PERFORMANCE ANALYSIS OF MULTIJUNCTION SOLAR CELL

M.Tech. Thesis

By

PRASHANT PURI

DISCIPLINE OF ELECTRICAL ENGINEERING

INDIAN INSTITUTE OF TECHNOLOGY INDORE

JUNE 2020

This page is intentionally left blank

PERFORMANCE ANALYSIS OF MULTIJUNCTION SOLAR CELL

A THESIS

Submitted in partial fulfillment of the requirements for the award of the degree
of
Master of Technology

by

PRASHANT PURI

DISCIPLINE OF ELECTRICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY INDORE

JUNE 2020

This page is intentionally left blank

4323

INDIAN INSTITUTE OF TECHNOLOGY INDORE

CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the thesis entitled **PERFORMANCE ANALYSIS OF MULTI-JUNCTION SOLAR CELL** in thepartial fulfillment of the requirements for the award of the degree of **MASTER OF TECHNOLOGY** and submitted in the **DISCIPLINE OF ELECTRICAL ENGINEERING, Indian Institute of Technology Indore**, is an authentic record of my own work carried out during the time period from JULY 2018 to JUNE 2020 under the supervision of Dr. Shaibal Mukherjee, Associate Professor, Indian Institute of Technology Indore.

The matter presented in this thesis has not been submitted by me for the award of any other degree of this or any other institute.

Prashant Puri
16/06/2020

Signature of the student with date
PRASHANT PURI

This is to certify that the above statement made by the candidate is correct to the best of my knowledge.

S. Mukherjee

Signature of the Supervisor of M.Tech. thesis (with date)

Dr. Shaibal Mukherjee

Prashant Puri has successfully given his M.Tech. Oral Examination held on **June 22, 2020**.

S. Mukherjee 22/6/2020
Signature(s) of Supervisor(s) of M.Tech. Thesis
Date:

Convener, DPGC
Date: 22-6-2020

22/6/2020 (Mukesh Kumar)
Signature of PSPC Member#1
Date:

S. Samal SUMANTA SAMAL
Signature of PSPC Member#2
Date: 22/06/2020

This page is intentionally left blank

ACKNOWLEDGMENTS

I sincerely like to express my gratitude to my M.Tech thesis supervisor **Dr.Shaibal Mukherjee**, Associate Professor, IIT Indore. At numerous instances in the course of this project I was stuck in my progress, he advised me in most efficient and useful ways. His positive approach and confidence in my work helped me go through the project work with ease.

Thanks to PSPC members **Dr.Sumanta Samal** and **Dr. Mukesh Kumar** for helping me out throughout the duration of my project on the college premises even during busy schedules of the college. Thanks to Dr. Santosh Kumar Vishwakarma, as he helped us in the domain of course work as well as introduced us to a whole new level of perspective of the electrical discipline.

During my M.Tech project work there were times when I was stuck with my lack of experience in the software approach, but thanks to **Mr. Gaurav Siddharth** I was always guided in the most accurate way to solve the problem related to my algorithms and code. I would also like to thank H.N.R.G research group for support and keeping a helpful and productive environment in the laboratory.

Special thanks to **Rana Sagar Kumar**, may god bless him. My gratitude to all my M.Tech batch mates for the wonderful experience I had with them in this course of time as they all helped me in my project in ways that are not quantifiable yet important.

IIT Indore played a vital role in providing me with the facilities, teaching assistantship, hostel accommodation, and lab computer and library resources that added to my knowledge and my project.

All this was made possible by the incredible support and bless and blessings of my parents who blessed me all the time, it would not have been possible without their love and support.

This page is intentionally left blank

DEDICATION

Dedicated to Lord Krishna

This page is intentionally left blank

Abstract

Due to the limited amount of fossil fuel left on earth, there is a need to increase the number of alternatives we currently have; such alternatives include solar energy which is inexhaustible by humans. In this work, I have focused on multijunction solar cells as it is a better choice owing to the limiting efficiencies of conventional single-junction solar cells that are abundantly available to us currently. Our focus has been on firstly verifying the parameters with a reference research paper results of multi-junction solar cells, then predict the behavior of our proposed material based on our simulation's prediction. The simulation has been performed on the simulation software called Silvaco TCAD. So, we have first verified the material characteristics of InGaN material based multi-junction solar cell array along with temperature varied from 220 kelvins to 380 kelvins. Parameters of our interest are the open circuit voltage, short circuit current, efficiency, and fill factor. The parameters are extracted from simulation results and then compared. On getting the expected result we then develop the same models for the multi-junction solar cells with different materials i.e. GaAs based and then we predict the behaviors for the material with a change in the temperature in the same range.

This page is intentionally left blank

Contents

LIST OF FIGURES

This page is intentionally left blank

LIST OF TABLES

ACRONYMS

WWF	world wildlife federation
SC	solar cell
STC	standard temperature and pressure
SQ	Shockley Queisser
AM	Air mass
AM0	Air mass zero
AM1	Air mass one
FF	Fill Factor
CEA	Central energy association
V_{oc}	Open circuit voltage
I_{sc}	Short circuit current
J_{sc}	Short circuit current density
kW	kilo Watt
MOS	Metal oxide semiconductor
BJT	Bipolar Transistor
PV	Photo Voltaic

This page is intentionally left blank

Chapter 1

Introduction

Energy is the basis of all life that we know because all living beings consume energy. Even the matter that we deal with in day to day life is all a form of energy. The sun has been shining for more than four billion years, and it will keep on shining for more than that long before turning into a red giant, engulfing earth in the entire process. Whereas producing radiations, the sun releases most of its energy of hydrogen as the sunlight, most of what is impossible to be seen by an unaided human eye. The peak of the sun's radiation is in the vis part of the visible spectrum. Living beings like green plants doing photosynthesis, human beings function at their best in the presence of green sunlight since they have adapted to the vital green light reaching and touching them. Since of what we know all the energy available to us here on earth is due to the virtue of the sun is responsible and if not, then other stars are that exploded before that lead to the formation of stardust which further leads to the miraculous formation of the earth where we live in. Exceptions are the moon's tidal effect, radioactive materials, and the earth's internal magma residual heat usable as geothermal heat energy. Everything else we know or see here on earth is a form of sun's energy transformed in many forms. Hydel power is generated from water motion in rivers and dams which flows by evaporation and heat due to suns treacherous and tremendous heat. The wind blows because of the uneven heating of the sun on the earth's visible surface. Our fossil fuels such as coal, petroleum and natural gas are the remains of dead organic life that existed eons ago and were nourished and nurtured by the sun's light energy, and solar-powered electricity is generated by photovoltaic effect directly from the sunlight by the conversion of the light energy of the sunlight by the help of free charged particles present in semiconductor materials.

1.1 Light energy and its nature

Sunlight appears white to us because it is made up of various colors combinedly, producing white light. All over the range of the visible and the invisible radiations of the electromagnetic radiation spectrum of the sun has different energy owing to the different frequencies. In the visible spectrum 400nm to 700nm, at the low energy end is the red-colored light and at the high energy, the end is the violet-colored light having more of the energy than that of the red light. Light in the infrared region (felt as heat) has less and less energy than that in the visible region. Light in the ultraviolet region has more energy than that in the visible light region. Studies of light and similar radiation show that how one light ray interacts with the other or the other tangible objects and often can be explained as if light were moving as a wave. Visible light stands for only a tiny part of a vast radiation spectrum. Studies of light and similar radiation show that how one light ray interacts with another or other physical objects often can be explained as if light were moving as a wave. This is the reason why; it has become mandatory to characterize light radiation by a parameter associated with the properties of waves. For light, all waves have a certain displacement between peaks called the spectral wavelength of the radiant energy taken into consideration. This spectral wavelength of the radiant energy considered can also be expressed as a frequency i.e. the number of peaks in a specified distance or during a specified period of propagation. Therefore, the wave with a longer distance between respective peaks i.e. long spectral wavelength of the radiant energy taken into account has a lower frequency than one with a shorter spectral wavelength of the radiant energy taken into account which is many peaks. Note that the frequency and the spectral wavelength of the radiant energy taken into account vary inversely with each other. For light energy waves, the energy associated with the respective energy waves increases with the increasing frequency (spectral wavelength of the radiant energy considered decreases).

