

# DESIGN OF THIN FILM CdTe SOLAR CELL USING PC1D

## Abstract

This study explores the performance of CdS/CdTe solar cells, focusing on the impact of the CdTe absorber layer thickness, using PC1D. Key findings include the significant effect of the absorber layer thickness on cell performance, with thinner layers potentially leading to performance limitations. Our analysis also provides valuable insights into the design and optimization of CdTe solar cells, highlighting the delicate balance between CdS thickness and optical properties in achieving high efficiency. The study offers valuable insights for further research and potential improvements in the design and efficiency of CdS/CdTe solar cells.

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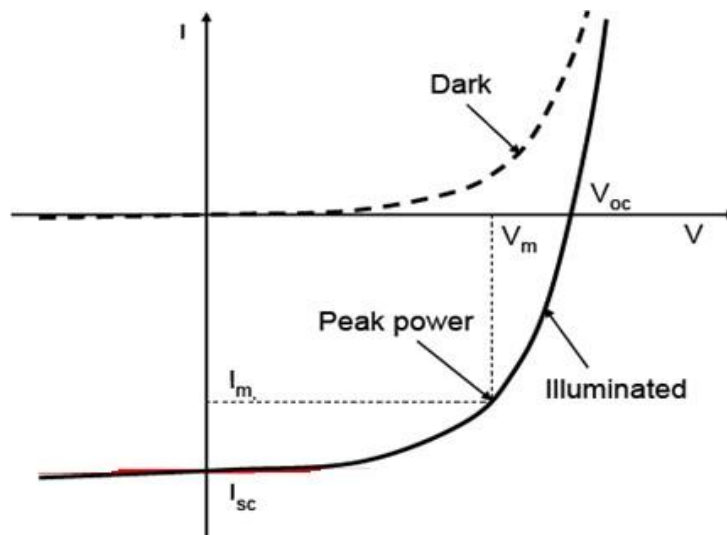
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## I. INTRODUCTION

- 1. The Need for Sustainable Energy Sources:** The world's energy demands have consistently surged, particularly in recent centuries, and are projected to continue rising in the future. This demand is primarily driven by two factors: the global population's growth and the technological and economic advancement of nations. However, this increasing energy demand places immense pressure on conventional energy sources, such as oil, gas, and coal. These fossil fuels are finite in quantity and contribute to environmental pollution. Consequently, there is a pressing need for alternative energy sources that can provide sustainable energy. Among these alternatives, solar energy from the sun emerges as a clear choice.
- 2. Advantages of Solar Energy:** Harnessing solar energy offers numerous advantages:
  - It is an everlasting and renewable energy source.
  - Solar energy is environmentally friendly, causing no harm to the environment.
  - The sun provides an immense energy source. The power Earth receives from the sun, approximately  $1.8 \times 10^{11}$  MW, is thousands of times greater than all other energy sources combined.
  - Solar energy is universally available and free, and its utilization does not produce pollution.
- 3. Solar Cells and Their Operational Principle:** Sunlight can be converted into electricity through the photovoltaic effect, first discovered by French scientist Edmund Becquerel in 1839. Sunlight consists of photons, discrete packets of energy. These photons carry varying amounts of energy corresponding to different wavelengths of light. When photons strike a solar cell, typically a semiconductor P-N junction device, they may be reflected, absorbed, or passed through the cell. When a photon is absorbed in a solar cell, it generates an electron-hole pair (EHP). When these EHPs are separated across the P-N junction, a voltage is generated, driving current in an external circuit and enabling power extraction from the solar cell or photovoltaic (PV) cell. The operational principle of modern solar cells is rooted in the photovoltaic effect. Essentially, this effect involves the generation of a potential difference at the junction of two different materials in response to visible or other radiation. The key processes behind the photovoltaic effect include the generation of carriers due to photon absorption, the subsequent separation of these photo-generated carriers (EHP) at the junction, and the collection of these carriers at the junction's terminals.

Generally, a solar cell structure comprises an absorber layer, where incident radiation's photons are efficiently absorbed, leading to the creation of electron-hole pairs. To separate the photo-generated electrons and holes, semi-permeable membranes are attached to both sides of the absorber. These semi-permeable membranes selectively permit only one type of charge carrier to pass through. Ensuring that the electrons and holes generated in the absorber layer reach the membranes is crucial for efficient solar cell design, requiring that the charge carriers' diffusion lengths are greater than the absorber's thickness.

