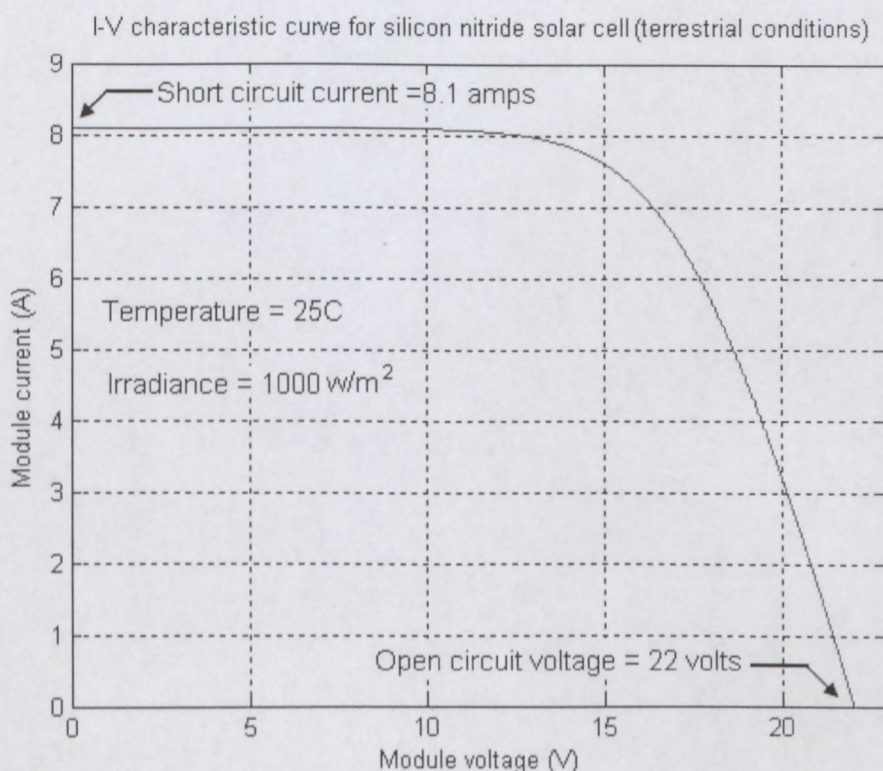


Figure 0.29 I-V curve for silicon nitride solar cell at temperature of 25C and 1 sun

5.5.2 I-V characteristic curve for silicon nitride solar cells (space conditions)

Simulation conditions are set as for space environment. The temperature is set at 75 degrees and the light intensity at 1367 watts. Simulation procedure is the same as for section 5.6.1 and the result is as shown in figure 5.30. Comparing these results with the ones for terrestrial conditions shown in figure 5.29, it can be seen that the voltage has reduced from 22 to 15.2 volts while the current has increased to 11.4 amps from 8.1 amps. The voltage has dropped by 18.18 % and the short circuit current has increased by 40.74%. Again, this shows that the combined effect of light intensity and temperature has a bigger positive effect on current than on voltage.

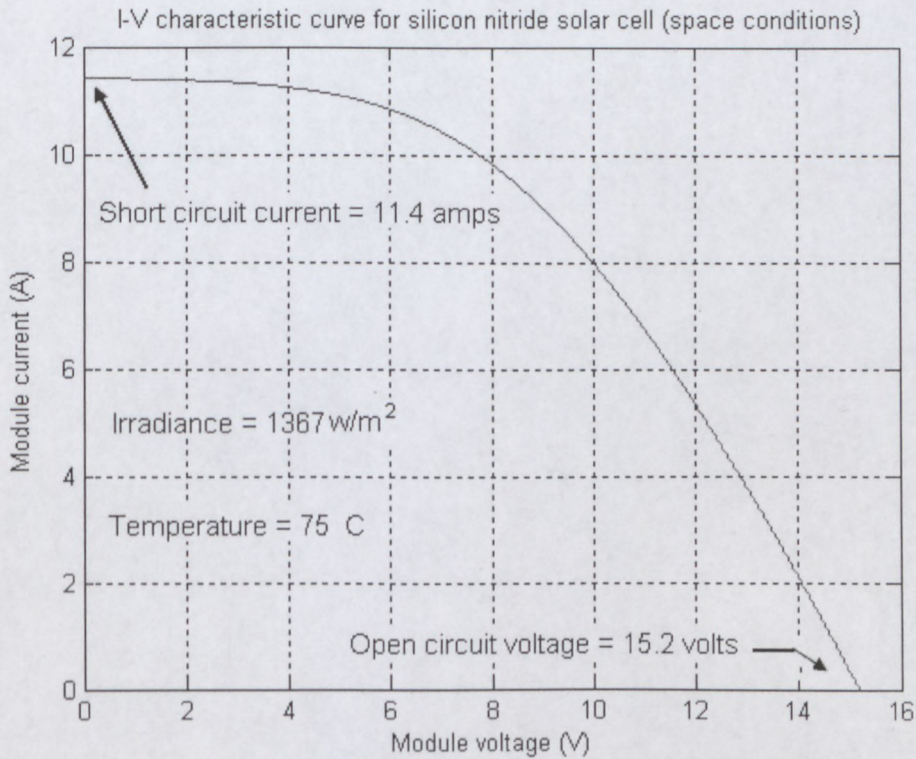


Figure 0.30 I-V curve for silicon nitride solar cell at temperature of 75°C and 1.367 suns

5.5.3 Determination of maximum voltage and current for silicon nitride solar cells (space conditions)

Simulation procedure and conditions is similar as for section 5.5.3. Figures 5.30, 5.31 & 5.32 show the results of simulations. From the results it can be seen that the value for maximum power is 1.16 watts, maximum current is 1.68 amps and maximum voltage is 0.68 volts.

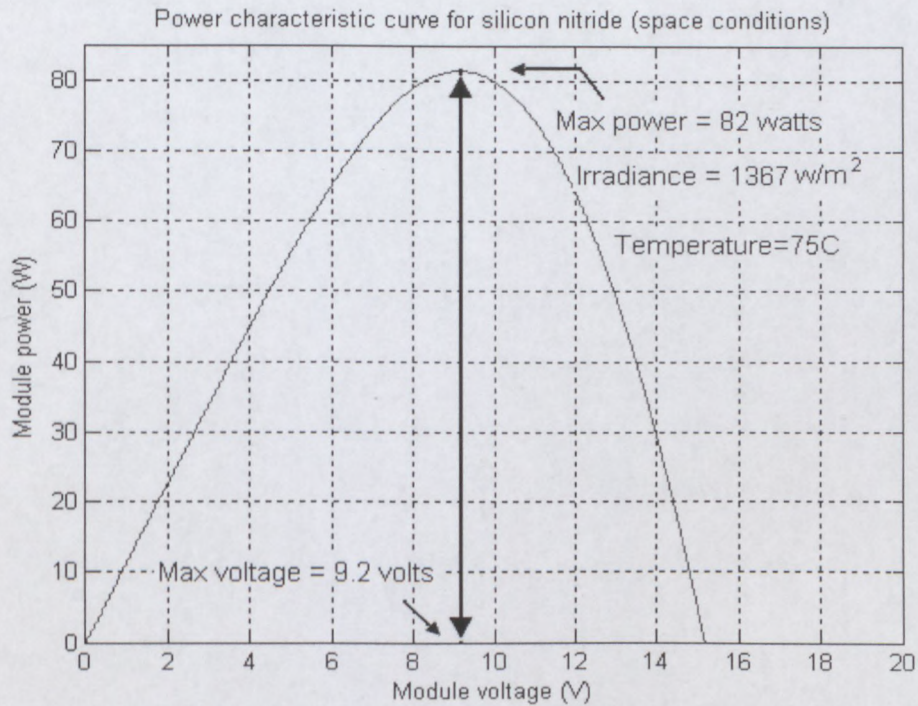


Figure 0.31 Power curve for silicon nitride solar cell at temperature of 75°C and 1.367 sun