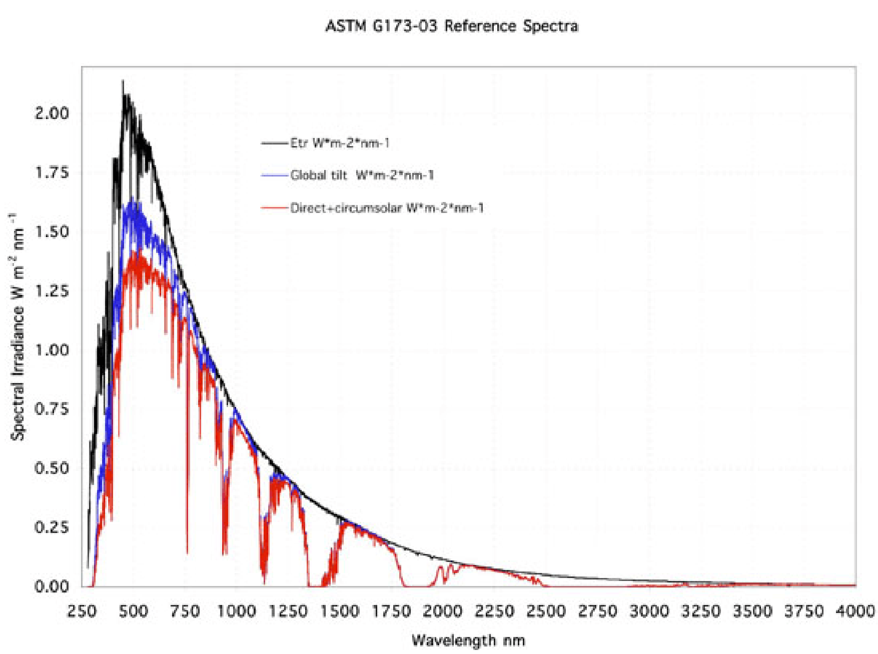

Figure 1.1 Solar spectrum [1]

Red light has a spectral wavelength of the radiant energy taken into account of about 0.66 micrometers (453 terahertz, or about 3 x 10 - 12 ergs (3 x 10 - 24 kW-h per particle of light also known as a photon), violet light, about 0.44 (682 terahertz, or about 4.5 x 10 -12 ergs 4.5 x 10 - 24 kW-h per photon) [2]. X-rays are even shorter and more energetic. Microwaves (of the order of centimeters in spectral wavelength of the radiant energy taken into account) are longer than light waves and carry less and less energy. It is valuable to relate the amount of sunlight at the earth's surface to the quantity, or air mass (AM) [2], [3], of the atmosphere, through which the light must pass. Radiation arriving at the surface of the earth is measured against that reaching the fringes of the atmosphere, where there is no air, and the air mass is zero (AMO). The light of the high-noon sun (and under further specified conditions) passes through an air mass of one (AM1).

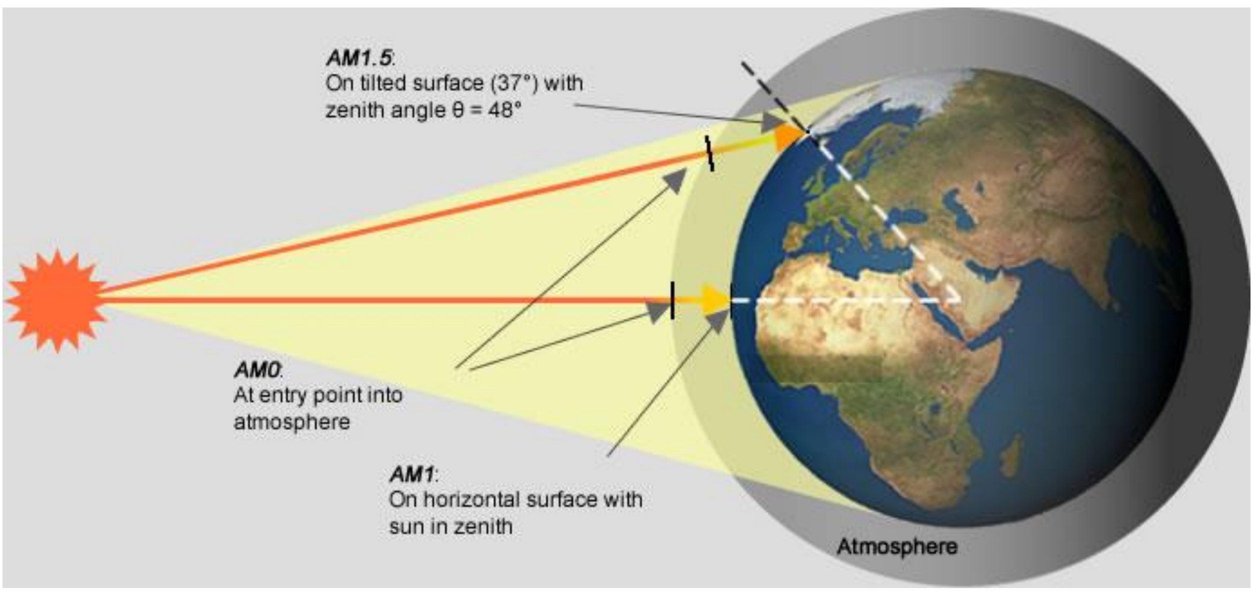

Figure 1.2 Standard spectra [1]

$AM = \frac{1}{cos\theta}$ere theta is the angle with the normal. AM is defined as the inverse of cos of the angle made with normal by the ray. The intensity of the sunlight reaching the ground weakens for sun angles approaching the horizon since the rays have more atmosphere, or air mass, to penetrate. The atmosphere is a powerful absorber and can cut the sun's energy reaching the earth by 50% and more. The peak intensity of sunlight at the surface of the earth is about 1 kW/m2. However, not all areas of the earth get the same average amounts of sunshine throughout the year. The most intensely bathed areas lie between 300 north and 300 south latitude since these areas have the least cloud cover. There also are, of course, seasonal radiation variations caused by the tilt of the earth concerning the sun. Thus, the winter sun will daily provide less and less than 20% of the summer sun's energy at some locations because it is lower in the sky and the days are shorter.

1.2 Why solar Energy

Following the DEA, the gross value of the sun's energy reaching the earth's surface in one hour is humongous compared to the total energy required by all humans on the planet in one whole year. In the year 2016, the solar power sector was one of the fastest gaining and growing sectors with a step thirty-three percent rise following the Bloomberg report [4]. Environment-related advantages and pros are the prime motivation behind the promotion of solar energy.

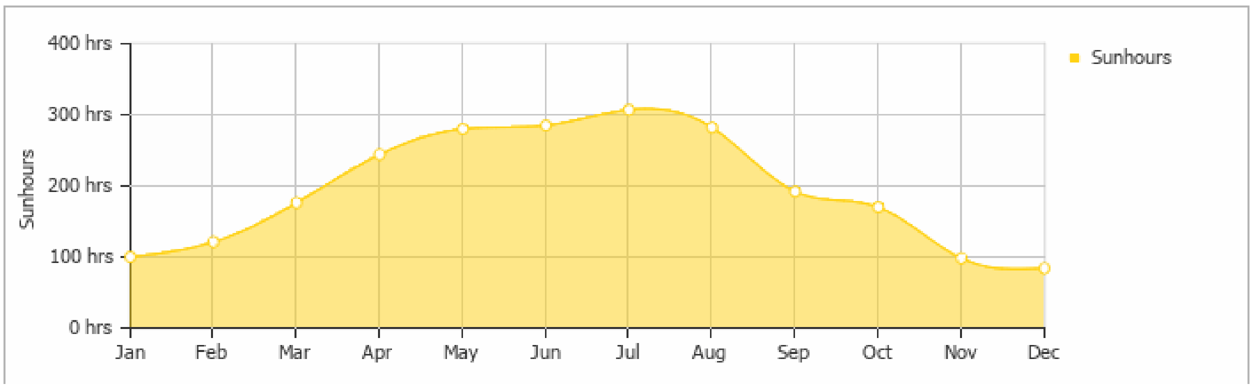

Figure 1.3 Typical variation of sunlight in 1 year [4]

As shown in the plot of obtained sunshine over the period of one year, it is clear that solar energy is abundant, and with proper arrangement of solar energy capturing apparatus we can harness tremendous amounts of energy.

1.2.1 Solar Energy Is Clean and Safe

Energy harnessed as so-called solar energy is a safer alternative that can replace current fossil fuels like coal, petroleum, and natural gas for the generation of electricity that produces air, water, and land pollution. World wildlife federation (WWF) points to the fact that the production of electricity from all the fossil-based fuels tends to pollute the atmosphere causing acid rains, damage to green forest covers, and severely affects agricultural crop production casing the loss of numerous habitats worldwide [1]. As a matter of factories use enormous amounts of litters of water mixed with chemicals for extraction of contaminants in the water being used, also with nearby water bodies. The continuous use of nuclear material for nuclear power tends to pollute the surrounding environment such as water and land in ways that are treacherous and have caused environmental catastrophes. By the use of solar energy, we will eliminate these unsafe, hazardous, unclean repercussions from using conventional fossil fuels.

Primeval forests are destroyed for the withdrawal of raw materials like a fossil that is the dead remains of some old ago living organisms. Green forest covers continuously replace carbon dioxide from the air, use it for performing photosynthesis to make their food based on carbon i.e. glucose, fructose, sucrose, and much more which is beyond the scope of our discussion in this literary work of thesis, and this energy is stored in various forms in plants. When these forests and green covers are cut down, depleted, severed to obtain useful raw materials i.e. wood, for fire, this natural oxygen generating carbon sink disappears and also promotes climate change. Most of the living organisms on land are living in forest covers, following WWF, and this depletion of forest which is a loss of their habitat diminishes their numbers. Opting to the limitless potential of the solar energy system is mandatory to keep the habitable lands and nature at peace for the living beings that reside here as well as help in maintaining balance and keeping the air clean.