- 4. Current-Voltage Parameters under Illumination:** Solar cell behavior is analyzed by examining three key parameters: the "open-circuit voltage" ( $V_{OC}$ ), which is the voltage when the device's impedance is lower than the load; the "short-circuit current" ( $I_{SC}$ ), which is the current when the device's impedance is higher than the load; and the "fill factor" ( $FF$ ), defined as the ratio of the maximum power output to the product of the open-circuit voltage and short-circuit current. The efficiency ( $\eta$ ) of a solar cell is defined as the ratio of the maximum or peak power output to the input power. Figure 1 illustrates the I-V curve of a solar cell under both dark and illuminated conditions.



**Figure 1:** Light and dark curves for solar cell

- 5. Overview of CdTe Solar Cells:** Historically, the dominant solar cell technology in the market has been based on crystalline silicon wafers. These cells are manufactured using bulk crystals, often recycled from the microelectronics industry. However, the production process for crystalline and multicrystalline silicon cells is costly, making them less competitive compared to fossil fuels for energy production.

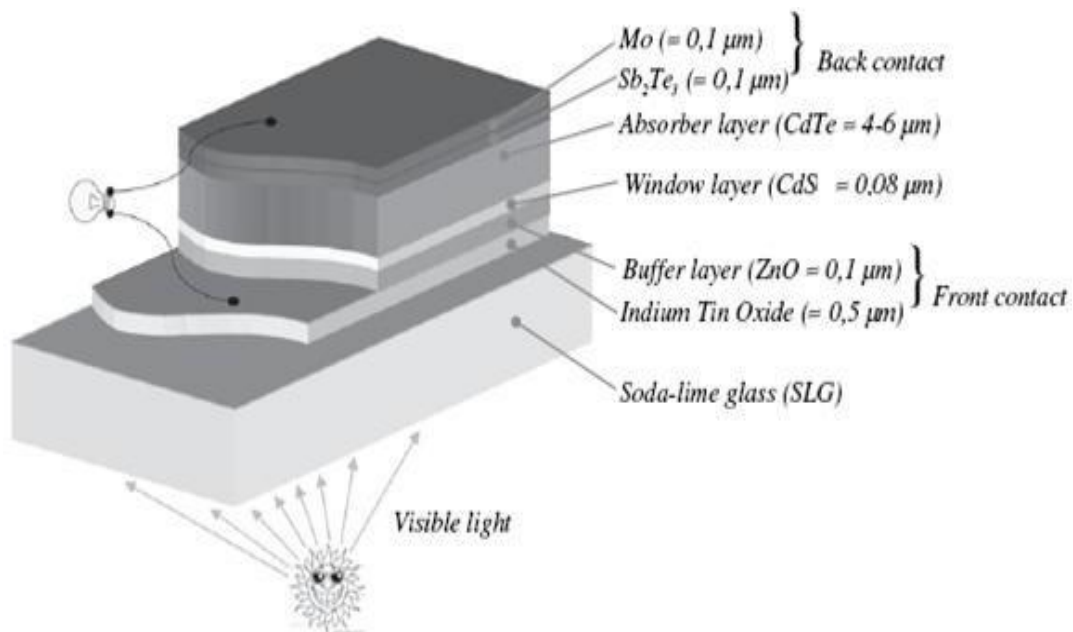
To address the need for lower-cost photovoltaic (PV) technologies, the concept of thin-film solar cells gained attention. Thin-film solar cells offer two distinct advantages: they require significantly less material, and their production processes are easily scalable. Consequently, it was projected that the average cost per watt of a thin-film solar cell would be lower than that of silicon-based cells. Thin-film solar cells operate by using thinner semiconductor layers, often just a few microns thick, to absorb and convert photons into electricity.

The first thin-film technology developed and manufactured was based on amorphous silicon. However, this technology faced limitations due to its low efficiency and slow deposition rates. Despite this, the PV market continued to be dominated by wafer-based crystalline silicon. Currently, two other thin-film technologies, Cadmium Telluride (CdTe) and Copper Indium Gallium diselenide (CIGS) alloys, are challenging the dominance of silicon-based cells.

