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INFLUENCE OF P-INP DOPING DENSITY ON THE PERFORMANCE OF SPUTTER-DEPOSITED ITO/INP HETEROJUNCTION SOLAR CELLS

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Abstract

This work presents a comprehensive and systematic investigation into the effects of varying the p-type doping density (N_A) of the Indium Phosphide (InP) base layer, from 1×10^{15} cm^{-3} to 1×10^{18} cm^{-3} on the performance and underlying electronic transport mechanisms of ITO/InP heterojunction solar cells. The devices were fabricated by depositing ZnCdS and Indium Tin Oxide (ITO) window layers onto single-crystal p-InP substrates using radio-frequency (RF) sputtering at an optimized temperature of 450°C. Current-voltage (J-V) characterization under dark and illuminated (AM1.5G) conditions was employed to extract key photovoltaic parameters open-circuit voltage (V_{OC}) short-circuit,current density (J_{SC}) fill factor (FF) efficiency (η) reverse saturation current density (J_0) and diode ideality factor (A). A profound and systematic shift in the dominant current transport mechanism was observed. As N_A increased, J_0 decreased dramatically by eight orders of magnitude from 1.01×10^{-8} A/cm^2 to 1.09×10^{-16} A/cm^2. Concurrently, the ideality factor A decreased from 1.70 to 1.07. This trend provides conclusive evidence of a transition from recombination-generation (R/G) current dominance within the space-charge region to injection-diffusion (I/D) current dominance. This transition directly resulted in a significant improvement of V_{OC} from 0.913 V to 1.087 V and FF from 79.72% to 82.43%. Although J_{SC} decreased from 23.23 mA/cm^2 to 19.34 mA/cm^2, likely due to reduced minority carrier diffusion length from increased ionized impurity scattering, the net effect was a peak conversion efficiency of 17.32% at N_A = 1×10^{18} cm^{-3}. This study conclusively demonstrates that base doping density is a critical and powerful parameter for engineering the electronic transport properties specifically for suppressing deleterious R/G currents, and for optimizing the overall performance of ITO/InP heterojunction solar cells.

INTRODUCTION

The global energy landscape is undergoing a paradigm shift, driven by the urgent need to transition from finite, polluting fossil fuels to sustainable, clean, and renewable energy sources [1, 2]. In this context, solar exploration of various semiconductor materials, from silicon to thin-film compounds and high-performance III-V multi-junctions, is central to this endeavor. Among III-V semiconductors, Indium Phosphide (InP) stands out as a particularly promising absorber material for single-junction solar cells. Its direct photovoltaics (PV) has emerged as a cornerstone technology, with relentless research efforts focused on enhancing conversion efficiency, reducing manufacturing costs, and improving device reliability [3]. The bandgap of 1.35 eV at room temperature is nearly ideal, closely matching the peak of the solar spectrum to maximize the theoretical conversion efficiency as per the Shockley-Queisser limit [4].below figure visually reinforces why InP is an ideal material.

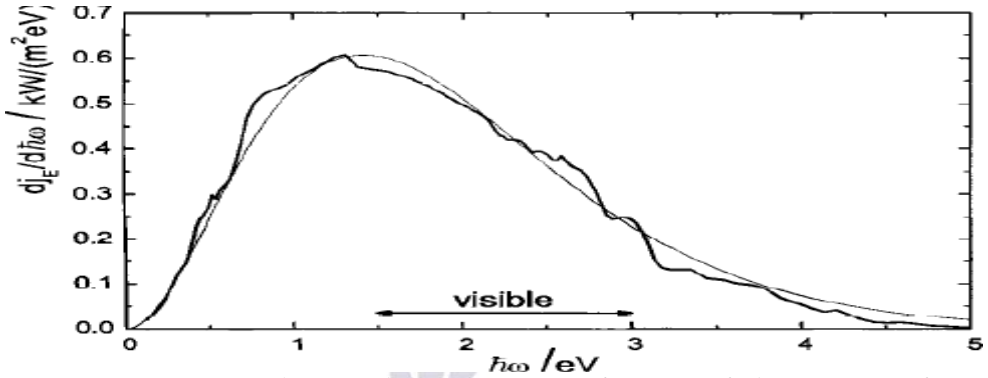


Figure 1: Energy current density/photon energy as a function of photon energy from sun just outside the earth atmosphere (thick line), and black body spectrum at 5800K (thin line) [4]

When top of valance band is at k=0 but conduction band minima is at k≠0, then an incident photon will be absorbed by an electron in the valance band and that electron make a transition to conduction band minima by absorbing or emitting a phonon. Such transition is called indirect transition and semiconductors having this type of transition are called indirect gap semiconductors

[17] as shown in Fig 2.

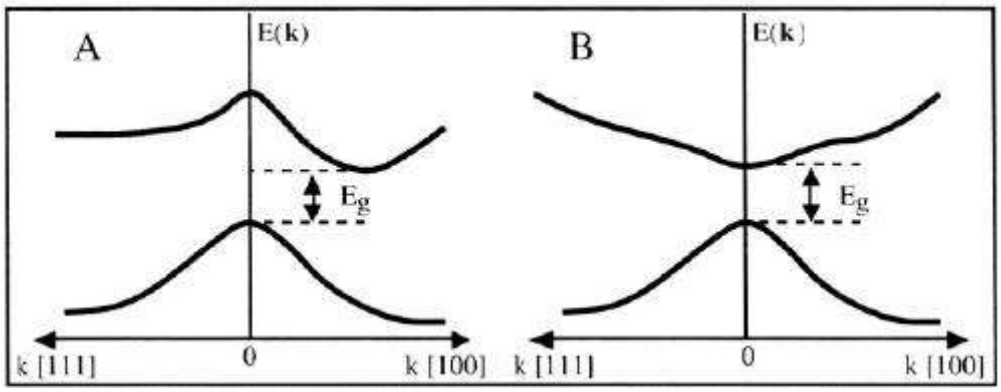


Figure 2: (A) Indirect B.G semiconductors, (B) Direct B.G semiconductors [16]

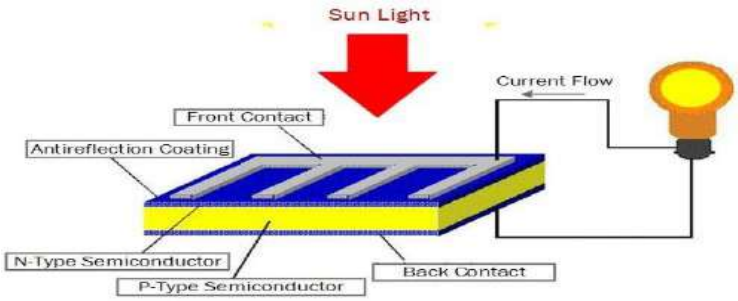


Figure 3 (A band diagram of the ITO/InP heterojunction, showing the depletion region and built-in potential)