1.2.2 Combats the disastrous Climate Change

Per the energy and power association, the greenhouse gas emissions in the year 2017 were about 13% less than those of the year 2005. Emissions are decreased by 0.5% from the year 2016 to the year 2017. For the abrupt and steep rise in the global temperatures, we have emissions to blame and abrupt changes in the weather behaviors leading to a continuous freight series of events and effects. The steady increase in disease-spreading microorganisms humongous and dangerous heat waves and insects daily cause health problems specifically for infants and the old because they have weak or completely compromised immune system given by nature or deteriorated over time.

Recent climatic changes have led to arise in river flooding also big typhoons because of severely disturbed weather status. Carbon dioxide concentrations of such high amounts are making the oceans more and more acidic and killing all sea creatures too, like coral reefs, and many predominant and primordial fish. Climate change has caused the extinction of species from the sub-arctic Borealis forests all over to the tropical Amazon rain forests. Also, higher levels of temperature result in the melting process of the frozen polar ice caps, thus reducing habitable places for the wildlife animals and also increases water levels of the sea which is dangerous for humans too. This will no doubt result in submersion of coast and slippage of landline along the coastline, causing displacement of people [4], [1]. Recent irregularities in rainfalls or increasing drought cycles affected agricultural activities and the basic livelihoods of the people and weaker sections of societies all over the world without any discrimination since nature is not biased.

Clean solar energy's greatest advantage is that it can be produced on small scale easily and directly by the consumers while, in contrast, the large centralized conventional energy sources which are controlled by large corporations can’t do so.

1.2.3 Cheaper in the long run and Reliable type of Energy Source

Recent technology-related advancements, policies, and subsided help from state governments have significantly lowered the superior installation cost of a system of solar-powered energy. The prices of commercially available solar panels have drastically decreased also the costs of the systems of solar electricity by fifty percent in accordance with the report of energy.gov [4]. Now we can say that solar-powered energy is very much competitive if compared with conventional energy sources.

The costs of running are going lesser and lesser and foundational investment costs has regained and thus leading to a subsequent reduction of the overall cost related to energy in accordance with the Greenpeace organization. This has happened since the sole requirement of solar-powered energy is the eternal, never-ending, free, omnipresent, omnipotent, humongous, and clean sun whereas fossil fuels are first mined from land or seabed and then transported over long distances in accordance with the Greenpeace’s myth report. The Greenpeace reports estimated that broadly in a country, the cost for dealing with all environment-related havocs due to the constant overuse of exhaustible and unclean energy sources have become more than two hundred percent the overall costs of the electric power obtained from the conventional type of sources of energy such as coal, petroleum and natural gas. The use of solar energy is therefore important in helping diminish and futureproof all of the added and hideous prices.

1.2.4 Renewable Energy

Solar energy obtained from the sun is treated to be a renewable energy resource, contrary to all the non-renewable energy sources, like all the fossil fuels, that are countable and finite. We get abundant amounts of solar energy from the sun daily and directly as the form of sunshine which can easily sum up for the varying energy requirements of all humans on this earth, even in the scenario of the Earth's population keeps on growing and consumes more energy.

1.2.5 Non-Polluting

The use of fossil fuel energy causes pollution as soon as they are consumed, whereas the use of solar-powered energy doesn’t, that is the other thing in which it encapsulates the principles pertaining to abstract sustainability. The solar system panels sit quietly on the top of the roof and in big sized solar system arrays in the fields also called as solar farms, they do no create any waste products, noise or any other products, just pure DC electricity which can be further converted to ac and stepped up using the power transformers and then transmitted using booster transformers which can be later distributed to users using distribution transformers to the end-users such as factories, hospitals, industries, commercials, domestic users.

1.3 The Photovoltaic effect

It is the phenomenon which is responsible for the conversion of light to electricity, the photovoltaic effect was first observed by a French physicist, Edmund Becquerel in 1839. In which noted that a voltage difference appeared when one of two identical electrodes dipped in a weak conducting salty solution was lit upon [5].

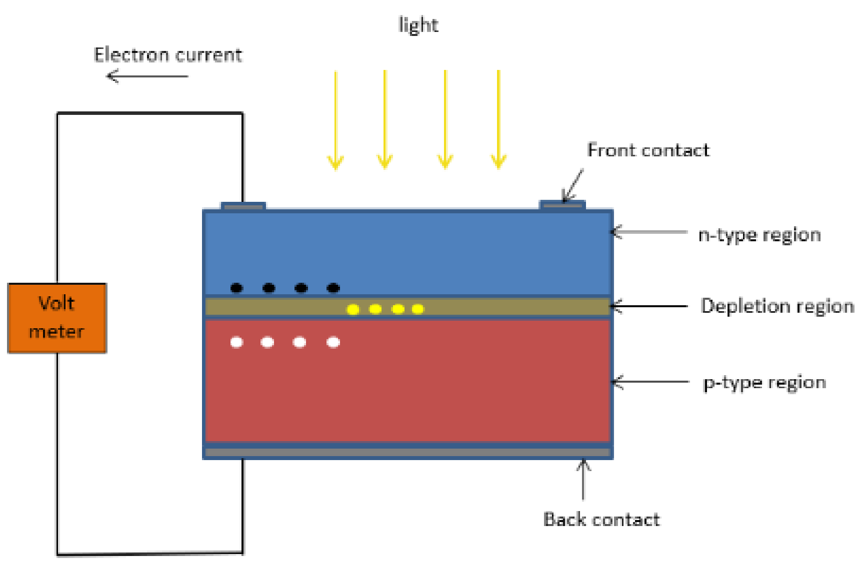

Figure 1.4 Photovoltaic effect

Figure 1.4 shows a simple mechanism of working of a p-n junction solar cell in general. The photovoltaic effect was then firstly studied in the solids, like selenium and others of a similar kind, in the decade the 1870s [6],[7]. In the decade 1880s, selenium based photovoltaic cells were built after doing tedious research and showed nearly 1%-2% efficiency in the conversion of light to electrical energy [3]. The material Selenium converts the photons in the visible part of the sunlight spectrum; therefore, it was quickly taken into account and quickly adopted by the then-emerging field of light photography for photometric which is light-measuring devices. And even today, the light-sensitive material cells on cameras used for adjustment of shutter speed to match luminescence are made material called selenium. A handful of schemes were tried on and on in the decade of the 1950s to make use of silicon-based PV cells commercially in the market. Most of them were for cells to be used in the regions geographically isolated from the electric transmission and utility lines. But miraculously due to an unexpected and unprecedented boom in PV technology came from a totally different quarter. In the calendar year 1958, the famous Vanguard space satellite was using a very small array of solar cells to power up its radio, small means less than one-watt [1]. The onboard solar cells worked so much well that concerned space scientists soon realized that the PV cells could be an efficient and effective energy source for any space mission from then on. The technological developments on solar cells have been an important part of all the space programs since then. And besides the NASA space programs, other sources, the transistor industries, contributed immensely to the growing solar-cell energy technology. MOS transistors, BJT, and PV cells are all made from similar materials, and their workings are based on lots of similar physical laws. A tremendous amount of research and development has already been performed in the improvement of the ever-useful transistor technology, and also there has been a constant turmoil of valuable information and data in relation to solar energy cells. But the situation has drastically reversed, or we can say changed recently: Most of the ongoing research being done in PV technology is now affecting all the transistor technology. Nowadays, the photovoltaic systems can transform from one kilowatt of solar energy falling on one square meter directly to nearly a hundred watts of electrical power. Thus, solar power energy used from the photovoltaic conversion of sunlight into electricity is abundant, totally inexhaustible, and completely clean; yet, it also requires special techniques to gather enough of it effectively.