CdTe-based heterojunction solar cells have been studied since the early 1960s, particularly for use in thin-film devices on glass substrates. CdTe offers advantages such as ease of growth and a bandgap (approximately 1.5 eV) that closely matches the absorption of solar spectrum photons, optimizing electricity conversion. CdTe is now considered a promising material for thin-film solar cells and plays a significant role in the rapidly expanding photovoltaic industry. Although CdTe thin-film solar cells exhibit substantial potential for low-cost photovoltaic energy conversion, their performance and reproducibility have been limited by the conventional SnO<sub>2</sub>/CdS/CdTe device structure used for over three decades. Nevertheless, thin-film CdTe solar cells have made a substantial impact on solar energy production.

CdTe boasts a bandgap of 1.45 eV, very close to the maximum for solar energy conversion. Its gap is direct, and its absorption coefficient ranges from 10<sup>4</sup> to 10<sup>5</sup> cm<sup>-1</sup> for photon energies exceeding the bandgap. This implies that only a few micrometers of CdTe material are sufficient to absorb all incident light. Theoretically, CdTe can achieve a maximum efficiency of over 27% and a practical efficiency of 18.5%, with an open-circuit voltage of 880 mV and a short-circuit current density of 27 mA/cm<sup>2</sup> (assuming a negligible thin layer of CdS). Notably, CdTe is one of the few II-VI compounds that can be prepared in both p-type and n-type forms.

- 6. Layers in CdTe/CdS Solar Cells:** Figure 2 illustrates the schematic structure of a typical CdTe/CdS polycrystalline thin-film solar cell used today. These cells are configured in a superstrate arrangement, with incident light passing through the substrate. The substrate can be made of soda-lime glass (common window glass) or specialized alkali-free glass. Choosing alkali-free glass ensures that no pollutants diffuse into the overlying films, offering greater flexibility in cell processing due to its higher softening temperature.



**Figure 2:** Schematic of the CdTe/CdS solar cell structure.

The front-contact layer is typically composed of a transparent conductive oxide (TCO) like indium tin oxide (ITO), fluorine-doped indium oxide (IFO), or fluorine-doped tin oxide (FTO). On top of this conductive layer, a buffer layer, often measuring a few nanometers (50-200 nm), is deposited. Materials like pure TCO, ZnO, or Ga<sub>2</sub>O<sub>3</sub> serve as a shield against potential diffusion of sodium (Na) and potassium (K) atoms. These buffer layers are generally resistive, with electrical resistivity in the range of 10<sup>2</sup> to 10<sup>5</sup> Ω-cm. Therefore, they are effective in preventing an increase in the reverse saturation current of the junction if there are any pinholes in the subsequent very thin CdS film.

The CdS film, serving as the window layer and representing the n-type portion of the junction, plays a crucial role in highly efficient CdTe-based solar cells. For these solar cells, CdS films are typically deposited using either Close-Spaced Sublimation (CSS) or sputtering methods. To maximize the photocurrent generated by the solar cell, it's essential to minimize the thickness of the CdS film. The presence of a buffer layer between the CdS and the Transparent Conductive Oxide (TCO) films aids in achieving this. Typically, CdS layer thickness falls within the range of 70 to 120 nm.

In efficient CdTe/CdS solar cells, CSS is the preferred technique for depositing CdTe films, which are relatively thick, ranging from 4 to 7 μm. These CdTe films are positioned on top of the CdS layer, as shown in Figure 2. CSS is particularly advantageous for large-scale applications due to its rapid deposition process, which takes only 1 or 2 minutes. The best cell performance is achieved when CdTe films are grown in an oxidizing atmosphere. Beyond the CdTe layer, there is the back contact layer, completing the solar cell structure.