The solar spectral irradiance (AM1.5G) compared to a black body spectrum at 5800 K, highlighting the close match with the bandgap of InP (1.35 eV).Furthermore InP exhibits exceptional radiation hardness a property that renders it supremely suitable for space applications where exposure to high-energy particles can rapidly degrade the performance of other solar cell materials like Silicon or Gallium Arsenide (GaAs) [5, 6].Heterojunction solar cell architectures, which combine a wide-bandgap "window" layer with a narrower-bandgap "absorber" layer, offer distinct advantages over their homojunction counterparts. The wide-bandgap window allows high-energy photons to pass through to the absorber layer with minimal absorption, thereby reducing surface recombination losses at the front contact. It also facilitates the creation of a strong built-in field for effective carrier separation [7]. Indium Tin Oxide (ITO) is an exemplary material for this role, serving a dual function as both a transparent window and a highly conductive front contact due to its high optical transparency in the visible spectrum and low electrical resistivity Schematic energy band diagram of the ITO/InP heterojunction under equilibrium showing the depletion region width (WW) and the built-in potential (Vbi*Vbi*).These factors have a direct and profound impact on key performance metrics such as the open-circuit voltage (V_{OC}), short-circuit current density (J_{SC}) fill factor (FF) and the [8].The fabrication technique plays a pivotal role in determining the morphological, optical, and electronic quality of the deposited layers. Radio-frequency (RF) magnetron sputtering is a widely adopted physical vapor deposition (PVD) technique known for its ability to produce highly uniform, dense, and adherent thin films with precise control over composition and thickness, even at relatively low substrate temperatures [9]. This makes it highly suitable for depositing complex oxide layers like ITO onto temperature-sensitive substrates.While the choice of materials and deposition technique sets the stage, the internal electronic properties of the device ultimately dictate its performance. Among these, the doping concentration in the base region of the solar cell is a fundamental and powerful parameter. It critically influences the width of the depletion region, the magnitude of the built-in potential, the minority carrier diffusion length, and, most importantly, the dominant current transport mechanism across the p-n junction under bias [10, 11].

reverse saturation current (J_0).Although ITO/InP solar cells have been studied in the past, a systematic and detailed investigation that correlates a wide range of p-InP substrate doping densities with the underlying current transport mechanism as revealed through meticulous dark and light J-V analysis is lacking. Such a study is not merely academic it is essential for the

targeted optimization and engineering of high-efficiency devices.In this comprehensive work, we fabricate a series of ITO/InP heterojunction solar cells via RF sputtering, systematically varying the p-InP base doping density over three orders of magnitude (from 1×10^{15} to 1×10^{18} cm^{-3}). We present a detailed analysis of how this variation influences the photovoltaic performance parameters. Crucially, we focus on the evolution of the reverse saturation current (J_0) and the diode ideality factor (A), extracted from dark J-V characteristics, to demonstrate and explain a clear transition in the dominant current transport mechanism. The insights gained from this study provide a valuable roadmap for the design and fabrication of optimized, high-efficiency InP-based heterojunction solar cells.

2 Existing Litrature

The literature review covers a range of studies that inform the current research on ITO/InP solar cells and the role of doping.

2.1 Early Development of InP/ITO Solar Cells: fabricated InP/ITO solar cells using reactive DC sputtering. Their work confirmed these devices as true heterojunctions, not buried homojunctions, and reported an efficiency of 4% with a 46% fill factor. They noted that the temperature increase during DC sputtering was disadvantageous compared to RF sputtering[19].

2.2 Radiation Resistance and Dopant Density: [13]investigated the radiation resistance of InP solar cells, varying the base dopant density between 3x10^15^ and 2x10^17^ cm^-3^. They found that all cells were highly radiation-resistant, with lightly doped base cells degrading more in open-circuit voltage (Voc) and less in short-circuit current (Jsc) than heavier-doped cells. Their modeling suggested that with a thin base and a back surface reflector, efficiencies up to 14.1% could be achievable after irradiation.

2.3 Heat Treatment Effects on Junctions: [14]s tudied the effects of heat treatments on ITO/InP junctions. They found that heat treatments increased the surface recombination velocity (SRV), which was correlated with phosphorus loss from the InP surface. This increase in SRV was demonstrated to negatively impact the open-circuit voltage of the solar cells.

2.4 Role of Excitons in Silicon Solar Cells: explored the influence of excitons (bound electron-hole pairs) in silicon solar cells across a doping range of 10^16^ to 10^18^ cm^-3^. The study concluded that excitons contribute to a large increase in dark current and a decline in Jsc, Voc, fill factor, and efficiency. An ideal base region doping level of less than 10^17^ cm^-3^ was identified to mitigate these negative effects[15].

2.5 Material Studies for High-Efficiency Cells: worked on developing low-bandgap n/p solar cells on InP substrates using less-toxic precursors. They investigated new absorber materials like GaAsSb and InAlGaAs, achieving internal quantum efficiencies comparable to more established materials like InGaAsP[16].

2.6 Studies on CdTe-based Solar Cells: CdTe-based solar cells.one group achieved 14.37% efficiency in a single-crystal CdTe/ZnCdS cell by reducing series resistance. Other team deposited ZnCdS and CdTe thin films via physical vapor deposition (PVD), characterizing their optical and electrical properties, with band gaps of 2.48 eV and 1.68 eV, and high resistivity values, respectively[18].

2.7 Nanowire Array Photodetectors: studied photodetectors based on InP nanowire arrays. They observed that the spectral responsivity could be tuned by bias voltage, attributed to a Schottky-like contact at the nanowire-ITO interface. Their work highlighted the importance of the doping profile and the nanowire-transparent contact interface[19].

2.8 Advanced Structures for Higher Efficiency: addressed the gap between the theoretical Shockley-Queisser limit (33.2%) and the recorded efficiency for InP cells

(24.2%). They proposed and demonstrated a new ITO/ZnO/i-InP/p+ InP structure. This design used a thin ZnO layer for passivation and electron selectivity, achieving a Voc of 819 mV and an efficiency of 18.12% without extrinsic doping, providing a path for a new generation of InP thin-film solar cells[9].

2.9 Carrier-Selective Contacts with Ta_2O_5: introduced tantalum oxide (Ta_2O_5) as a novel electron-selective contact for InP solar cells. With an 8 nm Ta_2O_5 layer, they demonstrated a device with a Voc of 822 mV (the highest reported for an InP heterojunction solar cell at that time), a Jsc of 30.1 mA/cm², and an overall efficiency of 19.1%[8].

2.10 Doped ZnO for Multifunctional Applications: examined vanadium-doped ZnO thin films. They reported that doping reduced the band gap and found that the films also exhibited antibacterial properties, suggesting their potential use in both solar cells and biomedical applications[7].

3. Experimental Methodology

This study investigates the effect of dopant variation in p-type Indium Phosphide (InP) on the performance of ITO/InP solar cells. The experimental approach comprised two main phases: (1) the fabrication of heterojunction solar cells using Radio Frequency (RF) Sputtering and (2) the subsequent analysis of the cell's current-voltage (J-V) characteristics using specialized software. This section details the materials, apparatus, and procedures employed.