1.4 Operation of solar cell

Photons can penetrate a semiconducting material and generate charge carriers. Absorption of one photon, with the energy of $h\nu > E_g$, in the region of a p–n junction leads to the creation of an electron and a hole. Minority carriers generated within the p–n junction diffusion length diffuse to the depletion layer, where the electrostatic field carries them across. The hole from an electron-hole pair, generated by a photon on the junction p-type side, stays on the p-type side because the potential barrier at the junction repels the hole, while an electron is impelled toward the n-type side. A similar situation occurs when the electron-hole pairs are generated by light on the junction n-type side. Equations are as follows [8]-[12]

$$V_{oc} = \frac{nkT}{dT} \ln\left(\frac{J_{sc}}{J_o} + 1\right)$$

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

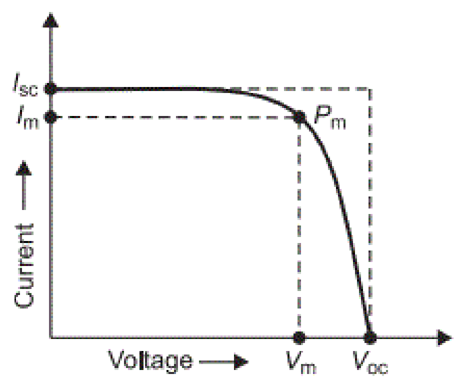

Figure 1.5 Characteristics of a solar cell [8]

Here, k is the Boltzmann constant, T is the temperature in kelvins. The light generated current is denoted by I_L. Short Circuit Current (I_{sc}) is the current that flows through the external circuit when the electrodes of the solar cell are short-circuited. Open-Circuit Voltage (V_{oc}) is the voltage at which no current flows through the external circuit. It is the maximum voltage that a solar cell can deliver. Maximum Power is denoted by P_m. Current at Maximum Power is denoted by I_m. The voltage at Maximum Power is denoted by V_m. Fill factor of Solar Cell is the voltage at which no current flows through the external circuit. It is the maximum voltage that a solar cell can deliver generated by a solar cell and the product of V_{oc} with J_{sc}, $FF = \frac{V_m * I_m}{V_{oc} * I_{sc}}$. The efficiency of Solar Cell is the ratio of P_m to P_{in} denoted by $\eta = \frac{P_m}{P_{in}}$.

Effect of temperature on the bandgap can also be found out by the equation shown as follows [5]

$$E_g(T) = E_g(300K) + \frac{dE_g}{dT}(T - 300K)$$

Where $E_g(T)$ is the energy bandgap as a function of temperature T [8].

1.5 Limits of single-junction solar cell

Firstly, calculated in values by the scientists Hans Queisser and William Shockley (SQ) in the year 1961. Complete solar cell's efficiency of energy conversion is defined to be the ratio of converted power energy from the incident sunlight to energy in the electrical form in presence of the STC. The STC conditions are considered to be approximate solar noon of the spring and the autumn equinoxes in all the continental regions of the globe with the surfaces of all solar cells aimed directly towards the sun.

The latest accepted value of SQ limits in the calculation was found to be a maximum of 33% efficiency for all types of single junctional single-layered solar cells. The original values calculated by SQ was found to be 30% for the silicon-based solar cell.

The best available modern production silicon cells show an efficiency of 24% at the individual cell levels and nearly 20% at the complete module levels as reported by the firm SunPower in March month of the year 2012. In an isolated laboratory, the recorded solar cell efficiency record is held by the so-called University of New South Wales, Sydney, Australia value is about 25%.

There are several assumptions associated with the SQ Limits that normally restrict the general applicability to all the types of solar cells available to human knowledge. Although there are numerous programs on the way to find ways about the SQ Limit, still it is applicable up to 99.9% of the solar cells present in the market to date.

1.5.1 Assumptions of the Critical SQ Limit

- One and only one semiconductor material per solar cell after excluding the doping materials.
- Only One p-n junction device per solar cell [9].
- Sunlight is also not concentrated - a single sun source [3].

- All the energy is converted into heat which is from photons having energies greater than the bandgap.

1.5.2 Reason for the difference in energy conversion

- About nearly 47% of the total incident solar energy automatically gets converted into heat [4].
- Nearly about 18% of all the photons pass directly through the solar cell [4].
- And about 2% of overall energy is lost due to local recombination of just created hole electron pairs.
- Theoretically, 33% of the sun's energy is converted directly to usable electrical energy [4].
- This sums up a total of 100% of the sun's incident energy.

If the so-called theoretical limits of the silicon cells are nearly about 30% in numerical [4], what is happening to the rest 6% which is lost even from the best production cell of efficiency of 24%? Some of the incident sunlight is always reflected called reflected sunlight from the surfaces of the cells even when the surfaces are texturized, polished, and coated with an advanced anti-reflective material coating. In addition to this, there are still some losses at the former junction of the silicon cells with those of the electrical contacts that carry the direct current to the loads. Finally, there are some losses due to manuals a matter of factoring impurities in the intrinsic silicon.

Listed below are the reasons responsible for lower actual efficiencies of cells compared to theoretically calculated limitations which are as follows:

1.High and unwanted reflection for incident sunlight light from the plain surface of cells. The anti-reflective material coating may very much minimize this. Here is an example, AR coatings can drastically diminish the reflectance from a Silicon-based cell to three percent from about than thirty percent of a normal from a general unaided solar cell unit of a module or a system.

2. Occasional shading of the solar cells by the virtue of contacts that collect current. This possibly can very much be reduced by diminishing the effective surface area of the cell’s contacts and also by increasing their transparency. Anyhow, either of the ways will also increase the effective resistance of this solar cell configuration to current flow.

3. The ever-present and irremovable internal resistance of the cell also referred to as parasitic resistance.

4. Mandatory recombination of electron-hole pairs before these can effectively contribute towards the flow of current. Though this effect can greatly reduce the polycrystalline also the amorphous cell by the use of hydrogen-based alloy materials.

1.6 Multi-junction solar cell

Around thirty percent is the efficiency obtained at max theoretically for a single-junction solar cell. Efficiency for the solar cell having a single junction is dependent upon the absorbing ability of the limited range of the sunlight spectrum. Finding better materials for solar cell research is being done and the combination of numerous single solar cells also known as the multijunction solar cells. Different cells are optimized for absorbing different parts of the sunlight spectrum in a multijunction solar cell, in order to improve the efficiency of the overall cell. Till now commercially available multijunction solar cells are able to achieve with concentrated sunlight a maximum of 40% of efficiency. The primary hindrance in the multi-junction solar cell is the fabrication cost and a very complex process of fabrication. Designs for multi-junction solar cells are highly complex and consideration of lots of parameters is needed. For multi-junction solar cells, the price-to-performance ratio has highly bounded their applications to specific architectural applications. Two principals of losses are there one is thermalization and the other is non-absorption, together they strongly diminish the efficiency of energy conversion in modern solar cells. Whenever the energy the absorbed by the individual photons is slightly higher than the bandgap of the cell material it leads to the demand for a tandem cell, these multi-junction devices incur a higher bandgap top cell for the absorption of high frequencies while letting the lesser energy radiation to pass through the top cell. The next material of slightly lesser bandgap is then made to be placed just below the higher bandgap cell junction in order to absorb radiations of just lesser energy having a longer spectral wavelength of the radiant energy taken into account. Typically, multijunction cells use two or more single-junction cells.

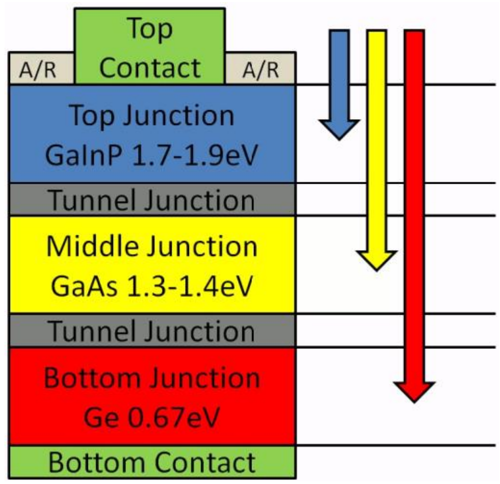

Figure 1.5 A multi-junction solar cell [5]

A typical example of the triple-junction solar cell shown in figure 1.5. A is can be observed that the bandgap of individual cells is reduced sequentially in order to trap photons of particular energy spectra. Theoretically, the maximum efficiency improves with the increase in the number of junctions as such. These multi-junction cells work in series having just two terminals for connecting externally, while they are connected internally via the tunnel junctions, displaying ohmic characteristics. The overall performance of a multijunction solar cell increases with the increase in the number of cells in a stack, having direct sunlight conversion efficiencies of up to a maximum of eighty-six percent that too for an infinite stack having independently operating cell under the effect of the concentrated sun. But complications arrive on increasing the number of cells and increases the sensitivity of cells to the irradiating light spectrum because these individual cells need a connection of series type having low ohmic resistances at contact and current matching is mandatory.

This page is intentionally left blank

Chapter 2

Current status of solar cell technology

Embarkment on the path of improvement of the efficiencies of SC devices started with the development of a technology called as the solar photovoltaic systems, along with the continuous and simultaneous solutions to the problems like reduction in the cost of manufacturing and utilization, an extension of the overall usable and serviceable life, and the improvements in the operational stability in the presence of varying environments such as an abrupt change in the humidity, cloud cover and ambient temperature, etc.. On the historical account, the first of the photoelectric SC was with the efficiencies well above one percent or can say about up to 6% which were the crystalline silicon solar cells [13].

2.1 First generation of solar cells

The so-called solar cells that belong to the first generation presently account for about more than ninety percent of all the available commercial SC market in the world and show, on an average, efficiencies of about twenty percent. These solar cells have several of the noticeable drawbacks, like very high fabrication costs, hazardous levels of toxicity in their productions, and very large amounts of a byproduct of production called as toxic wastes and many more.