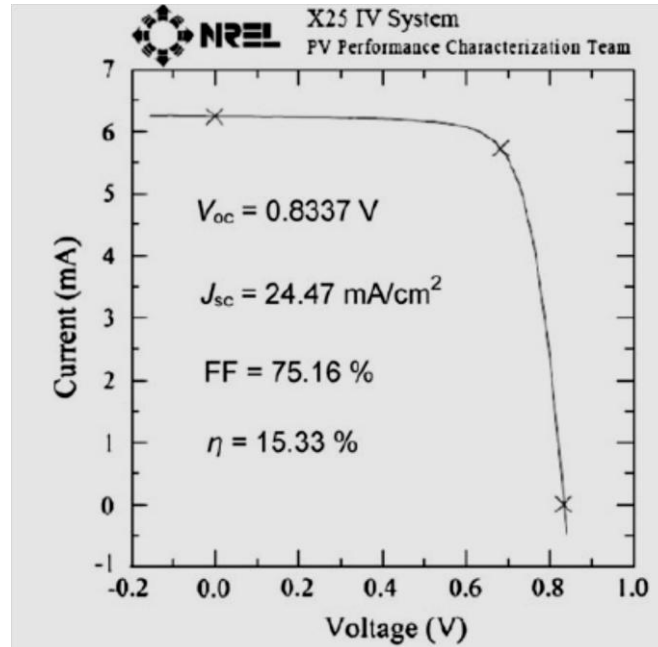
## II. REVIEW OF CDTE SOLAR CELLS

- 1. High-Efficiency Polycrystalline CdS/CdTe Solar Cells:** In the solar industry, the difference in efficiency between commercial modules and laboratory-scale cells remains a significant challenge. The CdS/CdTe solar cell exhibits a maximum theoretical efficiency of around 30%, with a more conservative practical limit of approximately 20%. Currently, the leader in CdTe solar technology reports record module efficiencies of 13.4% and a record laboratory cell efficiency of 17.3%. EPIR Technologies, Inc. (EPIR) achieved an NREL-verified efficiency of 15.3% in their best device. Notably, the average efficiency of hundreds of cells produced with a buffer layer between December 2010 and June 2011 is 14.4%. Quantum efficiency results are presented to illustrate EPIR's progress toward NREL's best-published outcomes.

EPIR Technologies, Inc. successfully produced multiple polycrystalline CdS/CdTe solar cells with efficiencies exceeding 15%. These cells were manufactured on buffered, commercially available Pilkington TEC Glass and were subsequently verified by the National Renewable Energy Laboratory (NREL). The growth of n-CdS and p- CdTe layers was accomplished through chemical bath deposition (CBD) and close space sublimation methods, respectively.

EPIR's achievements with cells on commercial glass were made possible by implementing a high-resistivity SnO<sub>2</sub> buffer layer and optimizing the thickness of the CdS window layer. The high-resistivity buffer layer serves to prevent the formation of

CdTe-TCO junctions, thereby maintaining a high open-circuit voltage and fill factor. Simultaneously, the use of a thin CdS layer reduces absorption losses and enhances the short-circuit current density, contributing to the overall efficiency of the CdS/CdTe solar cells.



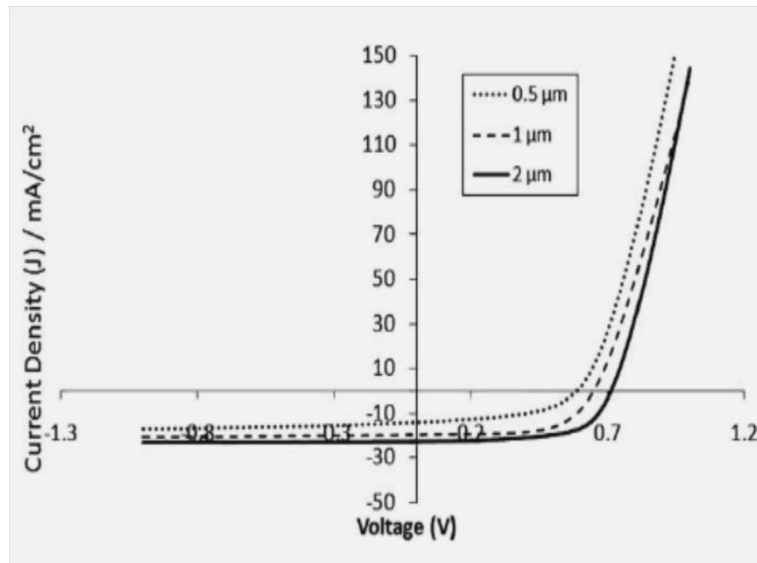
**Figure 3:** I-V curve and derived parameters of an NREL-verified, EPIR-produced, high-efficiency polycrystalline CdTe solar cell.