3.1. Thin-Film Deposition via RF Sputtering

The core fabrication step involved the deposition of Indium Tin Oxide (ITO) as a window layer onto single-crystal p-type InP substrates using an RF sputtering system. Sputtering a physical vapor deposition (PVD) technique, was selected for its ability to produce high-quality, uniform thin films with excellent adhesion [1, 2].

3.1.1. Principles of Sputtering

Sputtering is a process wherein atoms are ejected from the surface of a solid target material due to bombardment by energetic ions. In a vacuum chamber, a plasma is ignited in a low-pressure inert gas, typically Argon. The positive ions from this plasma are accelerated towards a negatively charged target (cathode). Upon impact, momentum transfer ejects neutral atoms from the target, which then travel and condense on a substrate to form a thin film [3]. A schematic of a typical sputtering vacuum chamber is presented in Figure 4.

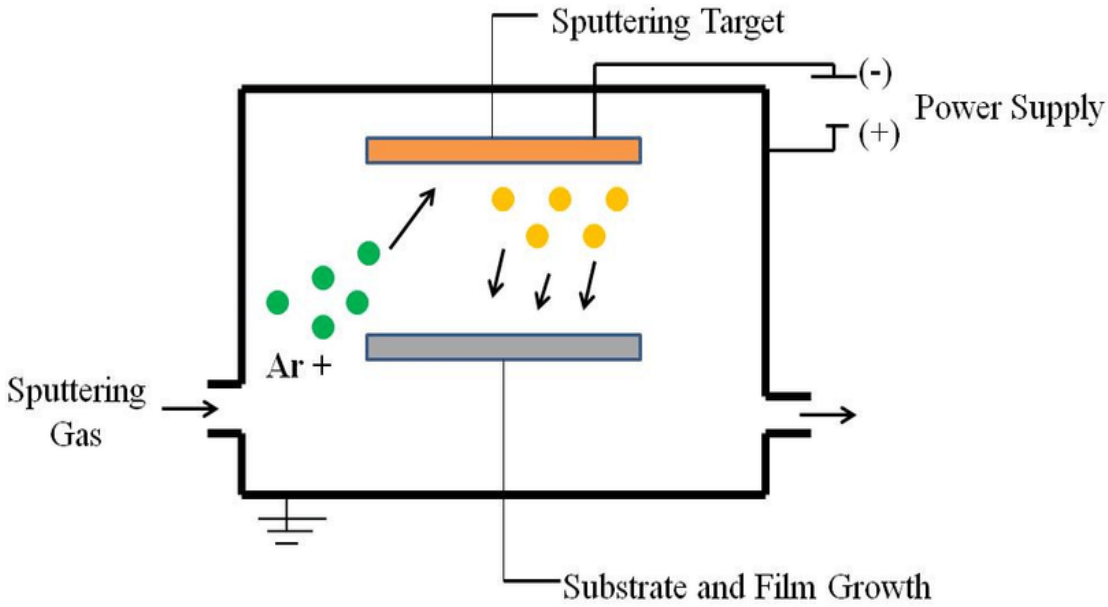


Figure 4: Schematic diagram of a generic sputtering vacuum chamber

3.1.2. Key Sputtering Terminology and Setup

The following components and parameters are critical to the sputtering process:

Source Material (Target): A high-purity ITO disc was used as the source material, connected to the RF power source (cathode). Cooling water was circulated to maintain target temperature.

Substrate: Single-crystal, zinc-doped p-type InP wafers served as the substrate. The substrate was mounted on a manipulator, which also functioned as the anode and allowed for heating and rotation to ensure uniform deposition.

Shutter: A rotating shutter was positioned between the target and substrate. It was used for pre-sputtering to clean the target surface and shield the substrate from initial contaminants.

Plasma: A plasma was created by ionizing high-purity Argon gas, providing the ions necessary for the sputtering process.

Working Pressure: The base pressure of the chamber was brought down to approximately 10^{-6} Torr before introducing the sputtering gas. The working pressure during deposition was maintained at a higher, optimized value to sustain the plasma.

Mean Free Path: This is the average distance a sputtered atom travels between collisions. A high vacuum ensures a long mean free path, reducing collisions with gas molecules and leading to higher-quality film deposition.

3.1.3. RF Sputtering System and Deposition Parameters

For depositing the ITO layer, an RF magnetron sputtering system was employed. This technique is particularly suited for dielectric materials like ITO because the RF field prevents charge buildup on the insulating target [4]. A schematic of the RF sputtering chamber is shown in Figure 5.

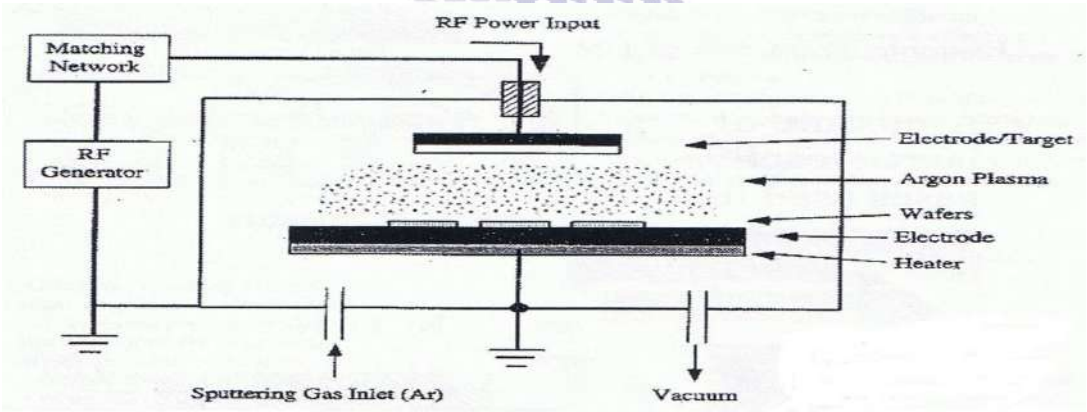


Figure 5. Schematic diagram of the RF magnetron sputtering chamber used for ITO deposition.

The deposition was carried out under the following optimized parameters:

- RF Power: 200 W
- Sputtering Gas (Argon) Flow Rate: 30 sccm
- Reactive Gas (Oxygen) Flow Rate: 30 sccm (This constitutes Reactive Sputtering)
- Deposition Time: 30 minutes
- Substrate Temperature: 450 °C

The p-InP substrates with varying doping densities ($1x10^{15}$ to $1x10^{18}$ cm^{-3}) were

coated under identical sputtering conditions to isolate the effect of dopant concentration on the final solar cell properties.

3.2. Data Acquisition and Analysis using Origin Lab Software

Following fabrication, the solar cells were characterized by measuring their current

density-voltage (J-V) characteristics under dark and illuminated conditions. The resulting data was analyzed using Origin Lab software (Version 2016, 64-bit).Origin Lab is a powerful scientific graphing and data analysis platform [5]. Its workspace, depicted in Figure 6 includes features such as a Project Explorer, Child Windows for graphs and worksheets, and various toolbars for data manipulation.