The development of alternatives to SCs are a result of the various attempts made to eliminate the evident disadvantages of solar cells belonging to the first generation, thin-film devices are also included, second-generation cells is what we call them now by our very own language selection which is now is not referred to as. The amorphous (a-Si), the microcrystalline (mc-Si), the polycrystalline (multi-cSi) silicon, the multicomponent A3B5 structure (examples are GaP, InP and GaAs) and A3B6 structure (example CdTe) semiconductors are various available structures available for the present solar cell technology in the considered second-generation of SCs [13]. Fabrication of these cells requires fewer amounts of raw materials and also consumes lesser amounts of energy, and they are far easier in production as compared to crystalline silicon SCs. Many of the solar cell-based batteries using such SCs are very much flexible and plasticky and thin filmed and also may be easily accommodated on a normal nonplanar surface. Merits like these lead to the rapidness in the development of the second generation of the SCs utilizing both the materials silicon and also multicomponent semiconductor material. Some of the leaders in the market of production and installation of the second-generation of SCs utilizing the properties of amorphous and microcrystalline silicon (having efficiencies of 7 with 10 percent tolerance) are the Sunlight Corporation and the Anwell Technologies Limited, Hong Kong [13]. Some of the leaders in the fields of production as well as the installation of second-generation SCs is using multicomponent based semiconductors with the overall efficiencies of above fifteen percent and are the First Solar Ltd. and General Electric Ltd. companies (both US-based companies). On average the market price of electricity produced by the second-generation of SC devices sums up to approximately 8 rupees per kWh. This is a very reasonable price, which is of interest to the market players and consumers.

2.2 Second generation of solar cells

But as a result, the changes to the second-generation of SCs reaped to be a bit unsuccessful. starting in the decade 1980s, about only 10 percent of the market was occupied by the commercial second-generation SCs with a typical efficiency of 15%, and presently no useful observance in their growth [4]. Numerous reasons are there for this failure with respect to the first generation. Which includes, presence of high toxicity from byproducts of the production of multi-component semiconductors and including several of the starting materials, they were dependent on the ambient condition requirements(i.e. a requirement to remove snowflakes and dust particles, the reduction in output of power with illumination under the presence of scattered light), the amorphous silicon SCs are unstable, and lastly, the large investor was not sure and was ambiguous about what material to use or completely rely on.

For obtaining higher efficiencies and getting relatively expensive SC made up of multiple components semiconductor, the choice is not practical, since the overall costs, as well as volumes of production, depends upon the levels of raw materials after their extractions. In this world, it is not able to predict the levels for starting material extraction: till now, the production output of the second-generation of SCs is not sufficiently large scale so as to foster the overall extraction itself. As consequence, second-generation SCs haven’t been revolutionizing solar cell photovoltaic technology. But, as mentioned later, second-generation of SCs no doubt is having the potential in the industry. The upcoming transcendental state for solar photovoltaic technology includes useful developments in the organics which is the third generation of SC. There has always been an irremovable adventure in solving these known set of problems, during the large scale manufacturing of all these solar cells: so as in order to get lower amounts of toxic waste during the production, the cost of manuals as a matter of facture as well as materials along with all the expenses of energy, also so as to raise the rate of manuals as a matter of facture and simplification of the process, also as well as so as to drastically increase the operational stabilities of all solar energy cells in different weather conditions.

2.3 Third generation of solar cells

A third of the generation of mainline SC comprises a comparatively broader class of all the cells while utilizing the conducting type polymers, such as pigments (also known as organic dyes), and also hot electrons SCs, and also quantum dots and also organic including or excluding inorganic semiconductors, and lastly, the SCs including a solar spectrum splitter technique. In the latest cascade solar cells or so-called multijunction SCs, having the photoelectric materials are formed by an application of a multilayer structure of thickness 1mm with a tolerance of 5 percent of overall thickness which holds several junctions of the semiconductor [4], [13]. Up to four junctions in practice. This structure is a series combination of some optically very thin SCs and nothing more, each of these junctions is improved for a comparatively narrow range of operation of the solar radiation spectrum. These include accurately the SCs which exhibited a really very high efficiency of 46 percent. All these solar cells are all made up of really high-quality solar cell semiconductor materials. Whose production cost is very much high; hence they are typically used for supply of energy and power in spacecraft and hence are not able to be compared with other commercially available SCs which are for civilian use, also for residential purposes. Other ways to overcome the hindrance includes the utilization of processes which are not linear in approach and will eventually hinder the dissipation of overall energy of motion of the free charge carriers due to high-energy photons

2.4 Scenario of solar power in India

Indian subcontinent lies in the tropical region of the globe. India is gifted with reliable sunlight and thus the potential for solar energy. A major portion of the Indian subcontinent gets more than 300 days of bright sunshine over the year. About $5x10^{15}$ kWh per year energy is incident over the land of the Indian area with most part receiving up to five kWh per square meters daily [1], [4]. Therefore, both the technologies together that are solar thermal systems and solar photovoltaic systems can no doubt effectively provide us with the huge capability of solar-powered energy here in India. Solar energy also is able to provide the abilities for the generation of power on a distributed basis i.e. pro-rata basis.

Table 2.1 Total installed capacity in India [15]

Fuel	MW	% of Total
Total Thermal	2,30,600	62.8%
Coal	1,98,525	54.2%
Lignite	6,610	1.7%
Gas	24,955	6.7%
Diesel	510	0.1%
Hydro (Renewable)	45,699	12.4%
Nuclear	6,780	1.9%
RES* (MNRE)	87,269	23.6%
Total	**370,348**	

As it can be observed from table 2.1 shown above the total installed capacity of energy in India is distributed amongst thermal, hydro, nuclear and renewable resources in a manner that fossil fuel requirement is high(owing to thermal energy) and renewable energy proportion is low due to lack of development in technology.

The distribution of solar energy system installation over years in India is summarized in table 2.2. As it can be observed that the total solar energy PV system installation has increased significantly over the period of eleven years from the year 2010 to the year 2020. The total installed capacity of solar energy PV systems has increased from a mere 161MW to humongous 37 GW. And we are planning to increase this number to above 100 GW in the next two years.

Table 2.2 Total Installed solar energy PV system on 31 March [15]

Year	Cumulative Capacity (in MW)
2010	161
2011	461
2012	1,205
2013	2,319
2014	2,632
2015	3,744
2016	6,763
2017	12,289
2018	21,651
2019	28,181
2020	37,627

A graphical representation of electrical power generation from the year 2009 to 2019 is shown in figure 2.1. It has every year range on the x-axis and electrical power generated in Terra watts on the y-axis.

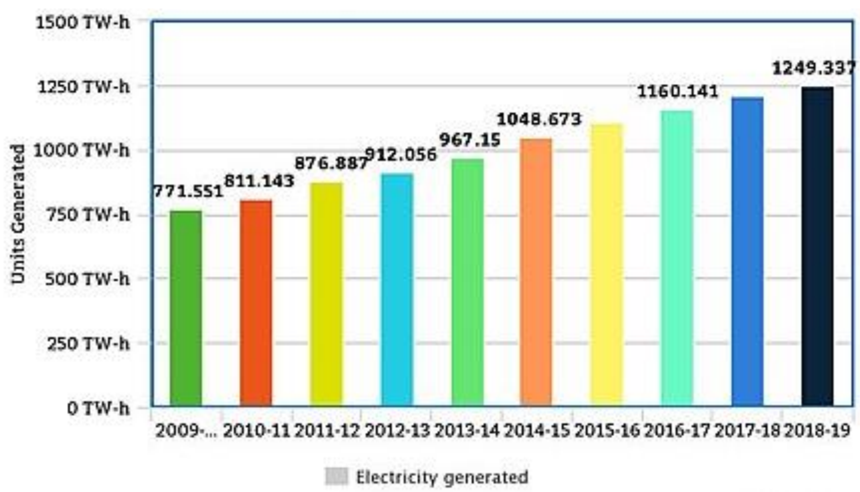

Figure 2.1 Year-wise electricity generation from conventional sources of energy [15]

We can see that the total energy generation has been increasing every year in a linear fashion slowly and steadily. The data in figure 2.1 is obtained from the website of the ministry of power. It clearly shows that the amount of energy generated has increased from just 771 TW to a tremendous 1249 TW in a course of ten years

2.5 Scenario of solar power in the world

Global energy production- both in terms of quantity and source- has changed over the long-term. In the visualization, the plot is of global energy consumption from 1800 through to 2018 [16].