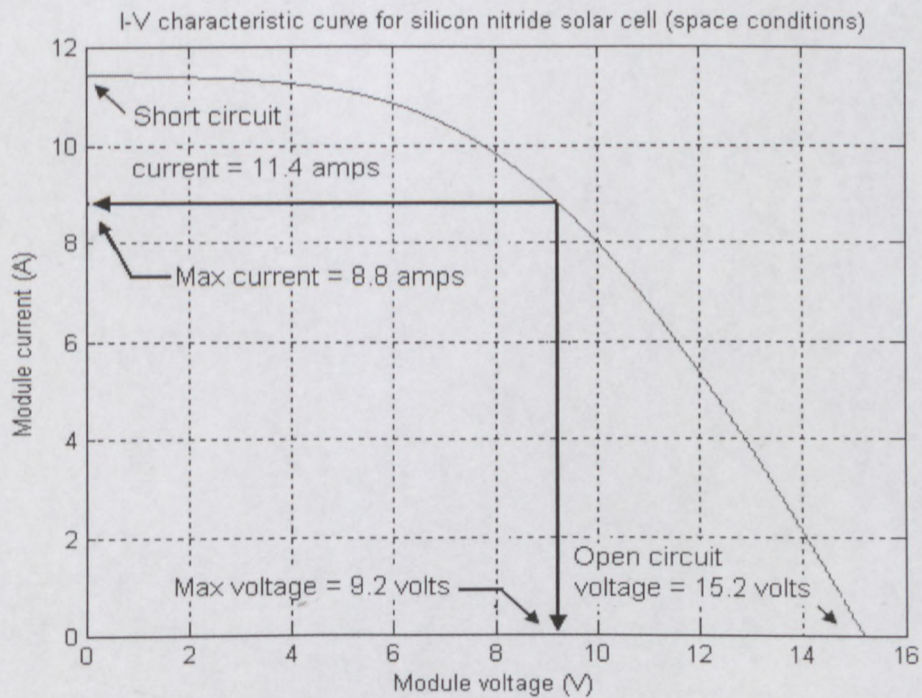


Figure 0.32 Maximum voltage and current for silicon nitride solar cells at 75°C and 1.367sun

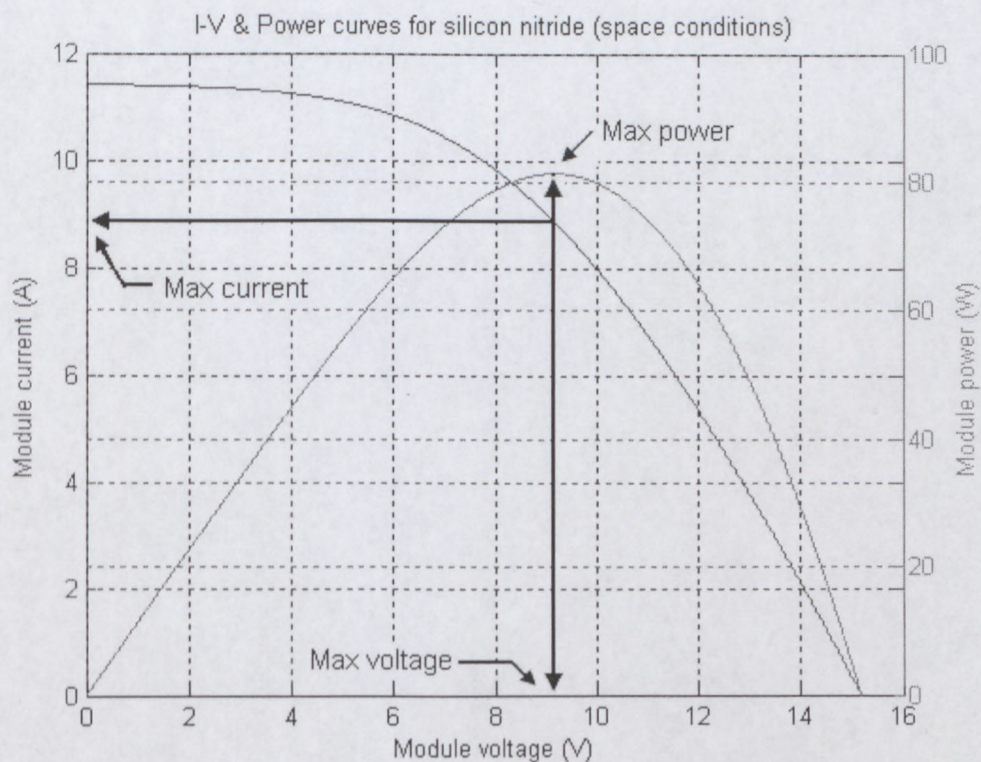


Figure 0.33 Maximum voltage, current & power for silicon nitride solar cells (space conditions)

5.5.4 Calculation of figures of merit for silicon nitride solar cell (space environment)

(1) Open circuit voltage per cell (V_{oc}) = $\frac{\text{Open circuit voltage}}{\text{Number of solar cells}} = \frac{15.2}{36} = 0.422$ volts.

(2) Maximum voltage per cell (V_{Max}) = $\frac{\text{Maximum voltage}}{\text{Number of solar cells}} = \frac{9.2}{36} = 0.256$ volts.

(3) Short circuit current per cell (I_{sc}) = 11.4 amps.

(4) Maximum current per cell (I_{Max}) = 8.8 amps.

(5) Short circuit current density per cell (J_{sc}) = $\frac{\text{Total short circuit current}}{\text{Total surface area of solar cells}}$

$$= \frac{11.4}{156\text{mm} \times 156\text{mm} \times 36} = \frac{11.4}{15.6\text{cm} \times 15.6\text{cm} \times 36} = 1.3 \text{ mA/cm}^2$$

(6) Cell fill factor = $\frac{Max\ Voltage \times Max\ Current}{Open\ circuit\ voltage \times Short\ circuit\ current} = \frac{0.256 \times 8.8}{0.422 \times 11.4} = 0.467 = 46.7\%$

(7) Cell efficiency = $\frac{Max\ power}{Irradiance \times Solar\ cell\ area} \times 100 = \frac{0.256 \times 8.8}{0.1367 \times 15.6 \times 15.6} \times 100 = 6.76\%$

Table 5.5 Results summary for silicon nitride solar panel with space conditions.

V_{OC} (volts)	V_{Max} (volts)	I_{SC} (amps)	I_{Max} (amps)	J_{SC} (mA/cm^2)	FF (%)	η (%)	Cell area (cm^2)
0.422	0.256	11.4	8.8	1.3	46.7	6.76	243.36

Table 0.5 Results summary of all simulated solar panels.

Cell Parameters	CIGS	CdTe	a-Si	GaAs	SiN
Cell voltage, V_{OC} (volts)	0.4	0.659	0.8	0.87	0.422
Cell maximum voltage, V_{Max} (volts)	0.271	0.573	0.689	0.68	0.256
Cell current, I_{SC} (amps)	9.2	1.719	2.026	1.84	11.4
Cell maximum current, I_{Max} (amps)	7.7	1.62	1.88	1.68	8.8
Cell current density, J_{SC} (mA/cm^2)	0.608	0.239	0.142	37.6	1.3
Cell fill factor, FF (%)	59.9	81.9	80	71.4	46.7
Cell efficiency, η (%)	7.26	11	7.02	17	6.76
Cell area, (cm^2)	210	62.06	135	49	243.36
Cell bandgap (eV)	1.5	1.44	1.7	1.4	5.3

5.6 Conclusion

In this chapter, behaviors of five different types of solar cells were investigated with different environmental conditions. Figures of merit for each type of cell such as open circuit voltage, short circuit current, etc were calculated and tabled. These parameters will be used in the next chapter for designing a multi-junction solar cell required for developing a space solar panel.

