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TEMPERATURE-DEPENDENT ANALYSIS OF GRADED JUNCTION SOLAR CELL PERFORMANCE USING CURRENT VOLTAGE CHARACTERIZATION

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Abstract

Now a days fossils fuels are depleting and are expensive source of energy. Therefore, it is important to find some alternative source of energy. Sunlight is costless and is always available throughout the world. Since many years, solar energy has become of great interest for public. Scientists and researchers are trying to explore properties of semiconductor materials in order to increase the efficiency of solar cell. Solar cells show better performance under high irradiance however, it has also ability to work even at low irradiance. In this work, simulations have been made to examine the impact of various external and internal parameters on the working efficiency of solar cell. Ideal diode equation is used to calculate dark data of J vs V, characterization of lnJ vs V at dark and illuminated data at different temperature and to calculate all external and internal parameters to compare theoretical data with experimental data by origin software. A detailed analysis is introduced for variations in external parameters such as (J_{sc}. V_{oc}. FF%, Eff %). Experimental values calculated for series resistance show good correlation with fitted values using Shockley equation. We have conducted results for solar cell external parameters as a function of doping density. Modeling for graded junction solar cell shows, J_{sc}, V_{oc}, FF and efficiency decreases by increasing the temperature. The internal parameters ideality factor A and Current density J_o also decrease with increasing the temperature.

INTRODUCTION

The world industrial capacity is inherently associated with having strong energy sources. With the invention of the condensation engine, petroleum became a powerful, cost-effective fuel, and it led to the emergence of the era that will later be enhanced by energy sources of sunlight, wind, hydropower, biomass and nuclear power [1]. Nonetheless, traditional sources of power generation, such as those that are based on heavy use of fossil fuels (as petroleum and coal) lead to serious environmental pollution by means of unburnt carbon and other toxic gases release, which is a major threat to human health and ecosystems [2]. Moreover, nuclear energy, in spite of its considerable power, is costly and poses insurmountable questions in terms of radioactive waste disposal and management.In its turn, solar energy comes across as a shining example of sustainability and renewable energy. It has significant benefits: it does not pollute air, water, or noises; it needs fewer maintenance; it avoids the problems of fuel transportation; and works continuously due to low costs of operating. Although these are strong incentives, the role of solar cells in the world energy equation is out of proportion with only 1% according to a statistical survey of 2007, coal (30%), gaseous gasoline (16%), hydropower (15%), lubricants (9%), and atomic reactors (4%) forming the majority [3]. Historically, the biggest obstacle to widespread implementation has been the capital cost of the technology of solar cells. However, this has changed in the modern times where solar energy is taking a new-found step of limelight in developed countries due to the increasing green issues and the intrinsic disadvantages to other energy sources like radioactive effects and rising levels of carbon dioxide in the air.

1.2 Energy Conversion Methods

The transformation of energy from one form to another is a fundamental principle of power generation. Diverse primary sources, including geothermal, wind, solar, and fossil fuel energy, can be harnessed through specific conversion processes.

1.2.1. Hydrogen as a Fuel Cell

Chemical energy can be converted directly into electrical energy employing hydrogen fuel cells, achieving a conversion efficiency of approximately 60%. This process is notably reversible through electrolysis, enabling energy storage [4].

1.2.2. Nuclear Energy into Electrical Energy

Nuclear power generation utilizes the heat produced by nuclear fission reactions. This thermal energy is subsequently converted into mechanical energy by heat engines and finally into electrical energy by electric generators [5].

1.2.3. Sunlight into Electricity

The direct conversion of solar energy into electrical energy is achieved via the **photovoltaic effect**, a process intrinsic to semiconductor materials. The term "photovoltaic" is derived from "photo" (light) and "volt" (electric potential) [6]. Alternatively, solar energy can be transformed into heat (solar thermal energy), which can then drive heat engines for electricity generation, particularly in concentrated solar power systems that employ high-temperature collectors [7].

1.2.4. Solar Energy into Chemical Energy

Solar energy can also be stored in chemical bonds, creating solar fuels. This is accomplished by integrating photovoltaic systems with regenerative fuel cells or through direct photochemical conversion devices [8].While fossil fuels and nuclear energy are considered non-renewable due to finite reserves, hydropower, wind, and solar power are classified as renewable. Electricity, a cornerstone of modern civilization, is predominantly generated from coal, oil, gas, nuclear, and hydropower. As of 2007, fossil fuels (coal and gas) were responsible for 65% of global electricity production, nuclear power for 16%, and hydropower for 19% [9]. The sun remains the most constant and abundant primary energy source, fundamentally driving wind patterns, hydrological cycles, and wave formation. Consequently, a strategic pivot towards the direct utilization of solar energy is a critical imperative for achieving a sustainable energy future.

1.3 Solar Cell

1.3.1 Working Principle of Solar Cell

A solar cell, or photovoltaic (PV) cell, is a semiconductor device that converts light energy directly into electrical energy. The most prevalent material for solar cell fabrication is silicon. A silicon atom possesses four valence electrons, and in its crystalline form, atoms bond covalently to create a stable lattice. The electrical properties are strategically engineered through "doping".p-type silicon is created by introducing elements like boron (with three valence electrons), generating positively charged "holes" as the majority charge carriers.

n-type silicon is formed by doping with elements like phosphorus (with five valence electrons) providing an abundance of free electrons.A functional solar cell is constructed by joining p-type and n-type silicon layers. Electrical contacts are affixed to both layers, and a protective glass cover is typically deployed to shield the device from environmental factors.