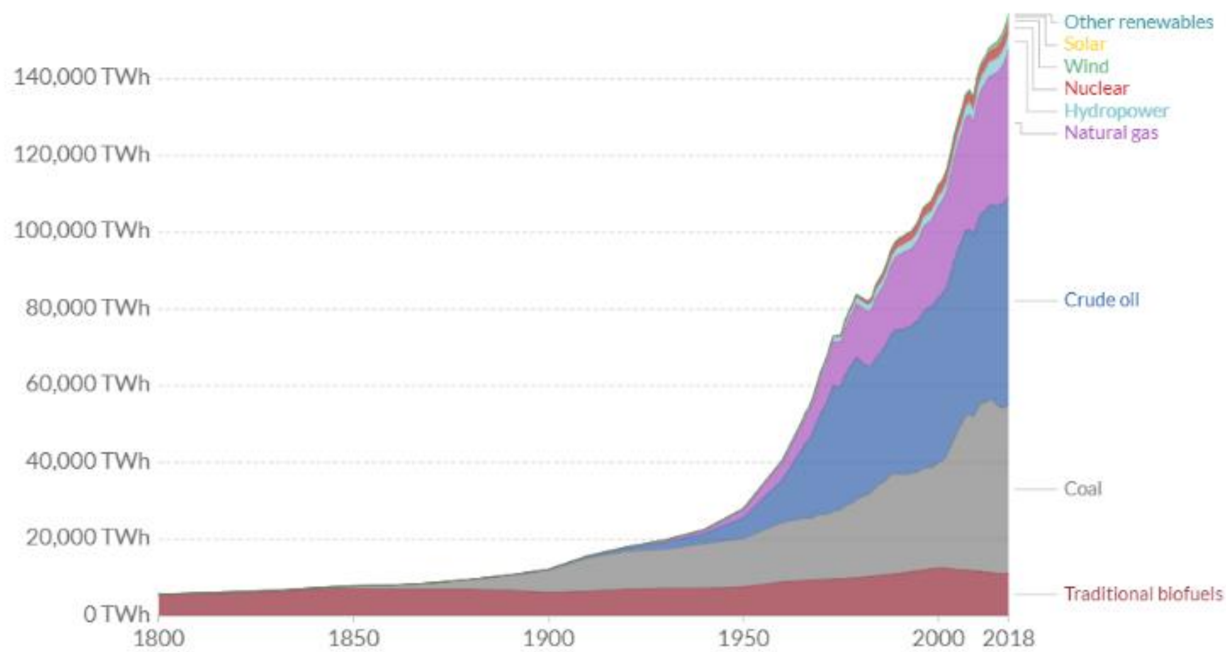

Figure 2.2 Global primary energy consumption chart [16]

With the rapid growth of electricity generation, renewable sources including solar, wind, and hydroelectric power are the fastest-growing energy source between 2018 and 2050, surpassing petroleum and other liquids to become the most used energy source in the Reference case. Worldwide renewable energy consumption increases by 3.1% per year between 2018 and 2050, compared with 0.6% annual growth in petroleum and other liquids, 0.4% growth in coal, and 1.1% annual growth in natural gas consumption [16].

Chapter 3

Simulation of solar cells

3.1 Photovoltaic Systems

It is possible to connect solar cells in both in series and in parallel, or in both so as to acquire the desired value of voltages and currents. In the case where two or more similar solar cells are to be connected in a series connection, the resulting output voltages and the currents are changed and are shown in the figure. Generally, a connection that is parallel among cells will result in the addition of all currents which is shown in the figure. And if cell 1 and cell 2 have different characteristics traits, then output characteristics of the joint arrangement will be changed which is shown in the Figure. A blocking diode is used generally in series with a solar cell module or a solar array to prevent the electrons from flowing backward. Taking an example, they form a battery to the cells equivalent to that in the dark conditions. To bypass the whole module if it is under the shade, a bypassing diode device is to be used in connection which is parallel with the module or an array.

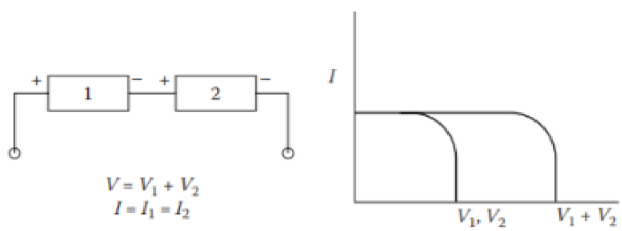

Figure 3.1 Series connected cells [14]

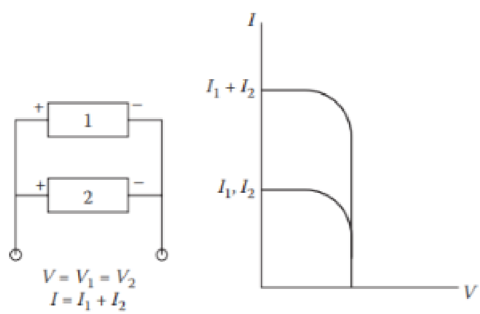

Figure 3.2 Parallel connected cells [14]

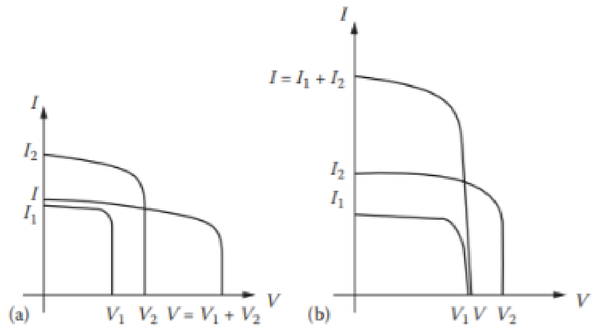

Figure 3.3 Combined effect of (a) series and (b) parallel combination of cells [14]

3.2 Modelling for simulation of solar cell

3.2.1 Silvaco TCAD models used

1. Shockley reed hall- Uses fixed minority carrier lifetimes. Used in most simulations
2. Optical - Bandgap recombination for direct materials only
3. Auger - Direct transition of three carriers. Important at high current densities
4. Bandgap narrowing-Important in heavily doped regions. Critical for bipolar gain
5. Concentration dependent-Uses concentration-dependent lifetimes.
6. Boltzmann- default model
7. Fermi-Dirac-reduced carrier concentration in the heavily doped region
8. Concentration dependent-Uses simple power-law temperature dependence
9. Parallel electric field dependence-Required to model any type of velocity saturation effect
10. Selberherr’s model-Uses fixed minority carrier lifetimes [18].

3.2.2 Solar cell used for verification

The multi-junction solar cell device used is shown in figure 3.4 is a schematic diagram including the material used along with the typical bandgap of the individual cell. The device is taken from reference literature [8].

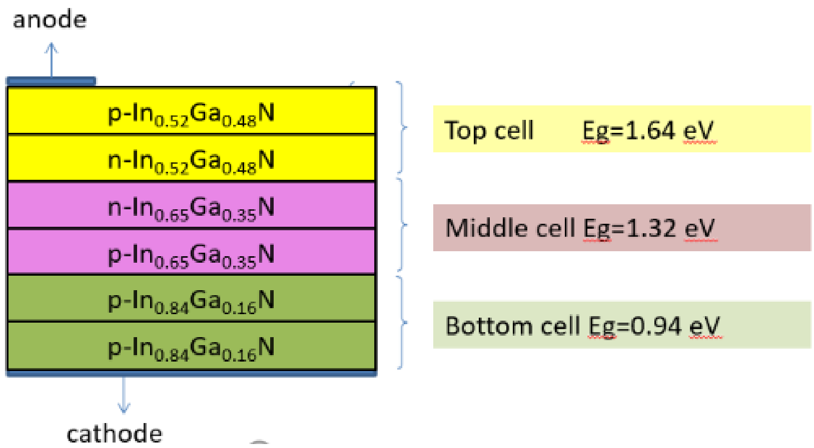

Figure 3.4 Schematic diagram of multi-junction solar cell used [19]

Table 3.1 Material parameters used [19]

Parameters	$In_{0.52}Ga_{0.48}N$ p-type	$In_{0.52}Ga_{0.48}N$ n-type	$In_{0.65}Ga_{0.35}N$ n-type	$In_{0.65}Ga_{0.35}N$ p-type	$In_{0.84}Ga_{0.16}N$ p-type	$In_{0.84}Ga_{0.16}N$ n-type
Thickness (um)	0.1	0.2	0.025	0.025	0.1	0.15
Dielectric constant	12.58	12.58	13.13	13.13	13.93	13.93
Electron mobility(cm^2/Vs)	685	685	685	685	685	685
Hole mobility(cm^2/Vs)	153	153	153.3	153.3	153.3	153.3
Carrier density(cm^{-3})	10^{15}-10^{19}	10^{15}-10^{19}	$5*10^{18}$	10^{18}	10^{18}	10^{18}
Optical band gap,Eg(eV)	1.64	1.64	1.32	1.32	0.94	0.94
Effective density,Nc (cm^{-3})	$1.57*10^{18}$	$1.57*10^{18}$	$1.39*10^{18}$	$1.39*10^{18}$	$1.12*10^{18}$	$1.12*10^{18}$
Effective density,Nv (cm^{-3})	$3.62*10^{19}$	$3.62*10^{19}$	$4.075*10^{18}$	$4.075*10^{18}$	$4.74*10^{19}$	$4.74*10^{19}$
Electron affinity(eV)	5.33	5.33	5.56	5.56	5.82	5.82

For the solar cell considered for verification, the material parameters are summarized in table 3.1 shown above. It includes parameters like thickness, permittivity, mobility, and others for each layer of the solar cell.