CHAPTER SIX DESIGNING OF MULTIJUNCTION SOLAR CELL AND DEVELOPMENT OF SOLAR PANEL

6.1 Introduction

This chapter will describe the method used to design the multi-junction solar cell that is used to develop the solar panel for this thesis. Multi-junction cell can be fabricated in one of the two ways that is monolithic or mechanically stacked. These cells are made of different semiconductor layers (layers) of epitaxially deposited films to efficiently absorb and convert a wider range of light wavelengths to electrical energy. Commercialized cells currently utilize tandem connection where the different semiconductor layers are connected in series through a tunnel diode. Tunnel diodes are used to provide a low electrical resistance and optically low-loss connection between two sub cells (Yamaguchi, Taka Moto, Araki, 2006, p.3070). Tandem connection has a major disadvantage due to current limitation. The individual layer currents have to be the same otherwise the efficiency will suffer. The multi-junction solar cell for this thesis will use parallel connection to overcome the above mentioned problems.

6.2 Solar panel Module

Solar cell panels consist of a number of individual solar cells usually connected in series to increase the voltage and power above that of a single cell. Most solar panels voltages are chosen to be compatible and to be able to charge a 12 or 24V battery. For this project, the solar panel will be designed to produce a voltage and current to support a satellite load requiring 9 volts and 6 watts. The solar panel output voltage depends on the number of series connected cells while the output current depends on the number solar cell strings in parallel.

6.3 Basic rules for designing a multi-junction solar cell

Designing of multi-junction solar cells is a complicated process due to the need to obtain both maximum efficiency from each junction layer and to match the current produced by each layer under optical load conditions. The following are some of the basic rules to be observed when designing a multi-junction solar cell.

- The different stacked semiconductor layers to be used must be arranged in descending order of bandgaps so as to enhance light spectrum absorption.

- The current passing through each semiconductor layer connected in series must be the same (matched) to avoid straining.
- The thickness of semiconductor layers must be of the order to allow for both light transparency and absorption.
- The area size of the semiconductor layers to be stuck upon another must be the same.

The design of this multi-junction cell will use a parallel mode of connection for the different semiconductor materials to allow for maximum output current.

6.4 Selection of material for designing the multi-junction solar cell

The multi-junction solar cell will be designed from a combination of three types of semiconductor materials. These three materials are selected from the solar cell simulation results in table 5.6, in terms of appropriate bandgap and best efficiency. As can be seen from the table, gallium arsenide has a bandgap of 1.4eV with an efficiency of 17% while cadmium telluride has a bandgap of 1.44eV with an efficiency of 11%. The two solar cells have almost the same bandgaps but since gallium has a higher efficiency, it is selected as the first material of choice for the design. The next selection will be copper indium gallium selenide material with an efficiency of 7.5% and an appropriate bandgap of 1.5eV. The third choice is decided between amorphous silicon and silicon nitride where amorphous is selected due to its high efficiency of 7.02% and its bandgap of 1.7eV.

6.5 Designing the multi-junction solar cell

The semiconductor solar cell materials which have been selected for the design will be connected in parallel and stack in layer form one upon the other in descending order of their bandgaps. The design rules requires that all the semiconductor layers that will be connected in parallel must have the same cross sectional area and so should be their terminal voltages. Comparing the voltages and sizes for the three materials, gallium arsenide has a terminal voltage of 0.9volts and an area size of 49 cm², copper indium gallium selenide (CIGS) has a terminal voltage of 0.4volts and area of 210 cm², while amorphous silicon has a terminal voltage of 0.8volts and an area of 135 cm². To come up with a properly working multi-junction solar cell from the three different materials, the connections must satisfy the voltage and area rule stated above. Since the CIGS cell has the lowest voltage of 0.4 volts, it can easily be raised to 0.8 volts by connecting two of

them in series. It will now be realized that out of the three cells, gallium cell has slightly exceeded the other two by only 0.1 volt and therefore, for this design, the terminal voltages will all be assumed to be 0.8volts. The three types of cells can now be connected in parallel as drawn in figure 6.1.

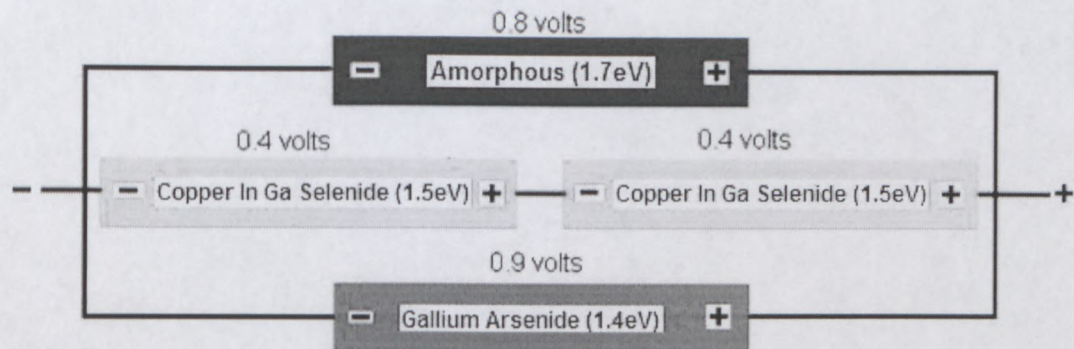


Figure 19.1 Parallel connection of three types of solar cell materials

The next thing to follow for the design is to make sure that the effective areas for all the solar cells in each parallel connection is the same as this is a requirement before the cell layers can be stack one upon the other. This means that if the size of one type of solar cell is used as reference, the other solar cell sizes will have to be changed. Output current from a solar cell is directly proportional to its surface area and the light intensity it receives (Calvin, 2010, p.118).Increasing solar cell area increases its light capturing effect which is equivalent to increasing light intensity. This means that altering solar sizes will affect their output currents.

Looking at the above combination, two cigs cells are used which make up a total area of 420 cm², while amorphous and gallium will have areas of 135 cm² and 49 cm² respectively. One way of reducing solar cell cost of production is to reduce the amount of construction material used by reducing solar cell sizes. For this reason, the 49 cm² will be taken as the base area for all the cells to be used in the design. From table 5.6, it can be seen that cigs has an output current of 9.2 amps, amorphous silicon has an output current of 2.026 amps and gallium has 1.84 amps. Changing cigs solar cell area from 420 cm² to 49 cm² will reduce the output current to $9.2 \times (49/420) = 1.073$ amps and amorphous will reduce to $2.026 \times (49/135) = 0.735$ amps and the contribution by the gallium cell will not change but remain at 1.84 amps. The total output current of the three solar cell connected in parallel will be 3.648 amps. The two cigs cell must be arranged

side by side to cover an area of 49 cm^2 . Figure 6.2 shows the arrangement of the three types of solar cells in a multi-junction showing their effective areas while figure 6.3 shows the parallel connections of the cells together with their total output current.