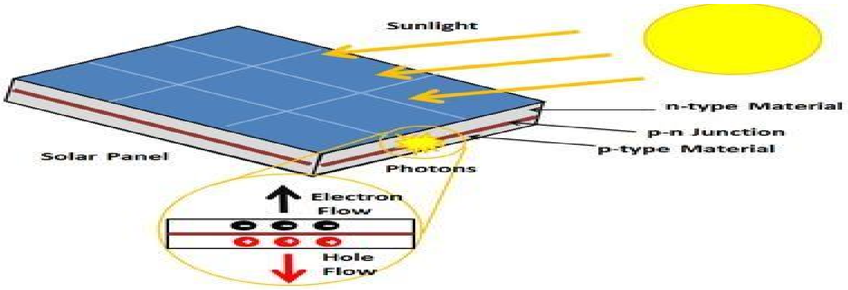

Figure 1.1: Schematic representation of a basic Solar Cell structure.

The operational principle is governed by the **photovoltaic effect**, which can be delineated into three sequential physical mechanisms:

Absorption and Carrier Generation: Photons from incident sunlight penetrate the semiconductor absorber layer. If a photon's energy exceeds the material's bandgap, it excites an electron from the valence band to the conduction band, creating a mobile electron-hole pair.

Charge Carrier Separation: The internal electric field established at the p-n junction acts as a force, efficiently separating the photogenerated electron-hole pairs. Electrons are driven towards the n-type region, while holes migrate towards the p-type region.

Charge Collection and Circulation: The separated charges are collected at their respective metallic contacts. When an external electrical load is connected, electrons flow through the circuit, performing useful work, and eventually recombine with holes at the opposite contact, completing the circuit.

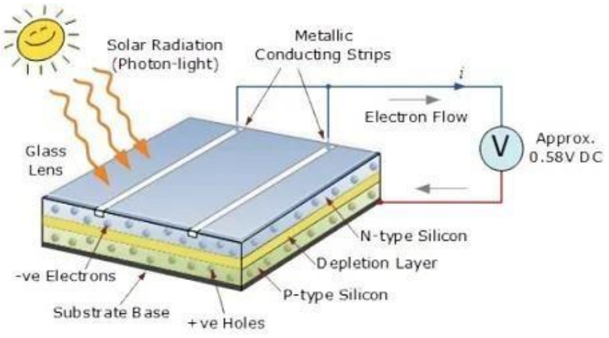

Figure 1.2: Illustration of the working principle of a solar cell, depicting photon absorption, charge carrier separation via the p-n junction, and current flow through an external load.

1.3.2. Types of Solar Cell

Commercial photovoltaic technologies are primarily categorized based on the crystalline nature of the active semiconductor material, most commonly silicon.

Monocrystalline: Fabricated from a single, continuous crystal structure of high-purity silicon, these cells offer the highest efficiency due to superior electronic properties. They are characterized by a uniform dark appearance and typically an octagonal wafer shape.Bandgap: ~1.12 eV [10].

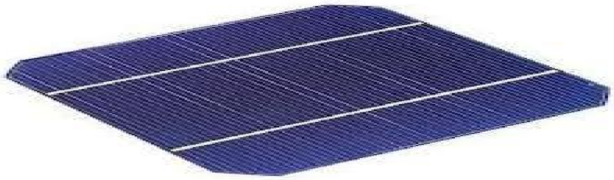

Figure 1.3: Monocrystalline Solar Cell

Polycrystalline: Composed of multiple smaller silicon crystals solidified together. This manufacturing process is less energy-intensive, resulting in lower costs but also marginally lower efficiency compared to monocrystalline cells. A visible grain structure is a hallmark of this technology.Bandgap: ~1.12 eV [11].

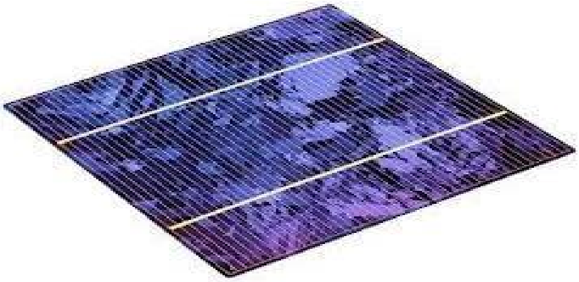

Figure 1.4: Polycrystalline Solar Cell

Thin Film or Amorphous Silicon: These cells are produced by depositing non-crystalline (amorphous) or microcrystalline silicon in thin layers onto a substrate such as glass, plastic, or metal. They offer advantages in lightweight, flexibility, and lower material usage, but at the expense of lower conversion efficiency.Bandgap: ~1.75 eV [12].

Figure 1.5: Thin Film Solar Cell

1.4 Photovoltaic Junctions

The essential component of a solar cell is a semiconductor junction that creates a potential energy barrier to separate photogenerated electrons and holes. The most fundamental structure is the p-n junction.

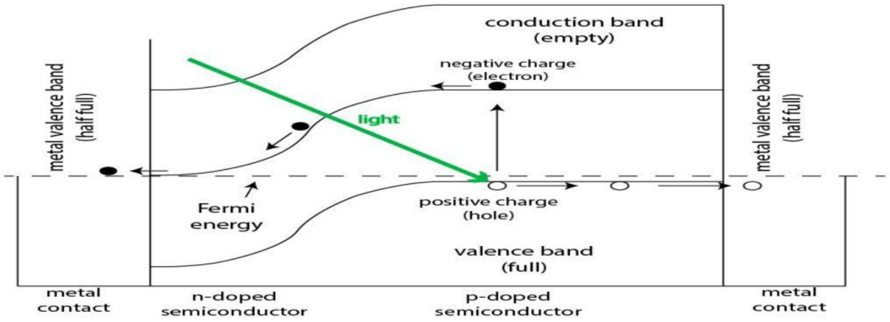

Figure 1.6: Diagram of a standard p-n junction Solar Cell.

Several advanced junction architectures have been developed to optimize performance and mitigate losses:

Homojunctions: The p-n junction is fabricated from the same semiconductor material (e.g., standard silicon cell). While they exhibit high junction efficiency, they can suffer from significant front surface recombination losses, particularly in materials with high absorption coefficients [13].