EPIR Technologies, through a series of focused process optimizations, has achieved the production of multiple polycrystalline CdS/CdTe solar cells on commercially available TCO-coated glass with efficiencies exceeding 15%. The highest-performing device, even without an antireflection coating (ARC), demonstrated an NREL-verified efficiency of 15.3%. Figure 3 displays the I-V characteristic and measured device parameters for this specific cell. It's important to note that the incorporation of a buffer layer has been instrumental in attaining these impressive results. While achieving high performance in a single cell is a crucial proof of concept for enhancing module efficiencies, maintaining consistently high performance across multiple cells is of paramount importance. The average efficiency of hundreds of cells produced at EPIR with the inclusion of a buffer layer between December 2010 and June 2011 is 14.4%.

- 2. Ultra-Thin CdTe Solar Cells Using MOCVD:** A study focused on extremely thin CdTe absorber layers, measuring less than 1  $\mu\text{m}$  in thickness, was conducted to investigate limitations in CdTe collection efficiency. By reducing the thickness of the CdTe absorber layer to levels below the absorption limit of 1  $\mu\text{m}$ , the goal was to minimize material usage and address carrier recombination losses that occur throughout the absorber layer.

In conventional thin-film CdTe solar cells, the absorber layer thickness typically ranges from 2 to 10  $\mu\text{m}$ . Thicker absorber layers are often used to prevent pinholes from

reaching through to the window layer, which could result in electrical shorts with the back contact.



**Figure 4:** Light J–V curves (under  $100 \text{ mW/cm}^2$  xenon lamp illumination) for i)  $0.5 \mu\text{m}$ , ii)  $1 \mu\text{m}$  and iii)  $2 \mu\text{m}$  absorber thicknesses

J–V (current-voltage) measurements on thin and ultra-thin absorber layers provide valuable insights into voltage-dependent collection in devices. It is suggested that reducing the thickness of the absorber layer enhances voltage-dependent collection, particularly at high forward bias. The figure above displays light J–V curves for various absorber layer devices.

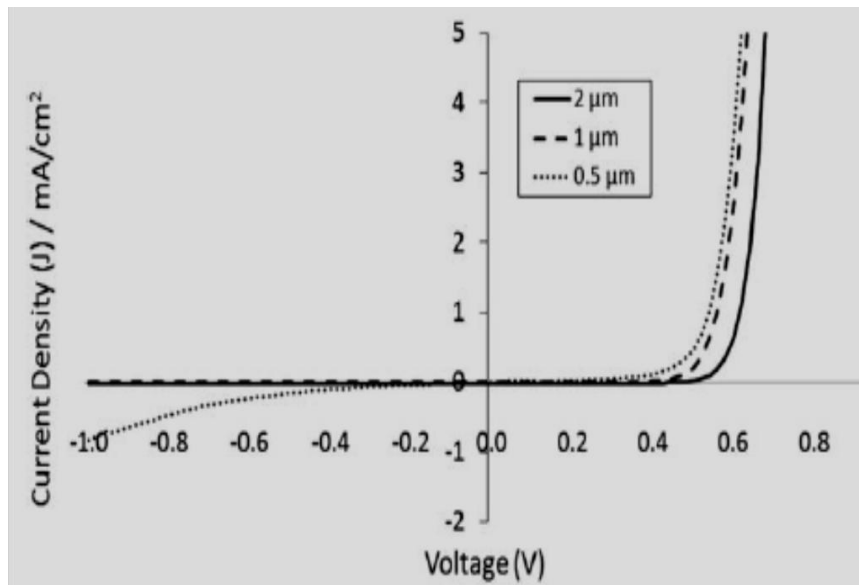
One notable observation is that the open-circuit voltage ( $V_{OC}$ ) increases with absorber thickness. This is primarily attributed to the rise in photocurrent ( $J_L$ ) as the absorption volume expands with thicker absorber layers.

An analysis of series resistances as they evolve with absorber thickness reveals minimal changes in series resistance. This indicates that the back contact barrier remains largely unaffected even with the pn junction in close proximity, even down to a thickness of  $200 \text{ nm}$  for the absorber.

However, there is a significant decrease in shunt resistance, approximated from the J–V curves, as the absorber thickness decreases. This increase in shunting is likely caused by leakage currents around the edges of the cell, considering the thin nature of the layers. Alternatively, it could be attributed to extended lattice defects such as grain boundaries and dislocations within the depletion region of the device.