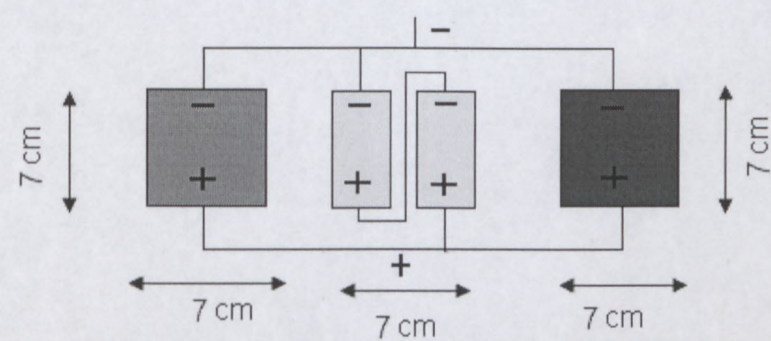
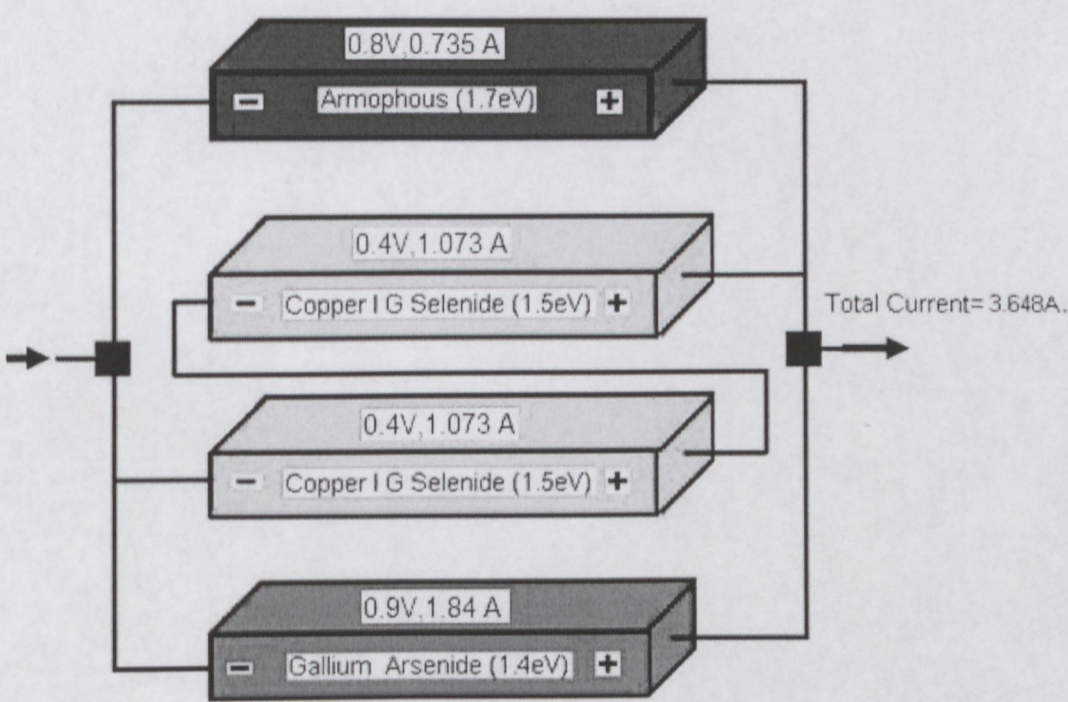


Figure 19.2 Parallel connection of solar



cells with same cross sectional area

Figure 19.3 Multi-junction solar cell arrangement showing currents and voltage values

6.6 Stacking and blocking diode connection for the multi-junction cell

The next thing to accomplish in the design is to connect diodes in series with the individual solar cells to prevent damage and to use transparent semiconductor insulators to isolate the parallel semiconductor layers. The individual solar cells in the multi-junction cell should be prevented from reverse biasing or changing one another which can easily occur if there is any slight difference in their individual terminal voltages. Multi-junction cells are very sensitive to reverse bias and can easily get damaged. To avoid such a problem from occurring, blocking diodes are usually connected in series with the solar cells within the multi-junction cell (Markvart & Castaner, 2003, p.526). After this is done, insulation of parallel cell layers must be made using a proper pure transparent semiconductor insulator. Germanium semiconductor material in its pure form can provide for a suitable insulation and can also be used as a base for epitaxial growth of the different solar cells in the multi-junction (Umicore, 2009). Figure 6.4 shows the final product of the multi-junction solar cell with blocking diodes together with its symbol.

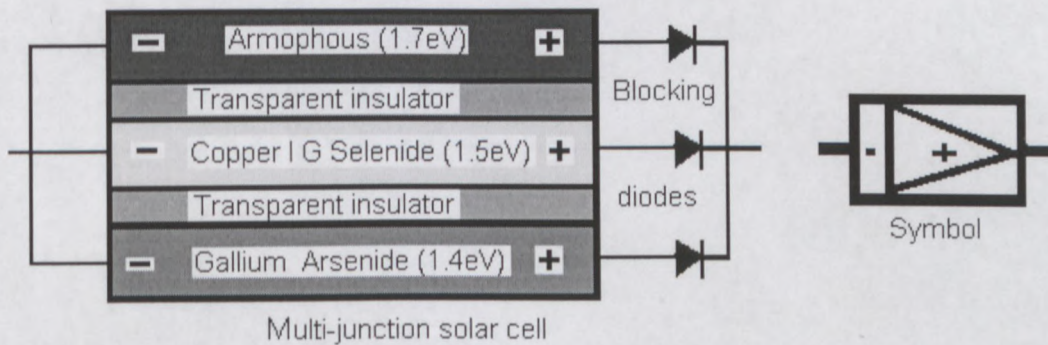


Figure 19.4 Multi-junction solar cell with its symbol

6.7 Estimation of the multi-junction solar cell efficiency

The total efficiency of the multi-junction solar cell can be estimated from the algebraic addition of individual solar cell efficiencies as they represent the percentage of sunlight energy they each convert to electricity from the 1367 watt photon package in space. Reading from table 5.6, the efficiencies for amorphous, copper indium gallium arsenide and gallium arsenide are 7.02%, 7.26% and 17% respectively amounting to 31.28%. This value can be verified from the following calculations.

Solar cell efficiency is equal to:-

$$\eta = \frac{V_{MAX} \times I_{MAX}}{Irradiance \times Cell\ area} \times 100 = \frac{FF \times V_{OC} \times I_{SC}}{Irradiance \times Cell\ area} \times 100$$

Where, $V_{oc}=0.8\text{ V}$, $I_{sc}=3.564$, $Irradiance = 1367\text{watts per } m^2$, $Cell\ area = 49\text{ cm}^2$ and fill factor, FF is the average of the three individual cell fill factors. The average of fill factor is 70.4%. Therefore, the multi-junction solar cell efficiency is:-

$$\eta = \frac{0.704 \times 0.8 \times 3.648}{0.1367 \times 49} \times 100 = 30.6\%.$$

For this multi-junction solar cell design, the parameters can be specified as

$V_{oc}=0.8\text{ V}$, $I_{sc}=3.648\text{A}$, $Cell\ area = 49\text{ cm}^2$ and efficiency $\approx 31\%$.

6.8 Developing space solar panel

A solar panel is a complete set up of a number of solar cells inter-connected in series and encapsulated in a frame work for stability and long lasting. Most solar panels are designed to charge standard battery sizes of 12 and 24 volts. Solar panels can be connected in series or parallel depending on the power and voltage required by a particular load.