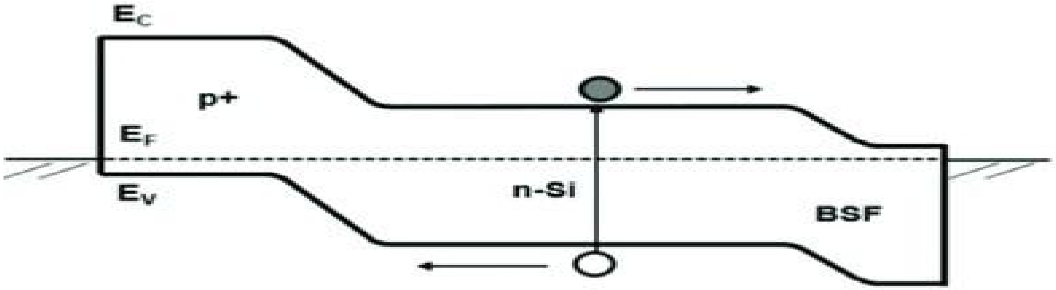

Figure 1.7: Structure of a Homojunction solar cell.

Heterojunctions: This design employs a junction between two different semiconductor materials, typically pairing a low-bandgap absorber with a high-bandgap "window" layer. This can effectively reduce front surface recombination, provided the lattice constants are well-matched to minimize interface state density [14].

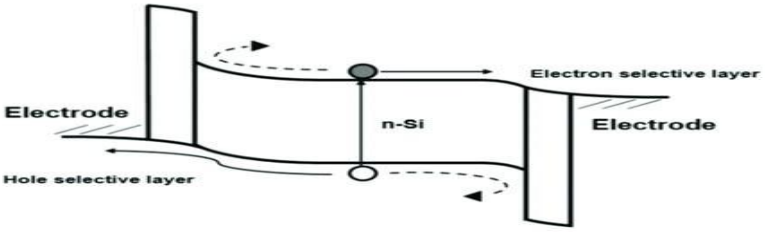

Figure 1.8: Structure of a Heterojunction solar cell.

Buried Homojunctions (Heteroface): This architecture incorporates a p-n homojunction with an additional high-bandgap heterojunction that acts as a passivating window layer. This design synergizes the advantages of both homojunctions and heterojunctions, mitigating front surface recombination while maintaining a high-quality junction.

Schottky Barriers: In this configuration the necessary band bending for charge separation occurs at the interface between a metal and a semiconductor, rather than within a p-n junction. A Schottky barrier is formed due to the difference in work functions between the metal and the semiconductor .

1.6 Graded Junction Solar Cell

The escalating global energy demand necessitates the development of novel solar cell architectures capable of delivering high efficiency alongside cost-effective electricity production. The graded junction solar cell represents one such promising design.In contrast to an abrupt p-n junction where the dopant concentration changes discontinuously, a graded junction features an impurity concentration that varies smoothly across the junction, often as a linear function of position. This deliberate gradation creates a built-in electric field that can significantly enhance the collection efficiency of photogenerated charge carriers. The fundamental principle underpinning a graded junction is a bandgap that varies spatially from one end of the device to the other. This engineering allows different segments of the solar spectrum to be absorbed optimally within distinct regions of the cell, thereby maximizing photon utilization.

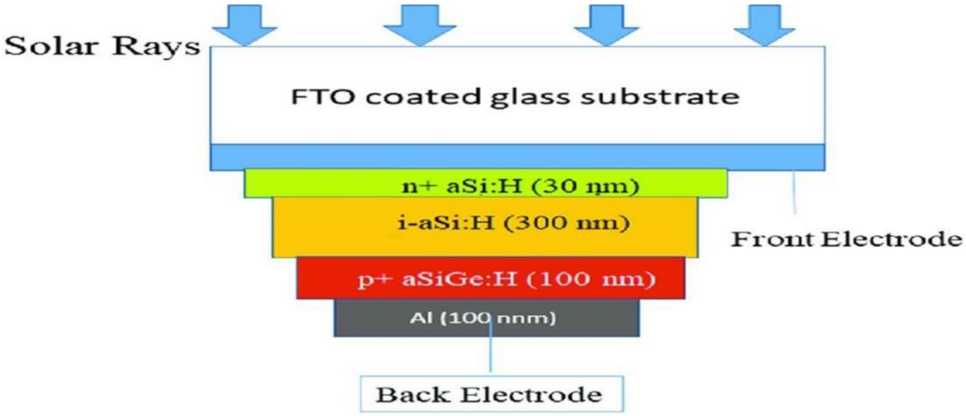

Figure 1.9: Schematic of a graded Solar Cell junction, illustrating the continuous variation in doping concentration and resultant bandgap.

1.7 Proposed Work

This research is dedicated to the modeling and characterization of a graded junction solar cell. To circumvent the animated recycler and high costs associated with iterative fabrication, simulation serves as a critical tool for predicting and optimizing device performance. The present work involves:Simulating the performance of a graded junction solar cell utilizing a one-diode model based on the Shockley ideal diode equation.Close-fitting experimental J-V data, obtained at various temperatures, to the one-diode model using OriginLab software.Extracting key internal photovoltaic parameters (e.g., JoJo, AA, JLJL) through non-linear curve fitting.Conducting a detailed analysis of the variations in external parameters (JscJsc, VocVoc, FF%, Eff%) with temperature.Correlating experimentally determined series resistance with fitted values derived from the Shockley equation.Performing a rigorous statistical analysis, including ANOVA and goodness-of-fit metrics.