Dark J–V curves (Figure 5) have also been measured, revealing increased recombination effects, particularly in the reverse bias region, for the  $500 \text{ nm}$  thick CdTe layer. These dark J–V curves highlight that as the absorber thickness is reduced below the CdTe absorption thickness (approximately  $1 \mu\text{m}$ ), recombination effects become more prominent and start to dominate the device characteristics. The substantial decrease in

device parameters as absorber thickness decreases below 1  $\mu\text{m}$  suggests that these cells face limitations not only due to optical factors but also interface issues, and possibly their proximity to the back contact. By introducing an acceptor defect between the CdS and CdTe layers, there was an improvement in the agreement between the basic model and measured results, particularly when ultra-thin absorbers were utilized. This improvement potentially signifies an increase in the interface defect density with thinner absorbers.

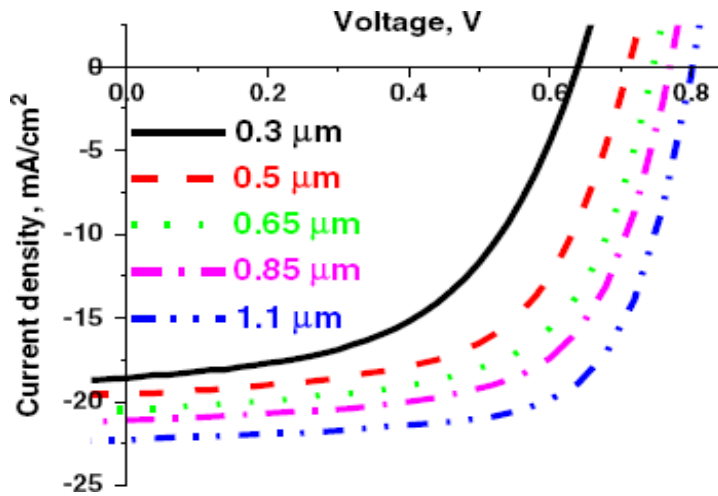


**Figure 5:** Dark J–V curves of cells with different absorber thickness showing increased recombination for the thinner cells.

- Thin-Film CdTe Cells - Reducing the CdTe Thickness:** CdTe, as a polycrystalline thin-film material, currently holds a dominant position in global photovoltaic manufacturing. Given the finite availability of tellurium (Te) resources worldwide, it becomes imperative to explore the possibility of reducing the thickness of the CdTe material in these devices.

Several advantages emerge from decreasing the absorber layer thickness in solar cells, especially for direct bandgap materials like CdTe. These advantages include reduced material usage, particularly for elements with low Earth abundance such as indium (In) and tellurium (Te), shortened post-deposition processing time, decreased deposition time, and a lower potential environmental impact.

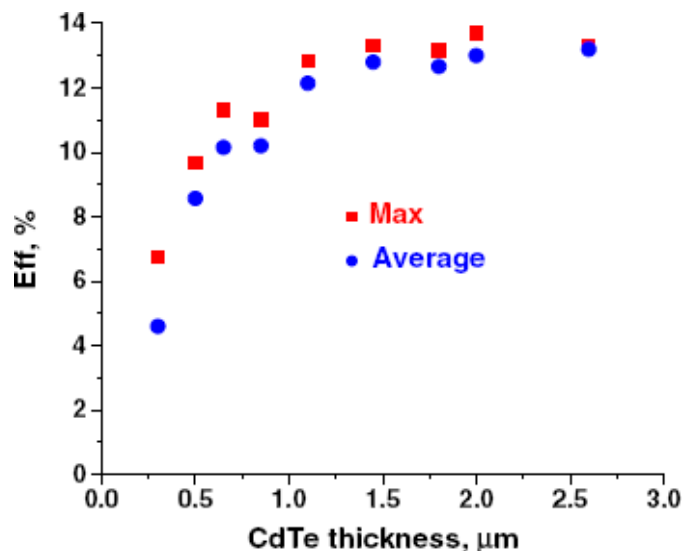




**Figure 6:** Different J–V characteristics of solar cells with different CdTe thickness.

Semiconductor absorber materials with a direct bandgap typically do not require thicknesses greater than one micron to absorb light effectively, especially beyond a few millielectronvolts (meV) of the band edge. CdTe solar cells are often constructed in a superstrate structure. Interestingly, back-contact processing might limit the reduction in CdTe thickness. This limitation can be attributed to chemical etching processes, like nitric–phosphoric acid etching, which primarily etch along grain boundaries. This process may lead to excessive shunting as efforts are made to reduce the thickness of CdTe layers, presenting a challenge in CdTe thickness reduction.