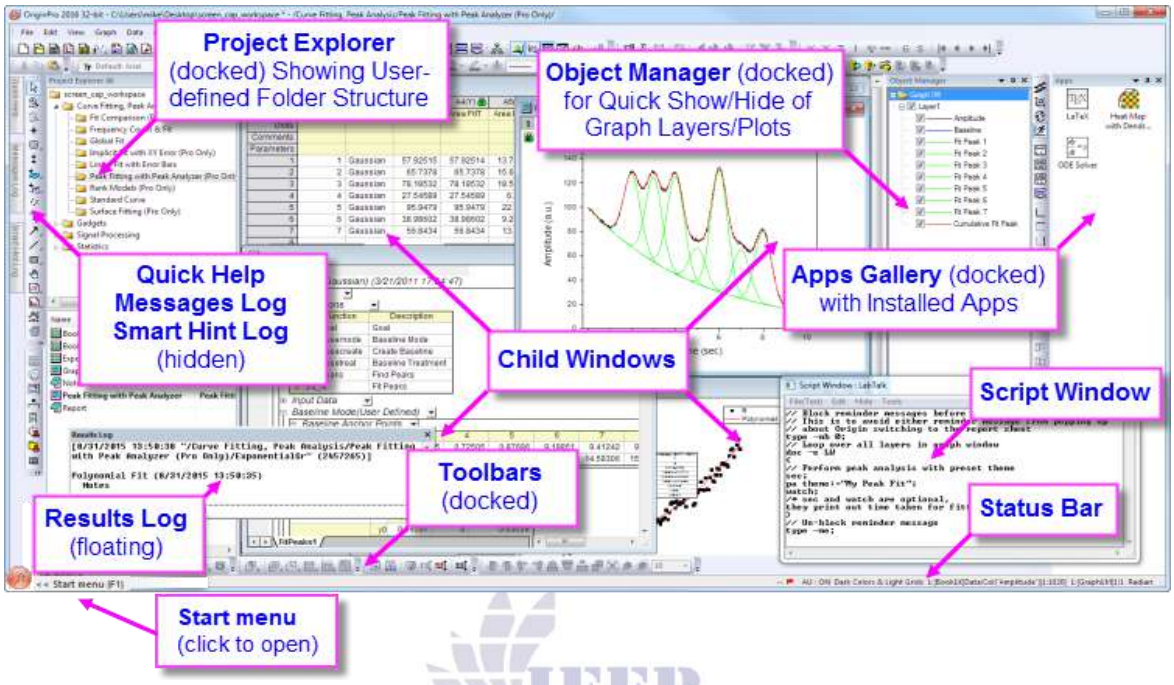


Figure 6. The Origin Lab workspace interface.

The software was utilized to:

- Import J-V data.
- Generate and plot J-V curves.
- Perform linear regression on the semi-logarithmic plots of dark J-V data to extract key diode parameters.
- Calculate photovoltaic parameters from the illuminated J-V curves.

The critical parameters extracted were:

Reverse Saturation Current Density (J_0) and Ideality Factor (A), determined from the dark J-V characteristics using the diode equation:

$$\ln J = (q/AkT) V - \ln J_0 \quad \textbf{Eq.....(1)}$$

where q is the electron charge, k is Boltzmann's constant, and T is the temperature. A plot of ln J vs. V yields a straight line where the slope gives A and the y-intercept gives J_0.

Photovoltaic Parameters, determined from the illuminated J-V curves:

- Short-Circuit Current Density (J_{sc})
- Open-Circuit Voltage (V_{oc})
- Fill Factor (FF)
- Conversion Efficiency (η)

The fill factor and efficiency were calculated using the standard equations:

$$FF = (V_{mp} * J_{mp}) / (V_{oc} * J_{sc}) \quad \textbf{Eq.....(2)}$$

$$\eta = (V_{oc} * J_{sc} * FF) / P_{in} \quad \textbf{Eq.....(3)}$$

where V_{mp} and J_{mp} are the voltage and current density at the maximum power point and P_{in} is the incident optical power.

4.1 Experimental Fabrication and Analysis Methodology

The solar cells under investigation were ITO/InP heterojunctions fabricated by depositing Indium Tin Oxide (ITO) thin films via RF sputtering onto single-crystal, zinc-doped p-type InP substrates. To isolate the effect of substrate doping, all other deposition parameters (ITO thickness, sputtering power, gas flows, temperature) were kept constant. The substrates were chosen with four distinct doping densities: 1×10^{15}, 1×10^{16}, 1×10^{17}, and 1×10^{18} cm^{-3}.

The characterization involved measuring Current Density-Voltage (J-V) curves under two conditions:

In the Dark: To analyze the diode's inherent properties.
Under Illumination: To evaluate its performance as a solar cell.
From these curves, key parameters were extracted, as summarized in the table below.

Doping Density (cm^{-3})	J_0 (Acm^{-2})	A (Ideality Factor)	V_oc (V)	J_sc ($mAcm^{-2}$)	FF (%)	Efficiency η (%)	V_mpp (V)	J_mpp ($mAcm^{-2}$)
10^{15}	1.01×10^{-8}	1.699506803	0.91268	23.23238	79.7187	16.9033	0.79998	21.12967
10^{16}	2.18×10^{-9}	1.669554997	0.965051	21.26895	80.2961	16.4813	0.86041	19.15514
10^{17}	7.01×10^{-13}	1.303383322	1.025132	19.58228	82.2698	16.5152	0.92627	17.82979
10^{18}	1.09×10^{-16}	1.071053703	1.086609	19.33808	82.4273	17.3204	0.988613	17.5199

Table 1. Summary of diode and photovoltaic parameters extracted for ITO/InP solar cells with varying p-type base doping density (NANA).

4.2 Detailed Discussion of Key Trends

4.2.1 Diode Properties: A Shift in Current Transport Mechanism

The dark J-V measurements reveal the most profound impact of doping variation.
Reverse Saturation Current Density (J_0): J_0 decreased dramatically by eight orders of magnitude, from 10^{-8} A/cm^2 to 10^{-16} A/cm^2, as doping increased from 10^{15} to 10^{18} cm^{-3}.
Ideality Factor (A): The ideality factor decreased consistently from ~1.70 to ~1.07.