1. Existing Literature

The chapter is a review of literature pertinent to the research on solar cells which gives a background to the current research on graded junction devices. The literature ranges back to the foundational works on the physics of devices, to some of the most recent works on new materials and nanostructures.An exhaustive early repository is the literature by in 2024 which gave a generic source on heterojunction and Schottky barrier cells, thin film devices and polycrystalline devices. It encompassed the mechanism of photocurrent generation, electrical behavior in the dark of spectral response in polycrystalline films, and the effect of grain boundaries on photo-induced charge transfer between donor-type semiconducting polymers and acceptor molecules such as C60, which formed a broad base on the analysis of solar cells based on polymers. This charge transfer was discovered to occur with very high speed (within 100 fs) and gave rise to a metastable charge-separated state causing a 3% power transformation efficacy in the device at then (Lopez-Bellagio 18). This development was faster as recapped by Li et al. (2012) who found out that power-conversion efficiency in polymer solar cells had improved to 3 percent to almost 9 percent.

Their survey has described the opportunities of solution-processable semiconducting polymers to low-cost solar energy collection to projecting applications in flexible modules and building-integrated photovoltaics [15]. His paper who concentrated on the kind of solar cells and their usage systematized the broader landscape, as though different materials may be utilized, semiconductor p-n junctions are applied in nearly all the conversion of photovoltaic energy [16].The period of innovation in organic photovoltaics was further chronicled by[18] through new materials and improved device structure. They highlighted that the potential for low-cost production strongly encouraged the advancement of organic photovoltaic devices [17]. also provided a dedicated focus on the principles and potential of organic solar cells .

Concurrent research on inorganic thin-film cells remained highly active. meticulously investigated the effects of deposition parameters on the structural, optical and electrical characteristics of aluminum-doped zinc oxide (ZnO:Al) films. They found that applying an extended chamber tension of 2.5 Paled to an overall increase of 10% in the solar cell efficacy compared to a cell without the ZnO:Al back reflector [18]. The challenges of interface management were highlighted by who studied surface damage in ITO/InP solar cells during production using RBS channeling methodology. They correlated the crystalline hurt formed during ITO deposition with the poor shift efficiencies in the range of 9.6–12 percent (AM 1.5) .The convergence of organic and inorganic materials led to hybrid solar cells. reviewed this class, which combines the exceptional film-forming properties of conjugated polymers with the high absorption coefficients and size tunability of inorganic semiconductor nanoparticles [19]. reinforced this perspective, noting that while silicon-based cells are highly efficient, their cost and manufacturing complexity make organic-Based cells attractive if their proficiency can be increased to healthy levels..The photovoltaic landscape was later revolutionized by metal halide perovskites. provided a landmark review of high-efficiency perovskite solar cells (PSCs) documenting their rapid rise to a power conversion efficiency (PCE) of 25%. They positioned PSCs as a strong candidate for next-generation solar energy harvesters due to their high performance and low expense of materials and processes . The materials odyssey for organic solar cells was detailed by who traced the molecular structure evolution of key donor and acceptor materials over 25 years, which culminated in modern devices achieving 18% efficiency .Advanced concepts like multi-junction cells have been pursued to surpass the efficiency limits of single-junction devices.demonstrated a two-junction cascade solar-cell structure in the AlGaAs/GaAs materials system, achieving an open-circuit voltage of 2.0 V, the highest reported for a single monolithic photovoltaic cell at the time [20]. provided a theoretical framework using their spectral p-n junction model for tandem solar-cell design calculating that a two-cell tandem system could achieve significantly higher efficiency with the potential for up to 94.9% in a ten-cell system under ideal conditions [21]. The application of new materials in extreme environments was explored by , who reviewed the progress of PSCs for space applications, citing their high specific power, flexibility and excellent radiation resistance].Research on specific absorber materials like kesterites has also been prolific. fabricated Cu22 ZnSnS44 (CZTS) thin films via RF magnetron sputtering, confirming a kieserite structure and an optical band energy of 1.51 eV deemed superior for photovoltaic materials. further investigated the effect of calcination temperature on CZTS films observing that increased temperature improved crystallinity and reduced the bandgap to 1.59 eV thereby enhancing the photochemical reaction .Nanostructuring has emerged as a powerful strategy to enhance performance. reported an n-type nc-Si:H/p-type c-Si heterojunction solar cell fabricated using RF-sputtered nanocrystalline silicon achieving a Vococ of 370 mV and a Jscsc of 6.5 mA/cm22 . By performed a computational optimization of ITO-free PEDOT:PSS/InP nanowire hybrid solar cells. Their FDTD and electrical simulations predicted a Jscsc of 34.2 mA/cm22 and an efficiency of up to 24%, outperforming analogous ITO-based structures . A seminal theoretical study by compared the device physics principles of planar and radial p-n junction nanorod solar cells. They demonstrated that the radial geometry could dramatically improve efficiency in materials with low minority-carrier diffusion lengths (e.g., from 1.5% to 11% in silicon with Lnn=100 nm) by decoupling the directions of light absorption and carrier collection .Further contributions to heterojunction technology include the work of auther who achieved a 2% efficiency with a heterojunction solar cell based on a Cu22 O substrate, the highest reported for this type of device at the time .Described a high-efficiency electroplated CdS/p-CdTe heterojunction solar cell where the active junction formed deep within the material, away from any potential outside effects . employed a detailed numerical computer program to investigate the efficiency of heterojunction and graded bandgap solar cells, providing early theoretical support for the potential of these advanced structures .Finally reviewed the commercial prospects of organic solar cells (OSCs)particularly small-molecule devices processed via vacuum evaporation. They identified the primary challenges as increasing the open-circuit voltage and short-circuit current while maintaining excellent device stabilities .This body of literature underscores a continuous trajectory of innovation across material systems and device architectures. The present work on graded junction solar cells builds upon this rich foundation aiming to contribute to the understanding of how temperature and internal parameters influence photovoltaic performance.