- Substrate selection
- Calculating the number of cells in series
- Cell interconnections and layout
- Cell protection and covering

6.9 Substrate selection

A substrate is the material on which the solar cells will be laid on to form the solar panel. Selection of a suitable substrate material especially for thin solar cells is very important as this also serves as a means of heat transfer for cooling the cells. The solar panel is supposed to be as light as possible since the weight of cube satellite itself is not going to be more than 3 kilograms. The substrate that will be used for this panel will be a flexible stainless steel sheets since they have a good thermal conductivity and also it is easier to do what is called "roll to roll" deposition than deposition on fragile and heavy glass sheet substrate (Castellano, 2010, p.87). To increase mechanical rigidity and stability, the substrate can be pasted on a light aluminum sheet.

6.10 Number of cells in series

The requirement of this solar panel is that it should be able to charge a battery which will support a satellite load requiring an input of 9 volts and 6 watts. From basic battery charging principles, a battery charger has a higher output voltage than that of the battery

it is charging. This means that our solar panel should have an output voltage slightly higher than 9 volts. In most cases, solar panels for charging 12 volts batteries are rated between 14 to 16 volts, which means the panel should produce a voltage of between 16% and 25% more compared to the battery voltage. Using this percentage ratio, the solar panel output voltage will be designed to be 12 volts. Since the multi-junction solar cell which has been designed above has an output voltage of only 0.8volts, then it means we will require 15 cells in series.

6.11 Cell bypass diode inter-connection

Solar cells in a panel can be connected in any desirable manner, but since our multi-junction is rectangular in nature and the calculated number of the cells is 12, the shape of our solar panel will be rectangular. The cells will be laid in a pattern of 5 x 3 with each positive of one cell connected to the negative of the other cell. After this is done bypass diodes will be connected in parallel with each solar cell but with opposite polarity. Bypass diodes prevents any bad or shadowed solar cells from acting as loads for healthy cells and becoming a source of heat, a phenomenon known as "hot spot".

6.12 Cell protection and covering

Solar cells must be protected against hazards such as rain fall, chemicals, dust, etc for terrestrial solar panels and high ionizing radiation, atomic oxygen, micrometeoroids and manmade debris for space solar panels. Several types of protections encapsulants which must be transparent to light are available, but for this design, Ethylene Vinyl Acetate will be used for back encapsulation and a tempered glass will be used for front coverage. Anti-reflection coating must then be applied which is used to increase the solar cell efficiency by reducing light reflection. Original idea was to design a 6 watt solar panel with an output of 9 volts. From the design work, the multi-junction solar arrived gives a voltage output of 0.8v with a current output of 3.648amps. Because of the reduction effects of temperature on terminal voltage, the design voltage has to be more than 9 volts to take care of reduction. The high voltage value used with the solar cell high output current is responsible for the high power obtained (44 watts). It is possible to re-design the project to get the low power of 6 watts but this will be at an expense of reducing efficiency and it will also be not economical. Figure 6.5 show a series arrangement of multi-junction solar cells forming a complete solar panel.

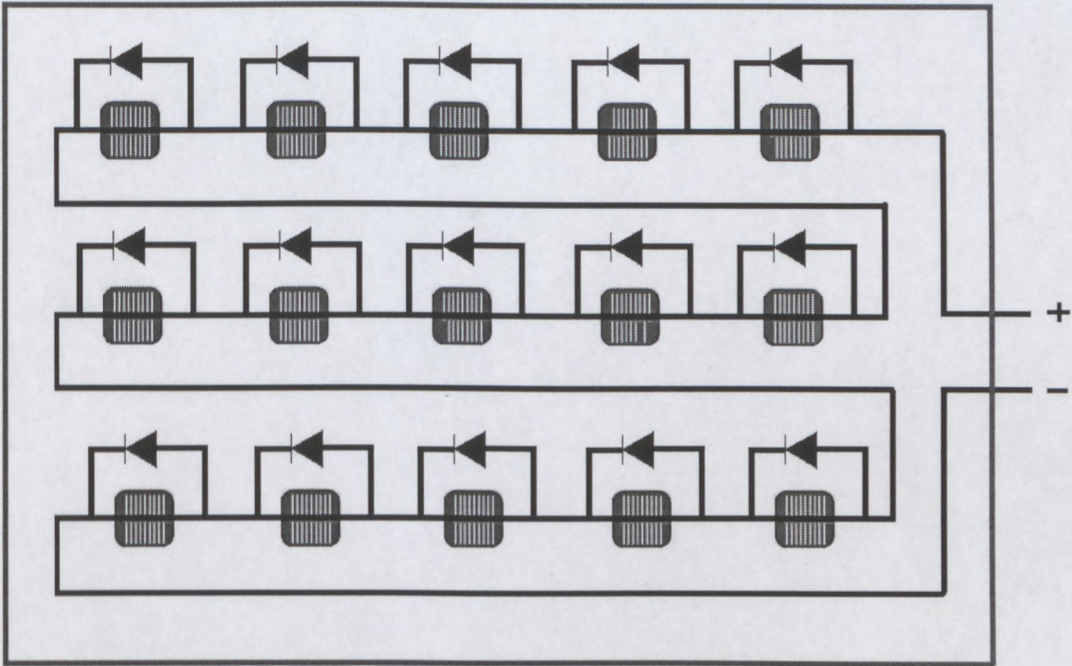


Figure 19.5 A solar panel made from multi-junction solar cells

6.13 Solar panel application and specifications

The individual cells making up the solar panel are designed from simulation results with space conditions. The current and voltage of each cell is what will be produced in space environment. The rated output voltage is 12 volts with an output current of 3.648. To use this solar panel to power or charge a load of 9 volts and 6 watts, voltage regulators and current limiters must be used. The table below shows the electrical specifications of the solar panel derived from simulation results.

Table 19.1Space solar panel electrical parameters

Solar panel parameter	Variable	Value
Short circuit current	I_{sc}	3.648 A
Open circuit voltage	V_{oc}	12 V
Cell area	A	4.9cm ²
Efficiency	η	31%
Number of cells connected in series	N_s	15
Nominal operating cell temperature	NOCT	75C
Total solar panel area	P_A	735cm ²

6.14 Comparison against TE 2000 solar panel

Tenesol solar panel is made from a series connection of 54 multi crystalline solar cells with an output of 220 watts. The individual solar cells measures 156mm X 156mm each and are laid on a panel area of 100 cm x 150cm = 15,000cm². For this model, it can be assumed that it requires an area of 15,000cm² to generate 220 watts. Figure 6.2 shows a picture of the solar panel model TE 2000 manufactured by Tenesol photovoltaic company (Tenesol -TE 2000, 2008).