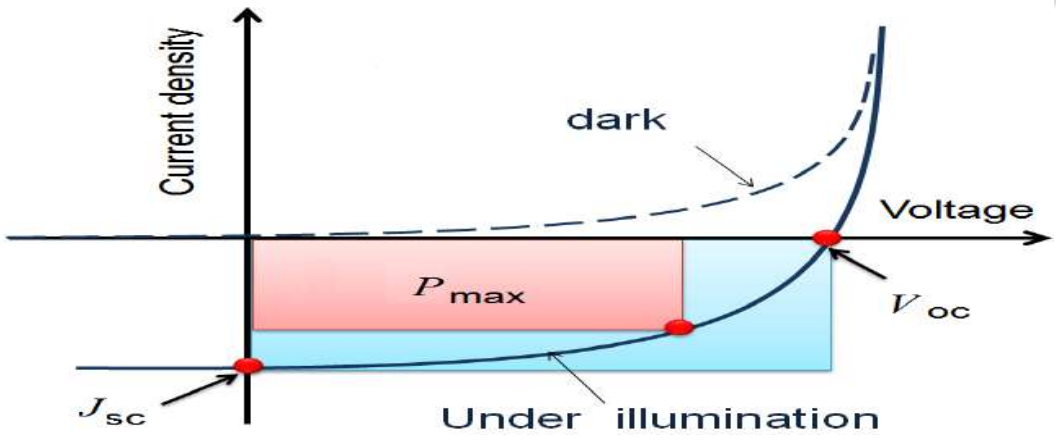


Figure 7 (A composite figure showing the dark ln(J0)lnJ-V curves for all four doping densities)

Interpretation: This drastic reduction in J_0 and the convergence of the ideality factor towards the ideal value of 1.0 indicate a fundamental shift in the dominant current transport mechanism within the junction..
This visually demonstrates the changing slope and intercept.Semi-logarithmic plot of dark J-V characteristics for ITO/InP solar cells with varying base doping densities. The systematic decrease in both the y-intercept (J0J0) and the slope (related to ideality factor AA) indicates a transition from recombination-generation (R/G) to injection-diffusion (I/D) current dominance.At low doping (10^{15} cm^{-3}), a higher A (~1.7) and J_0 (~10^{-8} A/cm^2) suggest that carrier Recombination and Generation (R/G) within the depletion region is the dominant process. This is often associated with defect states in the junction.At high doping (10^{18} cm^{-3}), a near-ideal A (~1.07) and an extremely low J_0 (~10^{-16} A/cm^2) confirm that Injection and Diffusion (I/D) of minority carriers has become the dominant mechanism. This is characteristic of a high-quality, well-passivated junction with minimal recombination losses.

4.2.2 Photovoltaic Performance: A Delicate Trade-Off

The illuminated J-V characteristics show a complex interplay between various performance parameters.

Open-Circuit Voltage (V_oc): V_oc showed a consistent and significant increase from 0.91V to 1.09V. This is a direct benefit of the reduced saturation current (J_0), as described by the diode equation:
V_oc = (AKT/q) * ln(J_sc/J_0 **Eq.....(3)**
A lower J_0 directly results in a higher V_oc.

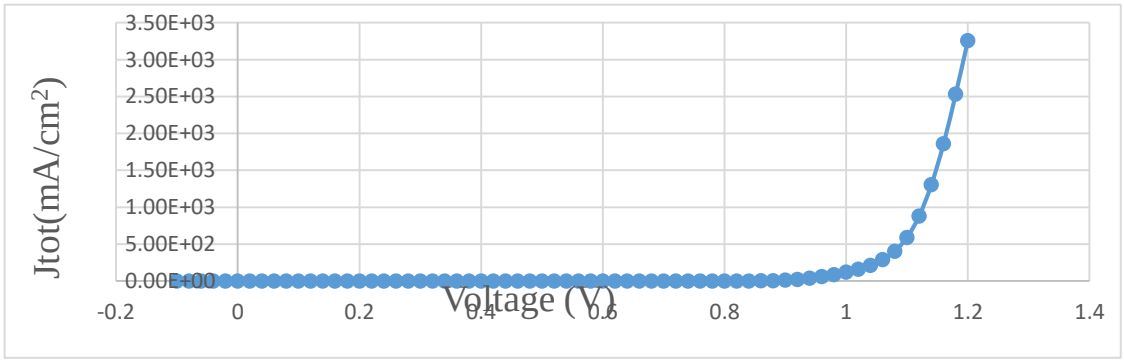


Figure 8. **Evolution of key photovoltaic parameters with base doping density.**

The increase in VOCVOC and $\eta\eta$ coupled with the decrease in JSCJSChighlights the performance trade-off governed by the shift in current transport mechanism.

Fill Factor (FF): The FF improved from ~79.7% to 82.4%. A higher FF indicates a "squarer" J-V curve, meaning the cell can deliver power closer to its theoretical maximum (V_oc × J_sc). This improvement is linked to the better diode quality (lower A) and potentially a favorable change in the cell's series resistance.

Short-Circuit Current Density (J_sc): In contrast to V_oc and FF, J_sc decreased from 23.23 mA/cm² to 19.34 mA/cm². This is attributed to increased carrier scattering at higher doping concentrations.

As more dopant atoms are introduced, they disrupt the crystal lattice, reducing carrier mobility and lifetime, which hinders the collection of photogenerated current.

Conversion Efficiency (η): The net result of these competing effects is a slight overall increase in efficiency, peaking at 17.32% for the highest doping level (10^{18} cm^{-3}). The gains from the significantly improved V_oc and FF were sufficient to outweigh the losses from the reduced J_sc.

4.3 Results

The study conclusively demonstrates that varying the doping density of the p-InP substrate is a powerful tool for engineering the properties of ITO/InP solar cells. Increasing the doping density from 10^{15} to 10^{18} cm^{-3}Fundamentally improves the

junction quality transitioning the current mechanism from defect-dominated recombination (R/G) to ideal diffusion (I/D).Creates a performance trade-off: It significantly enhances V_oc and Fill Factor but negatively impacts J_sc due to increased scattering.Leads to a net gain in efficiency under the tested conditions, with the optimally doped device in this study achieving 17.32% efficiency at a doping density of 10^{18} cm^{-3}.This analysis provides critical insight for the optimization of InP-based solar cells, highlighting that while high doping is beneficial for voltage and diode quality the associated current loss must be carefully managed to achieve peak performance.This article we will discuss about the results which we got through the current voltage graphs obtained through different doping substrate density. Taking the substrate density to be order of $1x10^{15}$ to $1x10^{18}$ cm^{-3} we obtained different current voltage graphs using MS software then we got values for output parameters of solar cell

4.3.1 J-V characteristics in Dark:

The dark current plot of ITO/InP solar cell that we prepared by sputtering ITO thin film onto single crystal p-type InP substrate. After putting front and back contacts, the solar cell was characterized for current – voltage characteristics. Jo is the saturation current. It is diffusion and recombination of electron and holes in the p- and n-regions. Jo can be found from the y-intercept of log J versus V plot. The value was found to be of the order of 10^{-8} A/cm^2. This shows that recombination type of current mechanism was involved. Ideality factor (A) was obtained from the slope of log J vs. V plot. The ideality factor is also a powerful tool for examining the recombination in a device

Voc = 0.91268 V Jsc = 23.23238 mA/cm^2 Jmax = 21.12967 Vmax = 0.79998 V Fill factor = 79.7187 % Efficiency (η) 16.9033%

J-V characteristics in Dark

Once again the reverse saturation current density and diode ideality factor were calculated from the dark data. The difference between the solar cells was the doping density of p-type InP that would be given in the end.