3. Theoretical Framework and Methodology

This chapter outlines the theoretical models and analytical methods used to characterize the solar cell performance. The analysis is based on the one-diode model derived from the Shockley equation, enabling the extraction of both external and internal photovoltaic parameters.

n Ideal Solar Cell

The electrical behavior of an ideal solar cell is represented by the current-voltage (I-V) characteristic following the Shockley diode equation:

$$I = Iph - Io(e\frac{qV}{KbT})$$

Where,

Iph = photo current

Io = reverse saturation current

V = applied voltage

T = absolute temperature

Kb = Boltzmann constant

The significant and basic parameter for an ideal solar cell is Isc (short circuit current) and Voc (open circuit voltage).

For an ideal case,

Isc = I |v=0 = - Iph

According to the middle equation, short circuit current is the current present when the voltage approaches zero.

A second very important term is open circuit V_{oc}

$$\text{Voc} = \text{V} \mid \text{I=0} = \frac{KT}{q}\, ln\, (\frac{I_{ph}}{I_o} + 1)$$

Iph/Io is much larger than I so,

$$V_{oc} = V_T\, ln(\frac{I_{ph}}{I_o})$$

When there is no current, this voltage exists. Therefore, the current in the prior equation is zeroed.

The equation demonstrates that we should have an extremely low I=0 in order to optimize or increase V_{oc}. And solar radiation plays a major role in determining I_{sc}. In order to maximize V_{oc}, we needed to keep Io as low as feasible, which is dictated by the p-n junction's characteristics.

Solar cell efficiency is calculated by the current at optical working point which is defined by,

$$\eta = \frac{I_{sc} V_{oc}\, FF}{P_{in}}$$

Where, FF = Fill factor

$$FF = \frac{J_m V_m}{J_{sc} V_{oc}}$$

I_m and V_m is the optical points of cell.

3.2. Practical Solar Cell

Actual solar cells' I-V curves deviate from those of ideal solar cells. In a twodiode model, we use series resistance and shunt resistance for non-ideal solar cells. A non-ideal scenario equation is given.

$$I = Iph - I_{01}\, (exp\frac{V+IR_s}{K_B\, T}) - I_{02}\, (exp\frac{V+IR_s}{2K_B\, T}) - \frac{V+IR_s}{R_p}$$

In non- ideal case power is not maximum and hence lower efficiency η

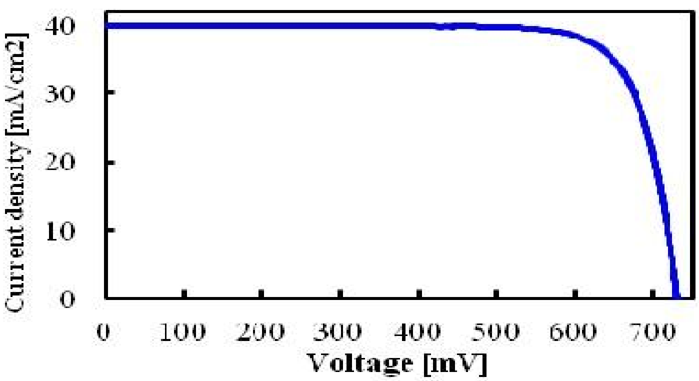

Figure 3.1: I-V Curve for ideal solar cell

3.3. Analysis of External Parameters

External parameters evaluated from J-V characteristics include:

3.3.1. Open Circuit Voltage

hen a solar cell is open circuited (not linked to a load), the voltage through the cell is at its highest and no current travels through the external circuit, which is known as open circuit voltage (V_{oc}).

Voc can be calculated by following equation,

$$J = J_o \left[\exp\left(\frac{qV}{AKT}\right) - 1\right] - J_L$$

For open circuit condition ($J=0$, $V=V_{oc}$), assuming that net current is zero,

$$0 = J_o \left[\exp\left(\frac{qV_{oc}}{AKT} - 1\right)\right] - J_L$$

We have,

$$V_{oc} = AKT \ln\left[1+\frac{J_L}{J_o}\right]$$

$$V_{oc} \approx \frac{AKT}{q} \ln\left[\frac{J_L}{J_o}\right]$$

Where the estimation for justification for $J_L \gg J_o$

V_{oc} is heavily dependent on J_o, the saturation current density, which is affected by recombination in the solar cell. V_{oc} thus measures the degree of recombination in a solar cell.

3.3.2. Short Circuit Current

Under short circuit condition ($J = J_{sc}$, $V = 0$),

$$Jsc = J_o \left[\exp\left(\frac{0}{AKT}\right) - 1\right] - JL$$

$$Jsc = -JL$$

3.3.3. Power Output

Therefore, voltage (V_{mp}) and current density (J_{mp}) are the conditions that provide the most power.

$$Pout = Vout \times Jout$$

$$\text{Rated power in watts} = P_{max} = V_{mp} \times I_{mp}$$

3.3.4. Fill Factor

fill factor is calculated as the ratio of the maximum solar power sold to the product of the open circuit voltage (V_{oc}) and short circuit density (J_{sc}).

$$FF = \frac{P_{max}}{J_{sc} \times V_{oc}} = \frac{J_m \times V_m}{J_{sc} \times V_{oc}}$$

Fill factor depends upon voltage. Higher the voltage, FF will be larger and rounded portion will take less area.

3.3.5. Solar Cell Efficiency

The ratio of maximal power to input power is known as efficiency.

$$\eta = \frac{P_{max}}{P_{in}} = \frac{V_{oc} J_{sc}\, FF}{P_{in}}$$

Where,

$$P^{max} = \frac{V_{oc} J_{sc}\, FF}{P_{in}}$$

Efficiency of cell depends on photons incident on solar cell and temperature of solar cell.

3.4. Calculation for Internal Parameters

Internal parameters are evaluated using one-diode Shockley model.