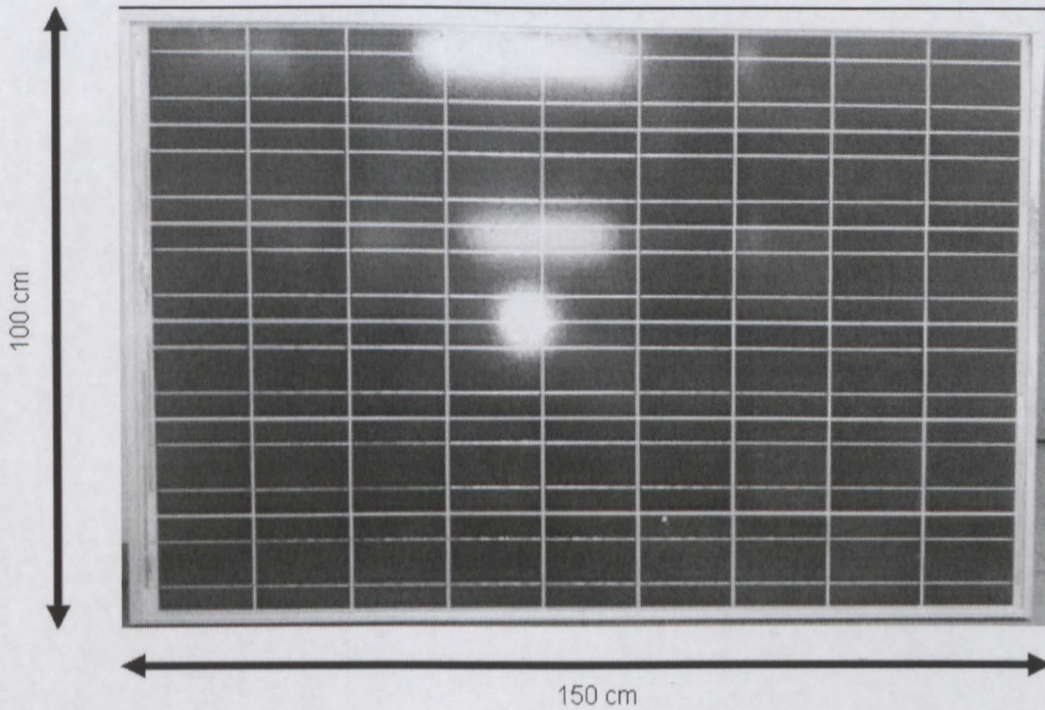


Figure 19.6 Tenesol solar panel

Tenesol solar panel model-TE 2000

The multi-junction solar panel that has been developed in this thesis has a series connection of 15 cells each measuring 7cm X 7cm giving a total coverage area of about 735 cm². If we include 2cm on each side to cover for frame work, the total area of the solar panel will be 851cm². The output voltage from this panel is 12 volts with an approximate power output of 44 watts. To equate this power to the one generated by the tenesol solar panel, it means that five multi-junction solar panels (44 x 5 = 220) must be connected either in series or in parallel. When these five multi-junction solar panels are connected together, they will cover a total area of 4255 cm² (851 x 5). For comparison

purposes, we will assumed that the five solar panels are assembled in a square frame work of 65cm x 65cm. The two types solar panels can now be compared in terms of sizes as shown in the picture of Figure 6.3.

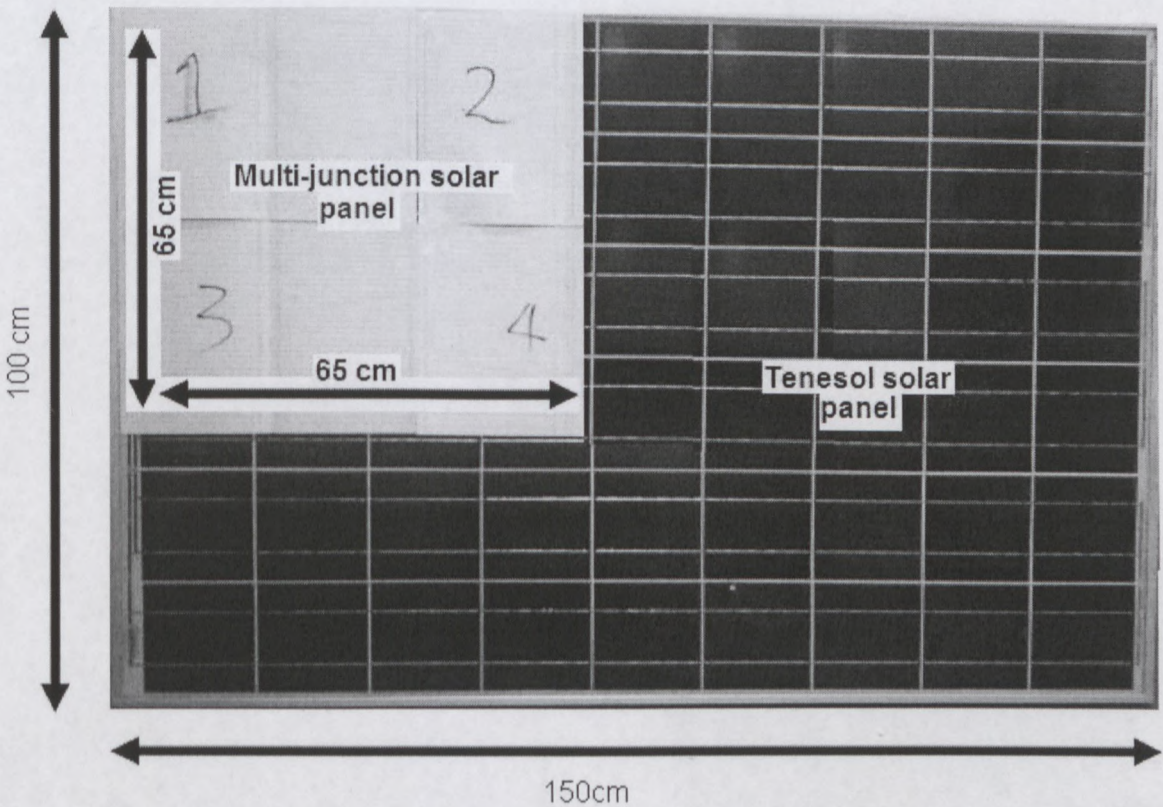


Figure 19.7 Comparison of Tenesol solar panel with multi-junction solar panel

Table 6.2 Comparison of Tenesol solar panel with developed Multi-junction solar panel

	Tenesol solar panel	Multi-junction solar panel
Area (To produce same power)	100 x150 cm	65 x65 cm
Weight	Heavier	Lighter
Size	Bigger (almost 4 times)	Smaller
Portability	Not portable	Portable
Out power	220 watts	44 watts

This comparison is further explained in the following section.

As can be seen from the comparison, the multi-junction solar panel takes a third of the area taken by the tenesol solar panel to generate the same power of 220watts.From

here we can see that the multi-junction solar panel that has been developed has several advantages compared to the tenesol solar panel :-

- The multi-junction solar panel requires a fraction of the area taken by tenesol panel to generate the same power. In terms of percentage, it is the same as $\frac{4255 \times 100}{15000} = 28.4\%$.
- The multi-junction solar panel is lighter as less frame work material is used.
- As the multi-junction solar panel is very small and light, it can easily be carried around as a portable source of power and also makes it a suitable choice for powering cube satellites.

6.15 Conclusion

This chapter discussed the various requirements for designing a multi-junction solar cell up to the connection of the cells to make a complete solar panel. The multi-junction solar cell was developed from a combination of three types of solar cells whose technology is already known and advanced which gives us an advantage of reduced design costs. The conditions considered during the entire design of the multi-junction solar cell are all for space and hence the solar panel is suitable for space work. The power for the multi-junction solar cell arrived at after the design work is higher than the one stated in the objectives. Taking advantage the extra power, the solar panel can be used with satellites requiring big power than the one designed for. The chapter has also discussed and presented a number of advantages found with the developed solar panel. The developed solar panel has the major requirements of a satellite solar panel since it small, light and delivers big power compared to other types of solar cells of the same size.

CHAPTER SEVEN CONCLUSION AND RECOMMENDATIONS

7.1 Summary

The main focus of this thesis has been to design a solar panel based on the multi-junction solar cell for low earth orbit and high altitude applications. Solar cells are p-n semiconductor devices which convert light energy to electrical energy by photovoltaic process. The most prevailing drawback with solar cells is the low light energy conversion efficiency. Majority of solar cells and panels in the market are silicon based and use single junction technology. The disadvantage with single junction technology is that the p-n junction is made of a single type of solar cell material which absorbs a very small fraction of light wavelength from the light spectrum. Sun light contains energy packets called photons. The energy in the photons is distributed in wavelengths from roughly 400nm to 800nm. The lower wavelengths contain higher energy values than the higher wavelengths. The amount of electricity generated by a solar cell depends on the wavelength it absorbs. Since single junction solar cells absorb only a small fraction of the wavelengths, most of the light energy is wasted as heat and hence the lower cell efficiency.