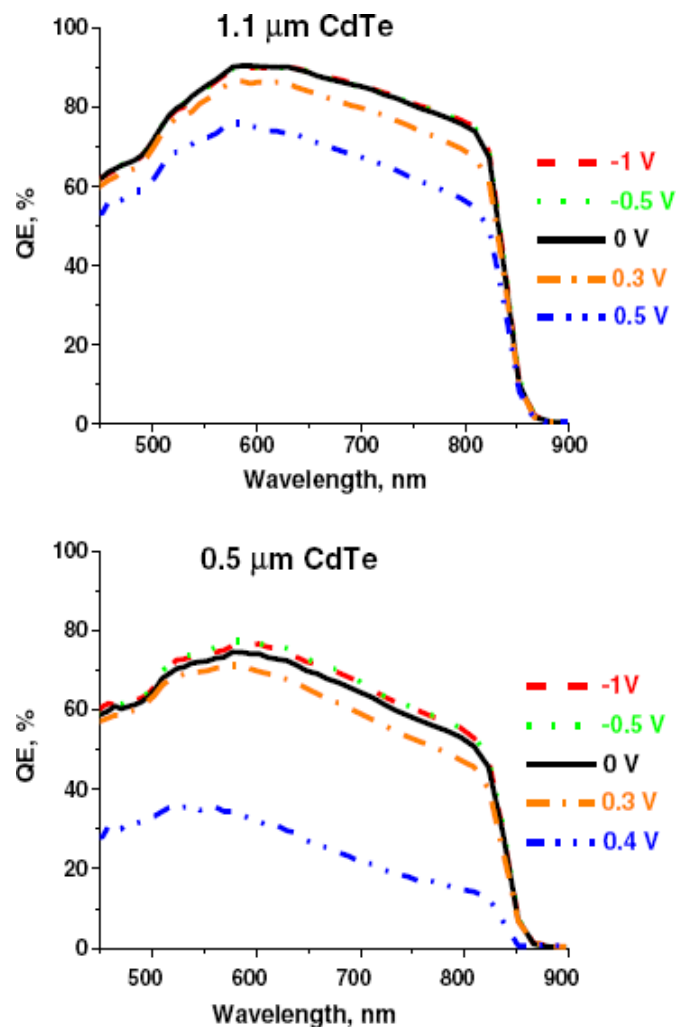
Various CdTe thicknesses ranging from 0.3  $\mu\text{m}$  to 2.6  $\mu\text{m}$  were selected for the study. It is notable that beyond 1.1  $\mu\text{m}$ , the J–V (current-voltage) characteristics exhibit a reduced dependency on CdTe thickness. The figure above illustrates the J–V characteristics of five different thin cell structures.



**Figure 7:** Maximum and average cell efficiencies with respect to the CdTe thickness.

A consistent decline in CdTe thickness coincides with a decrease in all primary cell parameters, including open-circuit voltage ( $V_{OC}$ ), short-circuit current ( $J_{SC}$ ), and fill factor (FF). This observation highlights the sensitivity of these parameters to changes in CdTe thickness. It's worth noting that an efficiency of 12% is achieved with a CdTe thickness of 1.1  $\mu\text{m}$ , while a slightly lower efficiency of 9.7% is attained with a CdTe thickness of 0.5  $\mu\text{m}$ .

The external quantum efficiency (QE), as shown in Figure 8, was measured at five different bias voltages (0.4 V, 0.3 V, 0 V, -0.5 V, and -1 V). Notably, there is very little voltage-dependent collection observed at higher thicknesses of CdTe. However, Figure 8 demonstrates a strong dependence on current collection at forward biases of 0.5 V and a moderate dependence at 0.4 V for CdTe thicknesses of 0.5  $\mu\text{m}$  and 1.1  $\mu\text{m}$ , respectively.