3.4.1. Shunt Resistance

Low value of shunt resistance leading to high power loss that show process defects. R_{sh} is evaluated from slop near V=0.

$$J = J_o \left[\exp\left(q\left(V - \frac{JR_s}{V_T}\right) - 1\right]\right. - \left(\frac{(V+JR_s)}{R_{sh}}\right)$$

Where, $V_T = \frac{AKT}{q}$

Differentiate with respect to ‗V‘,

$$\frac{dj}{dv} = \frac{J_o}{V_T}\left[e^{\frac{V+JR_s}{V_T}}\left(1 + R_s\frac{dI}{dv}\right)\right] - \frac{1}{R_{sh}} - \frac{R_s}{R_{sh}}\frac{dI}{dv}$$

$$\frac{dI}{dv}\left[1 + \frac{R_s}{R_{sh}} + \frac{I_o R_s}{V_T} e^{\frac{V+JR_s}{V_T}}\right] = \frac{-I_o}{V_T} e^{\frac{V+JR_s}{V_T}} - \frac{1}{R_{sh}}$$

Under short circuit condition,

$$J_o e^{\frac{V+JR_s}{V_T}} = J_o e^{\frac{J_{sc}R_s}{V_T}} \approx 0$$

$$R_s \ll R_{sh}$$

$$R_{sh} = \frac{-dv}{dI}$$

(At short circuit) Shunt resistance can be calculated by taking inverse of the slope on J-V curve near I_{sc}.

3.4.2. Series Resistance

With, $\frac{1}{R_{sh}} \ll \frac{J_{sc}}{V_T}$

$$R_s = -\frac{dj}{dv} - \frac{V_T}{J_{sc}}$$

(At open circuit) Shunt resistance can be calculated by taking inverse of the slope on J-V curve near I_{sc}.

3.4.3. Calculation for Ideality Factor and Reverse Saturation Current Density

The ideality component comes from dark J-V traits. The junction quality and kind of recombination in solar cells are actually measured by the ideality factor. The ideality factor will be n=1 if the neutral region's minority carriers' recombination limits the current. n=2 if recombination takes place in the space charge region.

Under ideal condition,

$$J = J_o\left[exp\left(\frac{qV}{AKT}\right) - 1\right]$$

By neglecting 1 from above equation we have,

$$J = J_o\left[exp\left(\frac{qV}{AKT}\right)\right]$$

By taking log on both sides,

$$ln\frac{J}{Jo} = \frac{qV}{AKT}$$

$$lnJ = \frac{qV}{AKT} + lnJ_o$$

J_o is reverse saturation current density that is result from diffusion and recombination of electrons and holes.

3.4.4. Photo Generated Current Density J_L

$$J = J_o\left[exp\left(\frac{qV}{AKT}\right) - 1\right] - J_L$$

Under short circuit condition,

3.5. Effect of Temperature

Temperature significantly affects solar cell performance under illumination. As temperature increases

Current increases slightly

Voltage decreases substantially

Power output decreases

Overall efficiency decreases

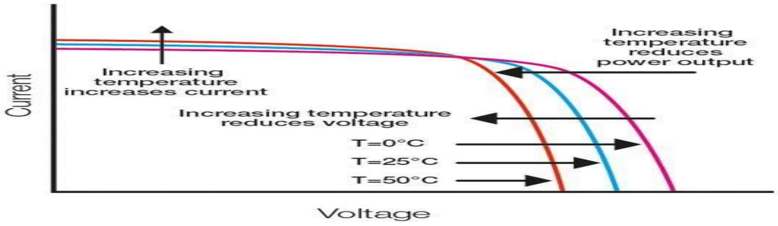

Figure 3.2: I-V curve for different values of temperature

3.6. Origin Lab Software

Origin Lab software (version 2016, 64-bit Windows) was used for graphical analysis and curve fitting of solar cell characteristics. The software supports multiple graphing formats in 2D and 3D versions and includes data analysis features such as peak analysis, signal processing, data fitting and statistical functions .This methodology enabled the extraction of key photovoltaic parameters from experimental J-V data at different temperatures providing a robust framework for analyzing graded junction solar cell performance.

2. Results

3. The performance of the fabricated ITO/InP graded junction solar cell was characterized by analyzing current-voltage (J-V) characteristics in both dark and illuminated conditions across a temperature range of 280 K to 320 K. The key external and internal parameters extracted from this analysis are presented below.

4.1. Temperature Dependence of External Parameters

The external photovoltaic parameters open-circuit voltage (VocVoc), short-circuit current density (JscJsc), fill factor (FF), and power conversion efficiency (η) were determined from J-V curves under illumination at different temperatures. The results, summarized in Table 1, demonstrate a clear degradation in cell performance with increasing temperature.