One way to go around the problem of efficiency is to use multi-junction solar cells. Multi-junction solar cells are designed to absorb a large fraction of the light spectrum and convert them to electrical energy which means less light energy is wasted as heat. The multi-junction solar cell design described in this thesis employs common semiconductor materials whose production technology has already been advanced giving us an advantage of reduced design cost. The development of this multi-junction solar cell was organized in chapter form. Chapter one discussed the general thesis pre-requisites such as the background information where the need for satellites and how they are powered was explained. The chapter also explained the statement of research problem, research questions, objectives and delineation. Chapter one further explained the significance of the research and concluded with how the thesis is arranged in chapter form. Chapter two generally discussed the literature review relevant to the research and how the review was organized. In this chapter, advantages and disadvantages of using solar energy compared to other sources of electrical energy was explained. The chapter concluded by mentioning types and applications of satellites. Chapter three dealt with the techniques of improving solar cell efficiency. In this chapter, various techniques such as anti-reflection surface coating, surface texturing, light trapping techniques among others

were discussed. The chapter also discussed the recent developed method of concentrating light to shine on a solar cell as another way to increase light to electricity conversion efficiency. Finally; the chapter discussed the modern technique for improving solar cell efficiency by using multi-junction solar cell technology. The actual research work started in chapter four. In this chapter, solar cell model for space environment and simulation program were developed. The chapter explained where and how the relevant research data was obtained. In chapter five, information obtained from various data sources was used to come up with the multi-junction solar cell. Simulations for different space and terrestrial conditions were used with different types of solar cell materials. The best simulation results were compiled and used to design the multi-junction solar cell. In this chapter, calculation for the multi-junction solar cell efficiency was also explained. The final design of the multi-junction solar cell was conducted in chapter six. The organization and basic rules for the design of multi-junction solar cell was thoroughly discussed in this chapter and the power and output voltage for the cell derived. The solar panel was finally developed by series connection of the designed multi-junction solar cell. After the development of the solar panel, it was compared with a solar panel from Tenesol from photo voltaic company and was found to have several advantages which make it better for space applications. Therefore, the fabrication of the multi-junction solar panel designed and developed in this research is highly recommended for space applications.

7.2 Future Research

The design of the multi-junction solar cell for the development of the solar panel for low earth orbit and high altitude application focused on light and temperature effects. Another serious aspect of design which should be looked into is the space radiation effects on the solar cell operation. Space radiation is generated by high energy particles such as high speed electrons emitted by solar activity. These high energy particles have a high electric field that affect the light generated current in the solar cell. If the solar panel or the cell is bombarded with excessive radiation, it may be degraded or even failed. To enhance availability and long life span, further research should be conducted on how to radiation harden the solar panel. Heating up of solar cell contribute to the reduction of solar cell efficiency. Part of this heat is caused by the light falling on the space of the solar panel that is not covered by solar cells. To reduce this heat, the empty

space should be painted with reflective colors or should be covered with pieces of reflective mirrors.

8. APPENDICES

APPENDIX A

Generalized MATLAB script file for determining solar cell I-V curves

```
% MSX-60 is the model number of the solar module is used to develop the file.
% Code generates current values for a given voltage, illumination and temperature
% the file can be used for any type of solar cell provided the parameters for that specific
cell are used
% the code can be used to draw current-voltage characteristic for solar cells at different
suns and at different temperatures
% the code can be modified to draw voltage-power characteristic for solar cells at
different suns and at different temperatures
% G, represents Sun intensity (G = 1000 W/m^2 standardized terrestrial level)
% T = Temp in Deg C
    k = 1.38e-23; % Boltzmann's constant
    q = 1.60e-19; % charge on an electron
% T, k & q are constants appearing in solar cell model.
Va = [0:0.001:25]; %input voltage range, the max value depends on solar panels
Suns = 1; %same as G, but expressed as a ratio (normalized) relative to 1000 W/m^2
TaC = 25; % operating temperature of the solar cell module
A = 1.2; % "diode quality" factor, in this example it's for mono crystalline silicon
Vg = 1.12; % Vg is the band gap value for silicon solar cell material,
% A and Vg values should be changed for other types of solar cells
Ns = 36; % number of solar cells connected in series, 36 cells for the case of MSX-60
solar module.
T1 = 273 + 25; % cell operating at temperature T1 expressed in Kelvin scale
Voc_T1 = 21.06 /Ns; % calculated open circuit voltage per cell at temperature T1
Isc_T1 = 3.80; % calculated short circuit current per cell at temp T1
T2 = 273 + 75; % cell operating at temperature T2 expressed in Kelvin scale
Voc_T2 = 17.05 /Ns; % open circuit voltage per cell at temperature T2
Isc_T2 = 3.92; % short circuit current per cell at temperature T2
TaK = 273 + TaC; % solar cell module working temperature
TrK = 273 + 25; % reference temperature
% when Va = 0, light generated current Iph_T1 = array short circuit current
```



```

% constant "a" can be determined from Isc vs T
lph_T1 = Isc_T1 * Suns; %equation (4) in section 4.4
a = (Isc_T2 - Isc_T1)/Isc_T1 * 1/(T2 - T1); %equation (5) in section 4.4
lph = lph_T1 * (1 + a*(TaK - T1)); %light generated current @ module temperature
Vt_T1 = k * T1 / q; % = A * kT/q, thermal voltage @ T1
lr_T1 = Isc_T1 / (exp(Voc_T1/(A*Vt_T1))-1);
lr_T2 = Isc_T2 / (exp(Voc_T2/(A*Vt_T1))-1);
b = Vg * q/(A*k);
lr = lr_T1 * (TaK/T1)^(3/A) .* exp(-b.*(1./TaK - 1/T1));
X2v = lr_T1/(A*Vt_T1) * exp(Voc_T1/(A*Vt_T1));
dVdl_Voc = - 1.15/Ns / 2; % dV/dI at Voc per cell --
% from manufacturers' data sheet
Rs = - dVdl_Voc - 1/X2v; % series resistance per cell
% Ia = 0:0.01: lph;
Vt_Ta = A * 1.38e-23 * TaK / 1.60e-19; % = A * kT/q
% Ia1 = lph - lr.*( exp((Vc+Ia.*Rs)./Vt_Ta) -1);
% solve for Ia: f(Ia) = lph - Ia - lr.*( exp((Vc+Ia.*Rs)./Vt_Ta) -1) = 0;
% Newton's method: Ia2 = Ia1 - f(Ia1)/f'(Ia1)
Vc = Va/Ns;
Ia = zeros(size(Vc));
% lav = Ia;
for j=1:5;
Ia = Ia - ...
(lph - Ia - lr.*( exp((Vc+Ia.*Rs)./Vt_Ta) -1))...
./ (-1 - (lr.*( exp((Vc+Ia.*Rs)./Vt_Ta) -1)).*Rs./Vt_Ta);
% lav = [lav;Ia]; % to observe convergence for debugging.
end