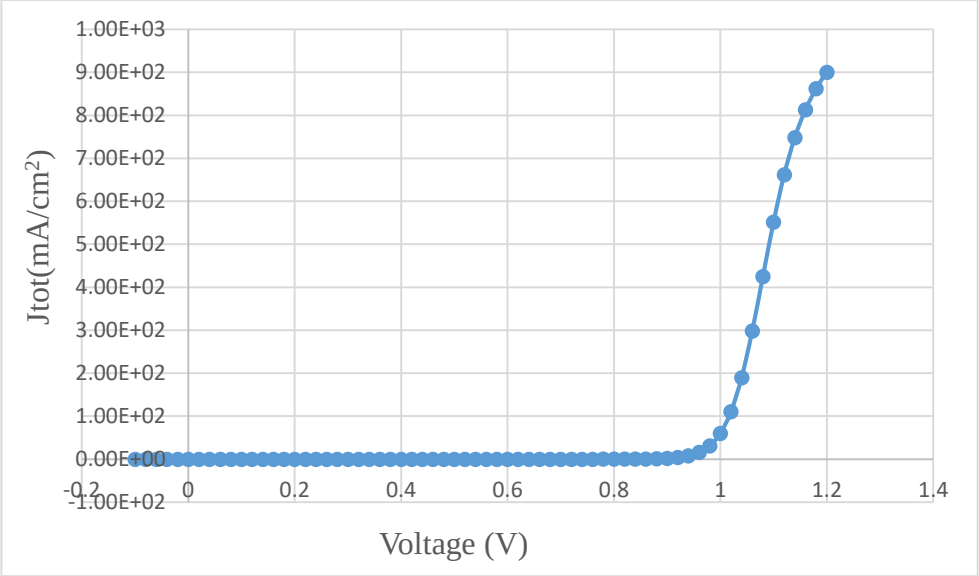


Figure 9: J-V measurement

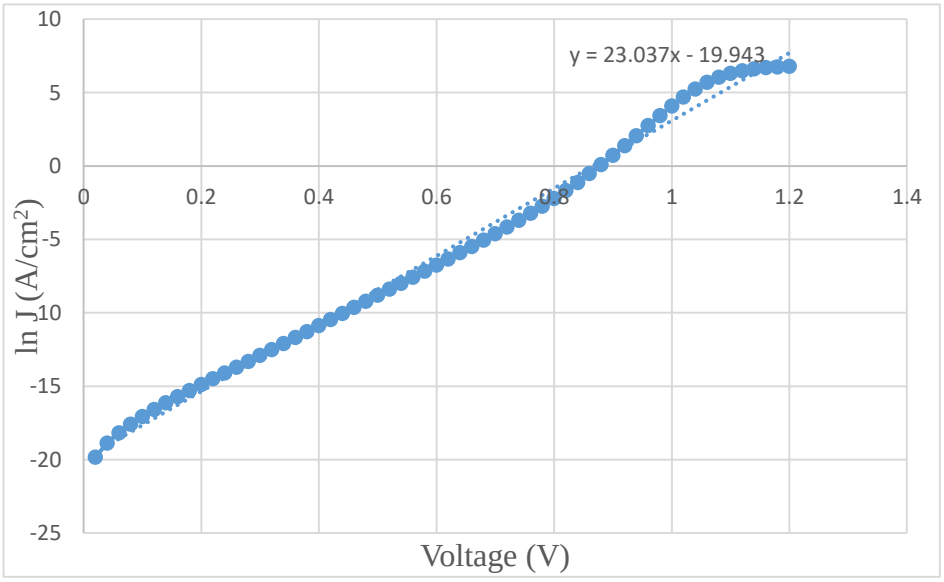


Figure 10: log J-V curve in dark

- J_o= 2.18205*10^{-9} A/cm^2
- A= 1.669554997

J-V characteristics under illumination

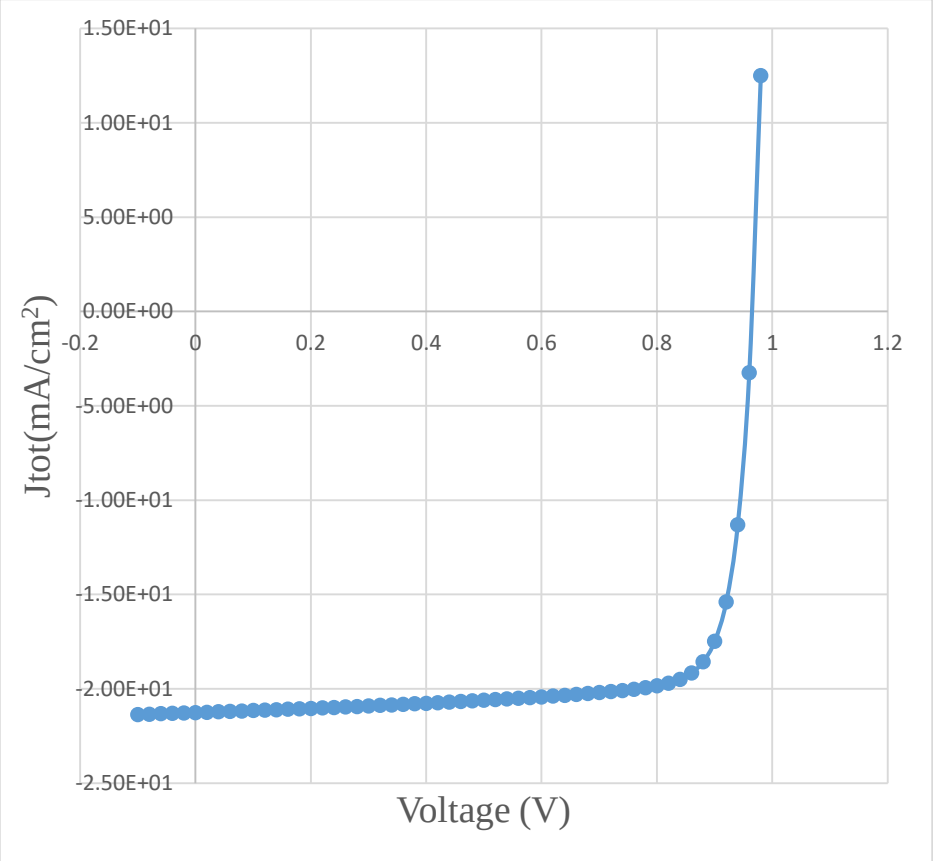


Figure 11: J-V curve under illumination

= 0.86041 V Fill factor = 80.2961 % Efficiency (16.4813%)

Voc = 0.965051 V Jsc = 21.26895 J-V characteristics in Dark mA/cm^2 Jmax = 19.15514 Vmax