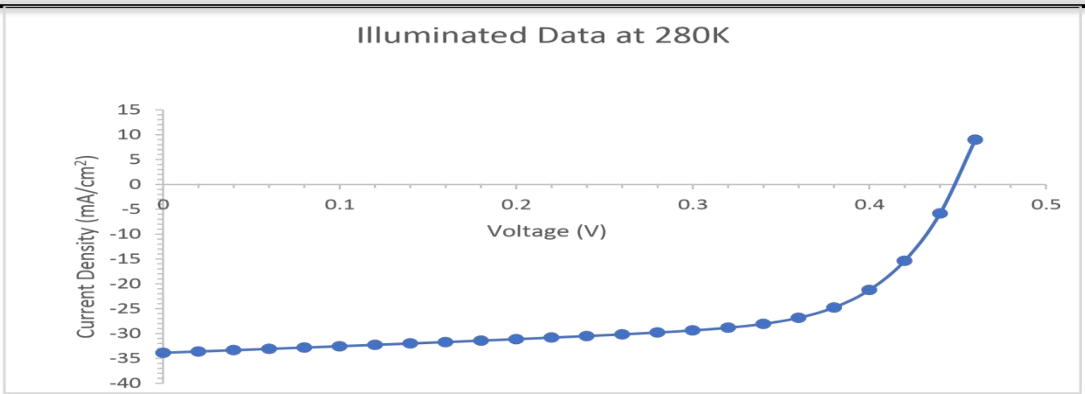

Figure 4.1: Characterization of J vs V under illumination at 280K

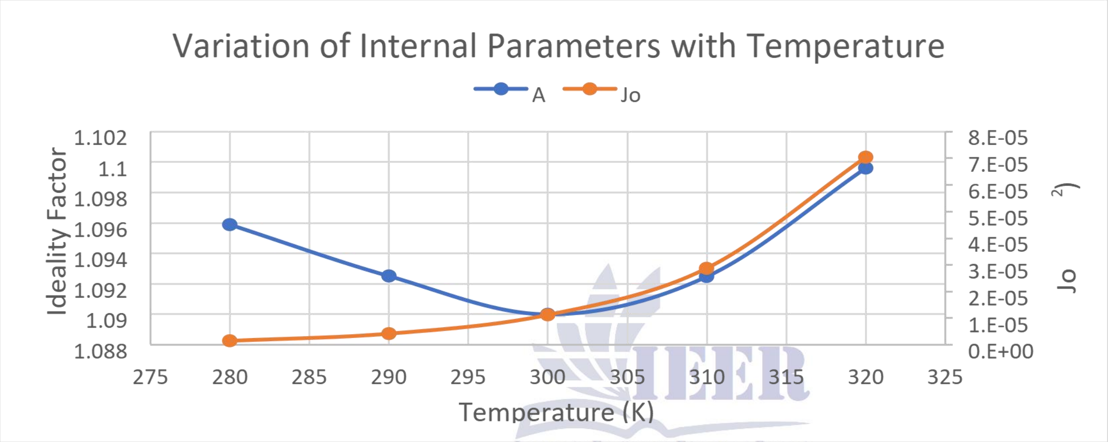

Figure 4.2: Characterization of J vs V under illumination at 320K

Temperature (K)	VocVoc (V)	JscJsc (mA/ cm^2)	Fill Factor (%)	Efficiency (%)
280	0.448	33.859	63.57	9.66
290	0.432	33.398	63.23	9.13
300	0.416	32.875	62.82	8.59
310	0.410	32.295	62.34	8.06
320	0.384	31.663	61.79	7.52

Table 4.1: External Photovoltaic Parameters Under Illumination at Different Temperatures

A consistent negative temperature coefficient was observed for all major performance metrics. Specifically, as the temperature increased from 280 K to 320 K, VocVoc decreased by 14.3%, JscJsc decreased by 6.5%, FF decreased by 2.8% and the overall power conversion efficiency experienced a significant relative drop of 22.2%.

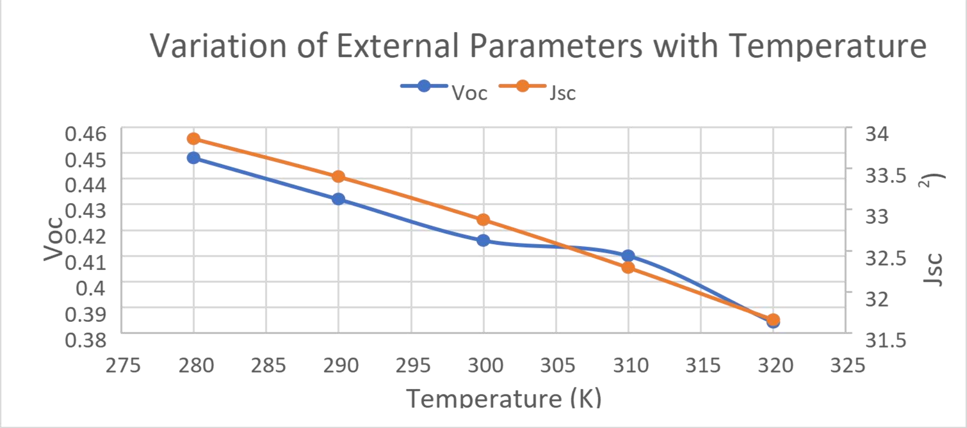

Figure 4.3: Variation of Voc vs Jsc with temperature

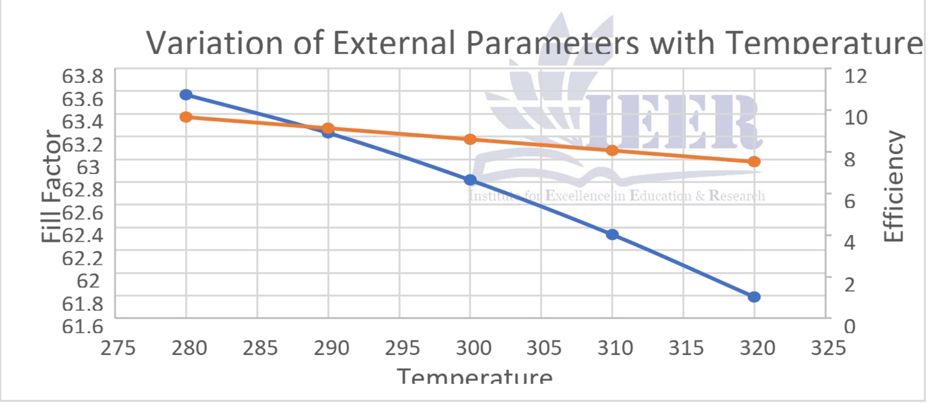

Figure 4.4: Variation of FF vs Eff with temperature

4.2. Temperature Dependence of Internal Parameters

The internal parameters, namely the diode ideality factor (A) and the reverse saturation current density (JoJo), were extracted from the dark J-V characteristics. The values of ln(J) were plotted against voltage (V), and the parameters were derived from the slope and intercept of the linear fits, respectively.