```


APPENDIX B

Generalized MATLAB script file for determining solar cell voltage-power characteristic curves

```
%function Ia = msx60 (Va, Suns, TaC)
% msx60 is a solar panel model.
% the output of this function code is current which depends on input voltage, illumination
and temperature
% Ia, Va = current & voltage array
% G = num of Suns (1 Sun = 1000 W/m^2)
% T = Temp in Deg C
k = 1.38e-23; % Boltzmann's const
q = 1.60e-19; % charge on an electron
% T, k & q are constants appearing in solar cell model.
Va = [0:0.001:25]; %input voltage range, the max value depends on solar panels
Suns = 1.00; %same as G, but expressed as a ratio (normalized) relative to 1000
W/m^2.the value can change according to simulation requirements
TaC = 25; % operating temperature of the solar cell module
A = 1.2; % "diode quality" factor, in this example, monocrystalline.
Vg = 1.12; % band gap voltage, in this example, monocrystalline.
Ns = 36; % number of solar cells connected in series, 36 cells for the case of MSX-60
solar module.
T1 = 273 + 25; % cell operating at temperature T1 expressed in Kelvin scale
Voc_T1 = 21.06 /Ns; % open cct voltage per cell at temperature T1
Isc_T1 = 3.80; % short cct current per cell at temp T1
T2 = 273 + 75; % cell operating at temperature T2 expressed in Kelvin scale
Voc_T2 = 17.05 /Ns; % open cct voltage per cell at temperature T2
Isc_T2 = 3.92; % short cct current per cell at temp T2
TaK = 273 + TaC; % array working temp
TrK = 273 + 25; % reference temp
% when Va = 0, light generated current lph_T1 = array short cct current
% constant "a" can be determined from Isc vs T
lph_T1 = Isc_T1 * Suns;
a = (Isc_T2 - Isc_T1)/Isc_T1 * 1/(T2 - T1);
lph = lph_T1 * (1 + a*(TaK - T1));
```



```

Vt_T1 = k * T1 / q; % = A * kT/q
Ir_T1 = Isc_T1 / (exp(Voc_T1/(A*Vt_T1))-1);
Ir_T2 = Isc_T2 / (exp(Voc_T2/(A*Vt_T1))-1);
b = Vg * q/(A*k);
Ir = Ir_T1 * (TaK/T1)^(3/A) .* exp(-b.*(1./TaK - 1/T1));
X2v = Ir_T1/(A*Vt_T1) * exp(Voc_T1/(A*Vt_T1));
dVdl_Voc = - 1.15/Ns / 2; % dV/dI at Voc per cell --
% from manufacturers datasheet
Rs = - dVdl_Voc - 1/X2v; % series resistance per cell
% Ia = 0:0.01:Iph;
Vt_Ta = A * 1.38e-23 * TaK / 1.60e-19; % = A * kT/q
% Ia1 = Iph - Ir.*( exp((Vc+Ia.*Rs)./Vt_Ta) -1);
% solve for Ia: f(Ia) = Iph - Ia - Ir.*( exp((Vc+Ia.*Rs)./Vt_Ta) -1) = 0;
% Newton's method: Ia2 = Ia1 - f(Ia1)/f'(Ia1)
Vc = Va/Ns;
Ia = zeros(size(Vc));
% lav = Ia;
for j=1:5;
Ia = Ia - ...
(Iph - Ia - Ir.*( exp((Vc+Ia.*Rs)./Vt_Ta) -1))...
./ (-1 - (Ir.*( exp((Vc+Ia.*Rs)./Vt_Ta) -1)).*Rs./Vt_Ta);
% lav = [lav;Ia]; % to observe convergence for debugging.
end
plot (Va,Ia);
>> Pa = Va.*Ia;
>> plot (Va,Pa)

```


APPENDIX C

Generalized MATLAB script file for determining maximum voltage and current from solar cell I-V characteristics curves.

```
%function Ia = msx60 (Va, Suns, TaC)
% msx60 is a solar panel model.
% the input for this code is current given voltage, illumination and temperature
% Ia = msx60 (Va, G, T) = the function for the code
% Ia, Va = current & voltage array
% G = num of Suns (1 Sun = 1000 W/m^2)
% T = Temp in Deg C
k = 1.38e-23; % Boltzmann's const
q = 1.60e-19; % charge on an electron
% T, k & q are constants appearing in solar cell model.
Va = [0:0.001:25]; %input voltage range, the max value depends on solar panels
Suns = 1.00; %same as G, but expressed as a ratio (normalised) relative to 1000
W/m^2. The value can change according to requirements
TaC = 25; % operating temperature of the solar cell module
A = 1.2; % "diode quality" factor, in this example, monocrystalline.
Vg = 1.12; % band gap voltage, in this example, monocrystalline.
Ns = 36; % number of solar cells connected in series, 36 cells for the case of MSX-60
solar module.
T1 = 273 + 25; % cell operating at temperature T1 expressed in Kelvin scale
Voc_T1 = 21.06 /Ns; % open cct voltage per cell at temperature T1
Isc_T1 = 3.80; % short cct current per cell at temp T1
T2 = 273 + 75; % cell operating at temperature T2 expressed in Kelvin scale
Voc_T2 = 17.05 /Ns; % open cct voltage per cell at temperature T2
Isc_T2 = 3.92; % short cct current per cell at temp T2
TaK = 273 + TaC; % array working temp
TrK = 273 + 25; % reference temp
% when Va = 0, light generated current Iph_T1 = array short cct current
% constant "a" can be determined from Isc vs T
Iph_T1 = Isc_T1 * Suns;
a = (Isc_T2 - Isc_T1)/Isc_T1 * 1/(T2 - T1);
Iph = Iph_T1 * (1 + a*(TaK - T1));
```



```

Vt_T1 = k * T1 / q; % = A * kT/q
Ir_T1 = Isc_T1 / (exp(Voc_T1/(A*Vt_T1))-1);
Ir_T2 = Isc_T2 / (exp(Voc_T2/(A*Vt_T1))-1);
b = Vg * q/(A*k);
Ir = Ir_T1 * (TaK/T1)^(3/A) .* exp(-b.*(1./TaK - 1/T1));
X2v = Ir_T1/(A*Vt_T1) * exp(Voc_T1/(A*Vt_T1));
dVdl_Voc = - 1.15/Ns / 2; % dV/dI at Voc per cell --
% from manufacturers datasheet
Rs = - dVdl_Voc - 1/X2v; % series resistance per cell
% Ia = 0:0.01:Iph;
Vt_Ta = A * 1.38e-23 * TaK / 1.60e-19; % = A * kT/q
% Ia1 = Iph - Ir.*( exp((Vc+Ia.*Rs)./Vt_Ta) -1);
% solve for Ia: f(Ia) = Iph - Ia - Ir.*( exp((Vc+Ia.*Rs)./Vt_Ta) -1) = 0;
% Newton's method: Ia2 = Ia1 - f(Ia1)/f'(Ia1)
Vc = Va/Ns;
Ia = zeros(size(Vc));
% Iav = Ia;
for j=1:5;
Ia = Ia - ...
(Iph - Ia - Ir.*( exp((Vc+Ia.*Rs)./Vt_Ta) -1))...
./ (-1 - (Ir.*( exp((Vc+Ia.*Rs)./Vt_Ta) -1)).*Rs./Vt_Ta);
% Iav = [Iav;Ia]; % to observe convergence for debugging.
end
Pa = Va.*Ia;
% Maximum Power Point
MPP = 0;
for i = 1:25/0.001;
    if( Pa(i)<Pa(i+1) && Pa(i+1)>0)
        MPP = i+1;
    end
end
Max = Pa(MPP);
plotyy(Va,Ia,Va,Pa)
grid on

```


%for calculating values

>> Pa(MPP)% to get the value maximum power

>> Ia(MPP) % to get the value maximum current

>> Va(MPP) % to get the value maximum voltage

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