3.2.3 Parameters comparison

A comparison of parameters obtained after stimulation with the reference values is shown in table 3.2 mentioned below.

Table 3.2 comparison of reference values with simulated values

Parameter	Reference Values	Simulated Ouput
Voc	1.26 V	1.204 V
Jsc	24.32 mA/cm^2	29 mA/cm^2
FF	0.90	0.88
Efficiency	27.62 %	31 %

After getting the desired results with the obtained data we can now further introduce the temperature problem in the simulation device which will no doubt create a whole new result. But before trying to predict the result with GaAs, we will be focusing our attention on the verification of model with the existing material InGaN based device.

3.2.4 Output parameters after varying doping density of top cell

After performing the simulation on a chosen solar cell the resulting values of parameters are summarized in Table 3.3 shown below.

Table 3.3 Parameters obtained from simulation

Parameters / Concentration cm^{-3}	V_{oc}(open circuit voltage) volts	J_{sc}(short circuit current density) mA/cm^2	P_m(maximum power) mW/cm^2	V_m(voltage at max power point) volts	J_m(current density at max power point) mA/cm^2	FF(Fill factor) %	Efficiency %
10^{15}	0.88	34.78	21.66	0.78	27.75	70.26	21.65
10^{16}	0.95	35.70	27.08	0.85	31.85	79.64	27.07
10^{17}	1.04	33.97	28.68	0.95	30.19	81.16	28.67
10^{18}	1.12	30.54	29.40	1.02	28.54	85.50	29.39
10^{19}	1.2	29.18	31.12	1.09	28.92	88.80	31.10

It includes the variation of solar cell parameters such as open circuit voltage, short circuit current, maximum power point, fill factor, efficiency, etc. with respect to change in doping density of the top cell.

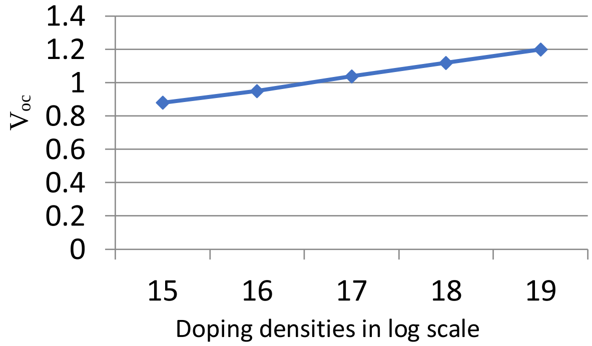

Figure 3.5 Doping density vs V_{oc}

Figure 3.5 has a log of doping densities in the x-axis and open-circuit voltage on the y-axis in volts.

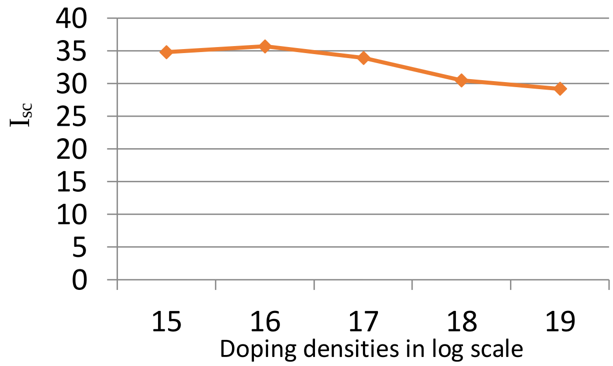

Figure 3.6 Doping density vs J_{sc}

Figure 3.6 has a log of doping densities in the x-axis and short-circuit current density whose unit is mA/cm^{-2} on the y-axis.

3.2.5 Comparison of parameters

A comparison of efficiency is obtained after simulation with respect to the reference values and an error vector is obtained and is shown in Table 3.4 mentioned below.

Table 3.4 Deviation of simulated values from reference values

Efficiency %	Reference efficiency %	Percentage error %
21.65	21.5	0.69
27.07	24.5	10.48
28.67	25	15.48
29.39	26	13.03
31.10	27	14.8

And the plot for the same is shown in figure 3.7.

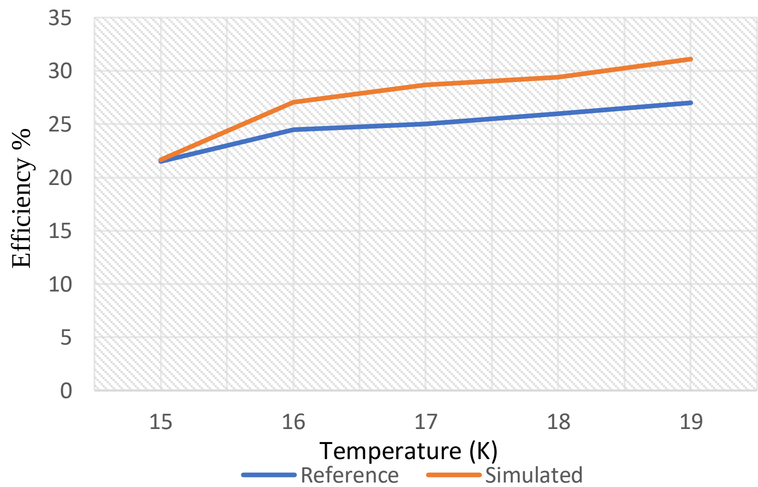

Figure 3.7 Plot for efficiencies if both cases

Chapter 4

Results, Analysis, and discussion

The results after doing the simulation are obtained and have been shown as in the following figures and no doubt we will be doing the analysis of these results and by doing so we will be getting the trend results of the obtained device of our solar cell which is a multi-junction solar cell.

4.1 Variation in open-circuit voltage with respect to temperature

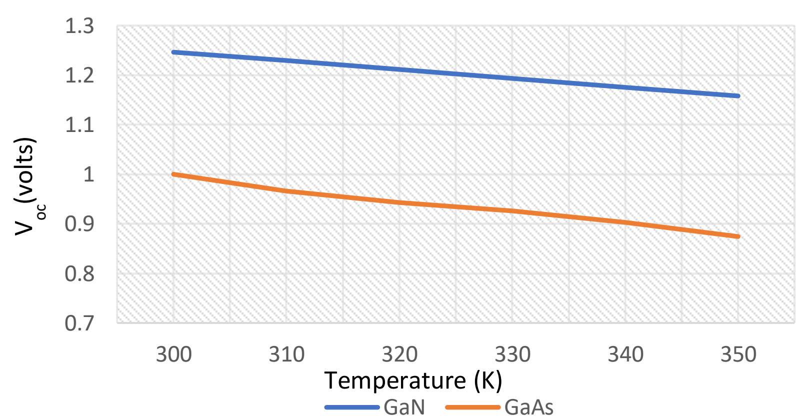

Figure 4.1 Temperature dependence of the V_{oc} of multi-junction solar cell

The variation of open-circuit voltage with respect to temperature has been plotted in the above graph. Temperature is being varied from 300K to 350 K which is the range of operation of the solar cell. As obtained from the literature, experimentally the open-circuit voltage of GaN-based multijunction solar cells is showing a decreasing trend in the value with respect to temperature.

4.2 Variation in short circuit current with respect to temperature

The variation of short circuit current with respect to temperature has been plotted in the below graph. Temperature is being varied from 300K to 350 K which is the range of operation of solar cells.

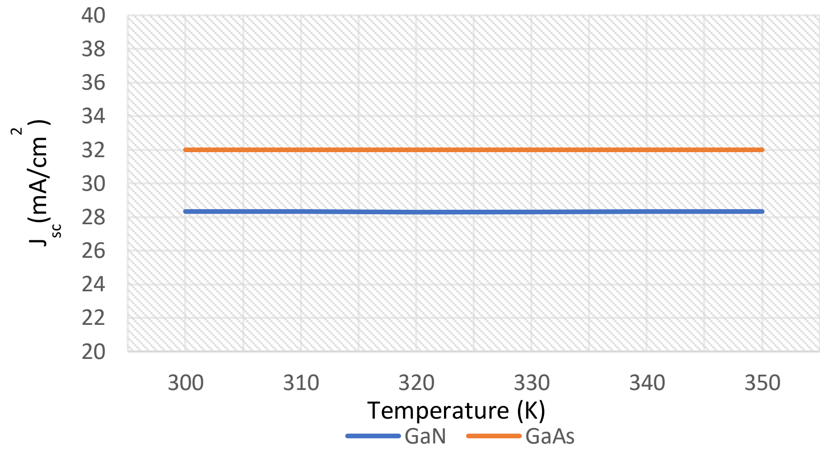

Figure 4.2 Temperature dependence of the J_{sc} of multi-junction solar cell

As obtained from the reference paper, experimentally the short circuit current of GaN-based multijunction solar cell is showing a minor increase in the value of current with respect to temperature.