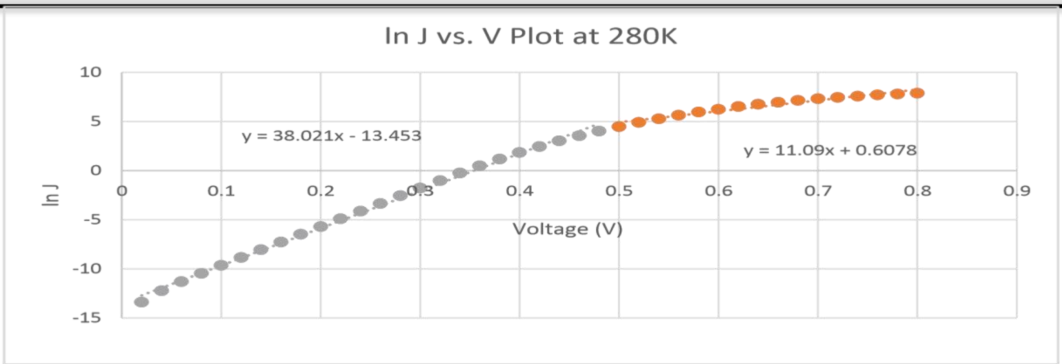

Figure 4.5: Characterization of Ln J vs V in Dark at 280K

J_o 2.87176E-05 J_o 3.65099597

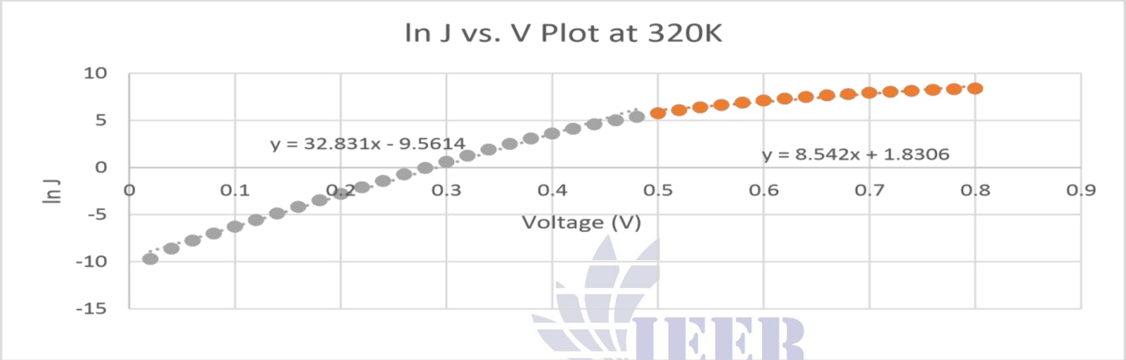

Figure 4.6: Characterization of Ln J vs V in Dark at 320K

Temperature (K)	Ideality Factor (A)	Reverse Saturation Current Density, JoJo (A/cm²)
280	1.096	1.44×10−61.44×10−6
290	1.093	4.14×10−64.14×10−6
300	1.090	1.12×10−51.12×10−5
310	1.092	2.87×10−52.87×10−5
320	1.100	7.04×10−57.04×10−5

Table 2: Internal Parameters Extracted from Dark J-V Characterization

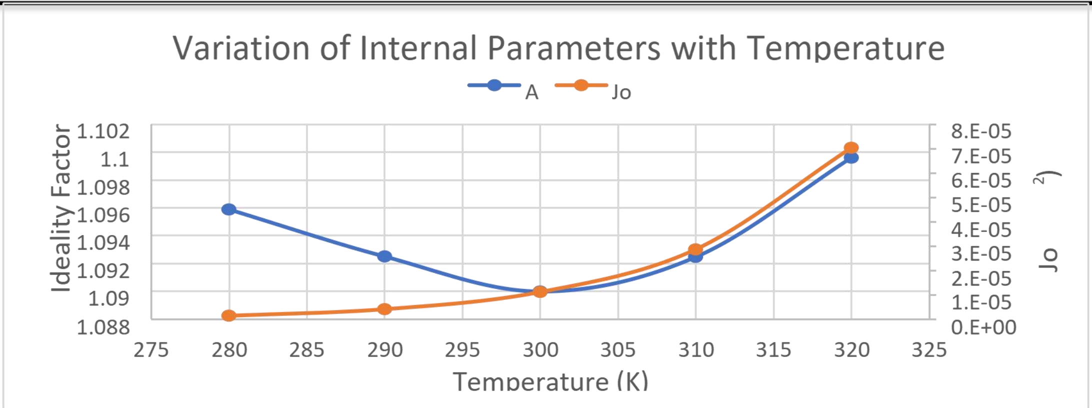

Figure 4.17: Characterization of A and JoJo with temperature

The results indicate that the ideality factor remained close to 1.09, suggesting a dominant recombination mechanism in the space charge region. Furthermore, the reverse saturation current density (JoJo) exhibited a strong positive correlation with temperature, increasing by nearly two orders of magnitude over the 40 K range investigated. This sharp increase in JoJo is a primary factor responsible for the observed decline in VocVoc and overall efficiency with rising temperature.

5.Conclusion

In this work, Experimental J-V data of graded junction solar sell was studied at different temperature by using Origin software and Ideal diode equation was used to calculate internal and external parameters. Graded junction solar cell parameters were calculated from J-V curve to examine the efficiency of solar cell. Ideal diode equation is used to calculate dark data of J vs V, characterization of lnJ vs V at dark and illuminated data at different temperature and to calculate all external and internal parameters to compare theoretical data with experimental data by origin software. A detailed analysis is introduced for variations in external parameters such as (J_{sc}. V_{oc}. FF%, Eff %). Experimental values calculated for series resistance show good correlation with fitted values using Shockley equation. We have conducted results for solar cell external parameters as a function of doping density. Modeling for graded junction solar cell shows, J_{sc}, V_{oc}, FF and efficiency decreases by increasing the temperature. The internal parameters ideality factor A and Current density J_o also decrease with increasing the temperature.

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