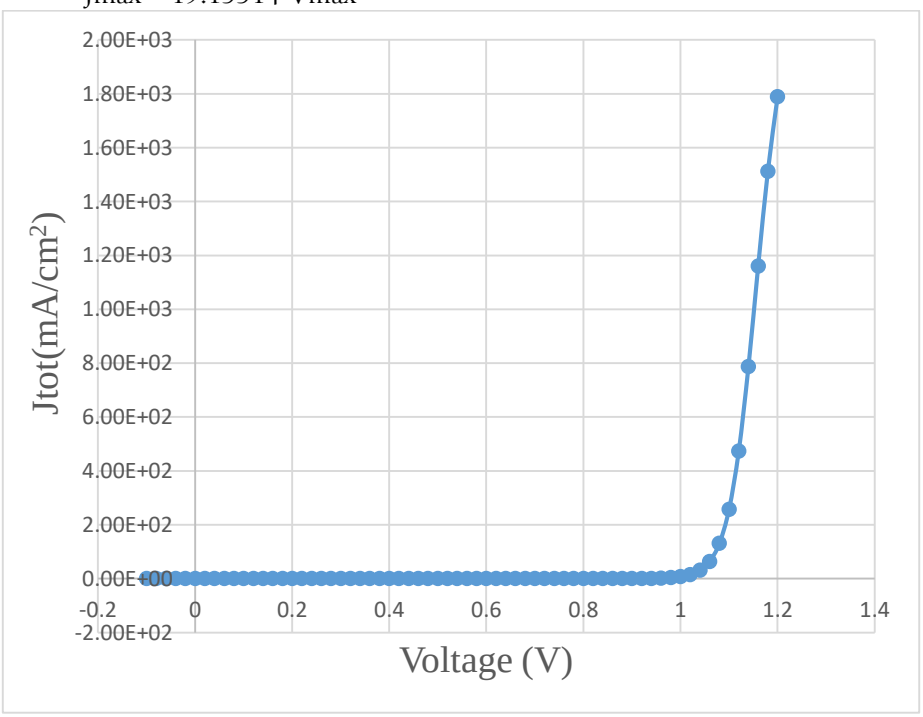


Figure 12: J-V measurement

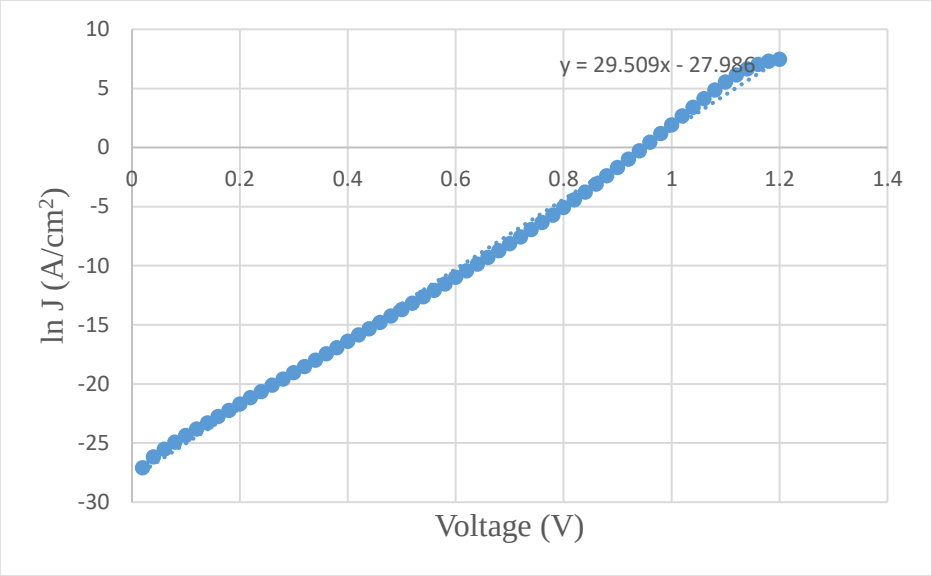


Figure 13: log J-V curve in dark

- A= 1.303383322
- J_o= 7.01188*10^{-13} A/cm^2

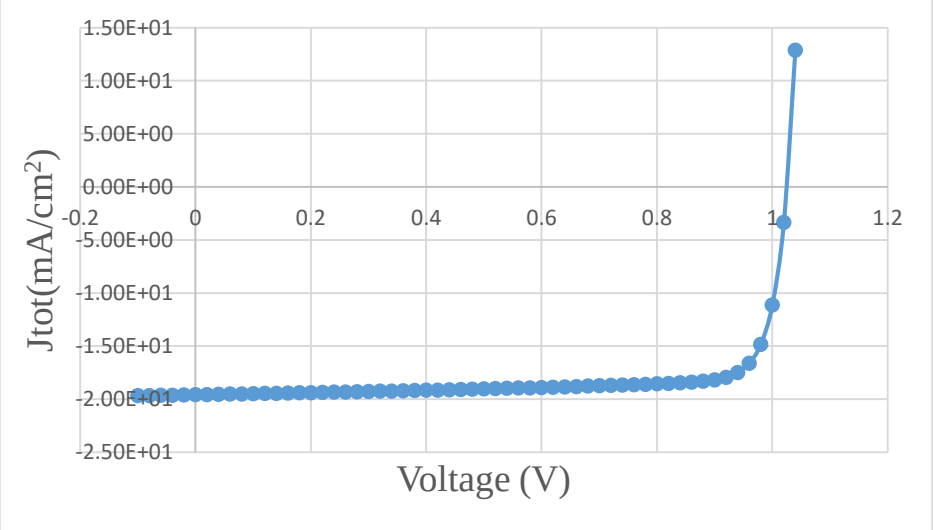


Figure 14: J-V curve under illumination

Voc = 1.025132 V Jsc = 19.58228 mA/cm^2 Jmax = 17.82979 mA/cm^2
Vmax = 0.92627 V Fill factor = 82.2698 % Efficiency (η) = 16.5152%