4.3 Variation in fill factor with respect to temperature

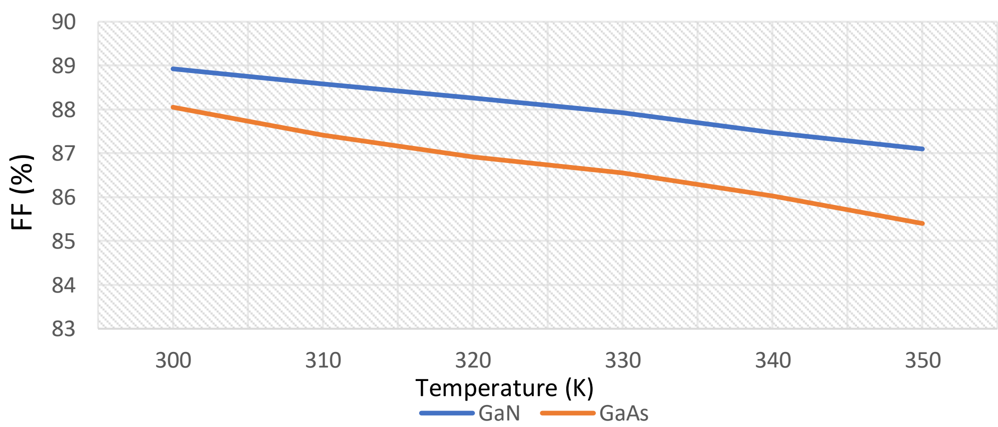

Figure 4.3 Temperature dependence of the FF of the multi-junction solar cell.

The variation of FF with respect to temperature has been plotted in the above Plot. Temperature is being varied from 300K to 350 K which is the range of working of the solar cell. As obtained from the literature, experimentally the FF of GaN-based multijunction solar cell is showing a decreasing trend in the value of FF with respect to change in temperature.

4.3 Variation inefficiency with respect to temperature

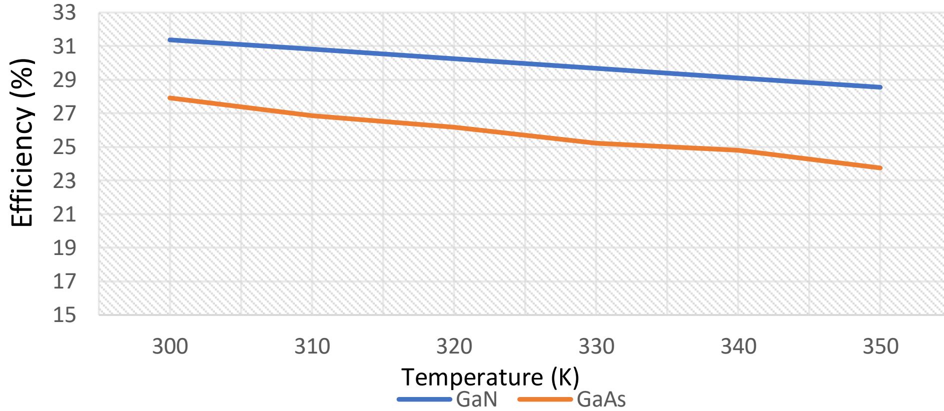

Figure 4.4 Temperature dependence of the efficiency of multi-junction solar cell

The variation of efficiency with respect to temperature has been shown in the above graph. Temperature is being varied from 300K to 350 K which is the range of operation of the solar cell. As obtained from the reference article, the open-circuit voltage of GaN-based multijunction solar cell is showing a decreasing trend in the value of efficiency with respect to temperature.

This page is intentionally left blank

Chapter 5

Conclusion and future scope of work

The ideal parameters behavior has been obtained for the GaAs based solar cell device which is on considering the similar trend of the reference InGaN material based solar cell device, and there is also the device on which the model is verified and found to be working mentioned in chapter 3.

Overall the result of the variation of temperature on the parameters which are open-circuit voltage, short circuit current, efficiency and fill factor has been observed in chapter 4. We can conclude various interpretations from the results obtained in the previous chapter.

On increasing the temperature of the solar cell device, the parameters vary in a certain trend. Open circuit voltage reduced drastically owing to the shift in bandgap with respect to the temperature which is incorporated by the thermally generated electrons.

The current show negligible variation with respect to temperature.

The efficiency and the fill factor show a reducing trend which is evident from the dominant effect of open-circuit voltage and feeble effect of short circuit current.

Future scope of work

The variation of parameters can be observed with variation in the concentration of sunlight and also with the number of junctions.

This page is intentionally left blank

REFERENCES

[1] Standard solar spectra, nrel.gov.in/

[2] Supriya Karmakar, High efficiency quantum well triple junction tandem solar cell, 1Electrical and Computer Engineering Technology, Farmingdale State College.

[3] Kensuke Nishioka, Tatsuya Takamoto, Takaaki Agui, Minoru Kaneiwa, Yukiharu Uraoka, Takashi Fuyuki, Evaluation of temperature characteristics of high-efficiency InGaP/InGaAs/Ge triple-junction solar cells under concentration, Graduate School of Materials Science, Nara Institute of Science and Technology, 8916-5 Takayama, Ikoma, Nara 630-0101, Japan

[4] Yearly variation of sunlight, powermine.nic.in/

[5] M.Y. Feteha, G.M. Eldallal, The effects of temperature and light concentration on the GaInP/GaAs multijunction solar cell's performance, Institute of Graduate Studies and Research, Alexandria University

[6] T. Sumita, M. Imaizumi, S. Matsuda, T. Ohshima, A. Ohi, H. Itoh, Proton radiation analysis of multi-junction space solar cells, Department of Research and Development, National Space Development Agency of Japan, *Science direct*

[7] Tatsuya Takamoto, Minoru Kaneiw, Mitsuru Imaizumi, Masafumi Yamaguchi, InGaP/GaAs-based Multijunction Solar Cells, 1SHARP Corporation, 492, Minosho-Cho, Yamatokoriyama, Nara, 639-1186, Japan, *PROGRESS IN PHOTOVOLTAICS: RESEARCH AND APPLICATIONS*

[8] Dennai Benmoussa, Hamid Khacahab, Hassane Benslimane, Simulation of the Indium aluminum nitride multijunction solar cell performances, Department of faculty science, University of Tahri Mohammed

[9] Jeffrey F. Wheeldon, Christopher E. Valdivia, Alexandre W. Walker, Gitanjali Kolhatkar, Abdelatif Jaouad, Artur Turala, Bruno Riel, Denis Masson, Norbert Puetz, Performance comparison of AlGaAs, GaAs and InGaP tunnel junctions for concentrated multijunction solar cells, Centre for Research in Photonics, University of Ottawa, Ottawa, ON, Canada, *Prog. Photovolt: Res. Appl. 2011; 19:442–452*

[10] Stephanie Essig, Jan Benick, Michael Schachtner, Alexander Wekkeli, Martin Hermle, Frank Dimroth, Member, Wafer-Bonded GaInP/GaAs//Si Solar Cells With

30% Efficiency Under Concentrated Sunlight, *IEEE JOURNAL OF PHOTOVOLTAICS, VOL. 5, NO. 3, MAY 2015*

[11] Mohammad I. Hossain, Abdelkader Bousselham, Fahhad H. Alharbi, Numerical analysis of the temperature effects on single junction solar cells efficiencies, Qatar Environment & Energy Research Institute (QEERI), Qatar Foundation, Doha, Qatar

[12] Gaurav Siddharth, Vivek Garg, Brajendra S. Sengar, Ritesh Bhardwaj, Pawan Kumar. Shaibal Mukherjee, Analytical Study of Performance Parameters of InGaN/GaN Multiple Quantum Well Solar Cell, *IEEE TRANSACTIONS ON ELECTRON DEVICES, VOL. 66, NO. 8, AUGUST 2019*

[13] D.Y. Goswami, A., Principles of solar engineering. Third edition. CRC Press, pp. 42-292 (ISBN).

[14] Benmoussa Dennai, A Hemmani, H-Ben Slimane, A.Helmaoui, Simulation of multi-junction solar cells based on InGaN using AMPS-1D, Laboratory in semiconductor device University of Bechar, Algeria, *International Journal of Engineering Research & Technology (IJERT)*

[15] Indian energy scenario, powermine.nic.in/

[16] World consumption statistics, yearbook.enerdata.net/total-energy/world-consumption-statistics

[17] World energy data, ourworldindata.org/energy

[18] Silvaco Atlas user manual, chapter 3, Physical models, pp. 72-140

[19] Dennai Benmoussa, Hamid Khacahab, Hassane Benslimane, Simulation of the Indium aluminum nitride multijunction solar cell performances, Department of faculty science, University of Tahri Mohammed