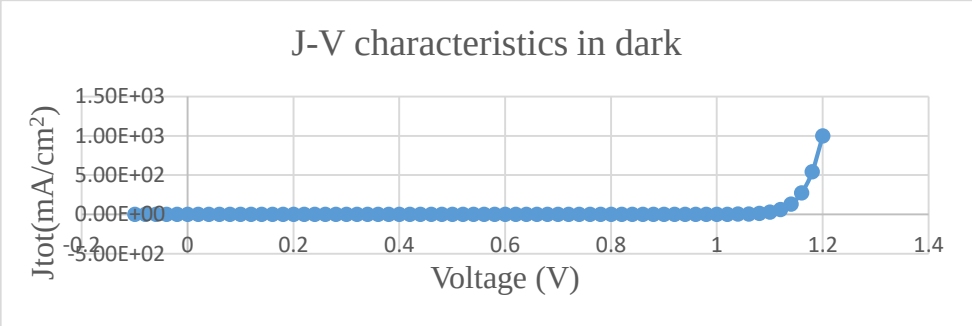


Figure 15: J-V measurement

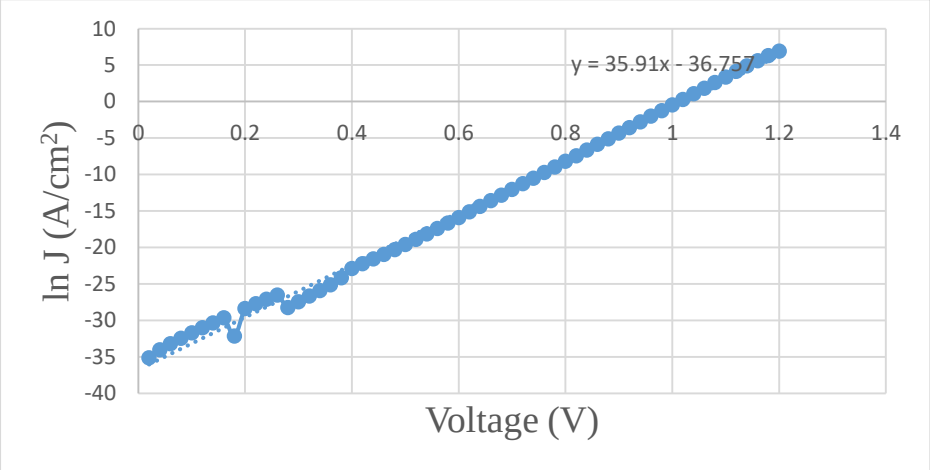


Figure 16: log J-V curve in dark

- J_o= 1.08802*10^{-16} A/cm^2
- A= 1.071053703

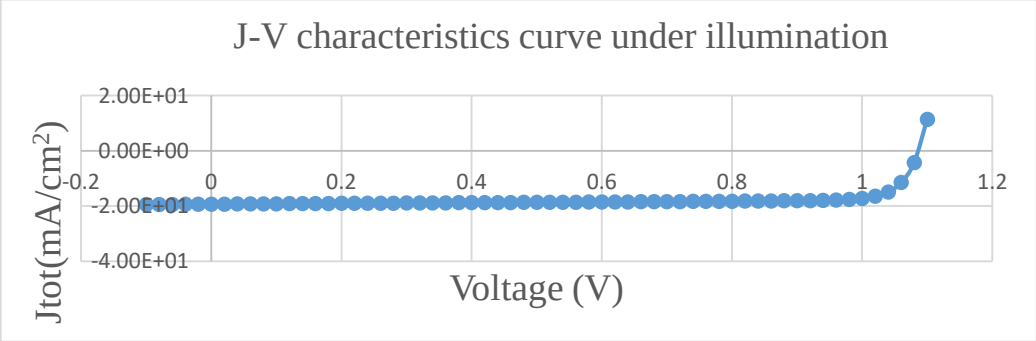


Figure 17: J-V curve under illumination

Voc = 1.086609 V Jsc = 19.33808 mA/cm^2 Jmax = 17.5199
Vmax = 0.988613 V Fill factor = 82.4273 % Efficiency (η17.3204%

Doping density (cm^{-3})	Jo (Acm^{-2})	A	Voc (V)	Jsc ($mAcm^{-2}$)	FF	Eta η (%)	Vmpp (V)	Jmpp (V)
10^{15}	$1.01*10^{-8}$	1.699506803	0.91268	23.2323	79.718	16.9033	0.79998	21.12967
10^{16}	$2.1820*10^{-9}$	1.669554997	0.965051	21.2689	80.296	16.4813	0.86041	19.15514
10^{17}	$7.0118*10^{-13}$	1.303383322	1.025132	19.5822	82.269	16.5152	0.92627	17.82979
10^{18}	$1.0880*10^{-16}$	1.071053703	1.086609	19.3380	82.427	17.3204	0.98861	17.5199

Table 2: Variation of Doping densities effect on device parameters

5 Conclusion

This research successfully fabricated and characterized ITO/InP heterojunction solar cells with p-type Indium Phosphide substrates of varying doping densities ($1x10^{15}$ to $1x10^{18}$ cm^{-3}). The primary goal was to systematically study the impact of this doping variation on the cell's electronic and photovoltaic properties. The thin films were deposited using the RF sputtering technique [1, 2], and the resulting devices were analyzed through current-density voltage (J-V) measurements under dark and illuminated conditions.The core finding of this thesis is that the doping concentration of the base p-InP layer is a critical determinant of the dominant current transport mechanism and, consequently, the overall performance of the solar cell. The following specific conclusions can be drawn.Transition in Current Transport Mechanism: The analysis of dark J-V characteristics revealed a profound shift in the diode's behavior. As the doping density increased, the reverse saturation current density (J_0) decreased dramatically from 10^{-8} A/cm^2 to 10^{-16} A/cm^2, and the ideality factor (A) approached unity, decreasing from 1.70 to 1.07. This unequivocally indicates a transition from a Recombination/Generation (R/G)-dominated current mechanism, prevalent in defective junctions, to an Injection/Diffusion (I/D)-dominated mechanism, which is characteristic of high-quality, well-behaved p-n junctions [3].Enhanced Voltage and Diode Quality: The significant reduction in J_0 directly led to a substantial improvement in the open-circuit voltage (V_{oc}), which increased from 0.91 V to 1.09 V. The fill factor (FF) also improved, indicating a more ideal diode characteristic and better power delivery capability.Trade-off in Current Collection: A counteracting effect was observed in the short-circuit current density (J_{sc}), which decreased with higher doping levels. This is attributed to increased carrier scattering due to the higher concentration of impurity atoms, which reduces carrier mobility and collection efficiency [4].Net Performance Outcome: Despite the decrease in J_{sc}, the combined gains in V_{oc} and FF resulted in a net improvement in the power conversion efficiency (η), with the highest efficiency of 17.32% achieved at the maximum doping density of $1x10^{18}$ cm^{-3}.In summary, this work demonstrates that optimizing the

substrate doping is essential for maximizing the performance of ITO/InP solar cells. Higher doping densities foster a more ideal junction, leading to superior voltage and fill factor, albeit with a careful trade-off against current loss due to scattering.

5.1 Implications of the Work

The findings of this study have several important implications:

- **For Device Physics:** It provides clear experimental evidence of how substrate doping can be used to engineer the current transport mechanism in a heterojunction solar cell, moving it from a recombination-limited to a diffusion-limited regime.
- **For InP Solar Cell Optimization:** It offers a practical pathway for improving the V_oc and efficiency of InP-based solar cells, which is crucial for applications where high performance is critical, such as in space photovoltaics.
- **For Fabrication Processes:** It underscores the importance of precise doping control during the substrate preparation stage, highlighting that it is as critical as the deposition parameters of the thin films themselves.

5.2 Recommendations for Future Work

Based on the conclusions and limitations encountered in this study, the following avenues are proposed for future research .Investigation of Intermediate Doping Levels Future studies should fabricate cells with doping densities between 10^{17} and 10^{18} cm^{-3} to more precisely pinpoint the optimal doping concentration that balances the improvement in V_oc with the degradation in J_sc.

- **Advanced Characterization**: Techniques such as C-V profiling and DLTS (Deep-Level Transient Spectroscopy) could be employed to quantitatively analyze the changing depletion width and identify the specific defect states responsible for recombination at lower doping levels [5].
- **Thickness Variation Study:** A synergistic study varying both the substrate doping density and the thickness of the base layer could be conducted. This would help determine if a thinner, highly doped layer could minimize the J_sc loss while still benefiting from the high V_oc.
- **Exploration of Alternative Window Layers**: The successful use of ITO invites comparison with other transparent conducting oxides (TCOs) or carrier-selective contacts (like the Ta_2O_5 mentioned in the literature review [6]) on these optimized, highly-doped substrates to further enhance performance.

Radiation Hardness Testing: Given InP's known radiation resistance, future work could subject these optimized cells to electron or proton irradiation to determine if the higher doping density also confers superior endurance, building upon the literature findings of [7].

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