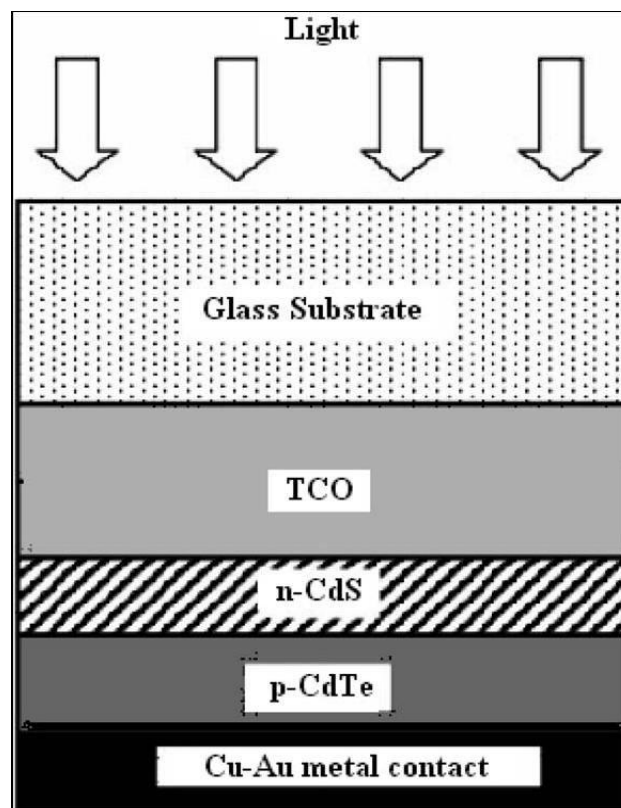
**Figure 8:** QE vs. wavelength of 1.1  $\mu\text{m}$  and 0.5  $\mu\text{m}$  cells.

This behaviour is particularly evident in the thinner cells where, when the CdTe layer is not fully depleted, such as at +0.4 V or +0.5 V, and when a strong applied electric field is reduced, the collection of minority carriers becomes less efficient. This phenomenon is attributed to factors related to the back contact. Specifically, it is caused

by reduced absorber minority carrier lifetime due to the interface with the back contact and the presence of copper (Cu) recombination centers in close proximity to the back contact.

### III. DESIGN OF HIGH-EFFICIENCY CDTE SOLAR CELLS USING PC1D

**1. Introduction:** Polycrystalline thin-film CdTe is emerging as a leading material in the photovoltaic industry, offering a cost-effective and reliable solution for solar cells. This popularity is attributed to several attractive properties, including its bandgap of 1.5 eV, which is close to the ideal value of 1.45 eV for solar energy conversion, and its high optical absorptivity. In heterojunction thin-film CdTe solar cells, CdS is commonly employed as the window layer. While impressive efficiencies of up to 16.5% have been achieved, there is still room for improvement in enhancing the efficiency of CdTe solar cells.



**Figure 9:** Schematics of a typical superstrate CdS/CdTe solar cell structure.

In Figure 9, we can observe the typical four-layer structure of a CdTe/CdS solar cell, as outlined below:

- The Transparent and Conducting Oxide (TCO) serves as the front contact.
- The CdS film acts as the window layer.
- CdTe film serves as the absorber layer, positioned atop the CdS layer.
- The back contact is situated on top of the CdTe layer.

- The Transparent and Conducting Oxide (TCO) needs to exhibit specific characteristics to function effectively as a front contact in thin-film CdTe/CdS solar cells:
  - It must possess a high level of transparency, exceeding 85%, within the desired wavelength range of 400–900 nm.
  - The TCO material should have a low resistivity, typically on the order of  $2 \times 10^{-4} \Omega\text{-cm}$ .
  - Additionally, it should exhibit good stability at high temperatures, ensuring that there is no undesirable diffusion from the transparent conductive oxide layers into the subsequent layers when they are stacked.

For the development of high-efficiency, cost-effective thin-film polycrystalline solar cells, CdTe is a highly suitable absorber material. CdTe boasts a direct bandgap with an energy gap of 1.5 eV and an absorption coefficient of approximately  $10^4 \text{ cm}^{-1}$  in the visible region. Consequently, only a few micrometers of CdTe layer thickness are necessary to absorb 90% of the incident photons.

2. **PC1D Overview:** PC1D is a computer program designed to solve the fully coupled nonlinear equations governing the transport of electrons and holes in quasi-one-dimensional crystalline semiconductor devices, with a particular emphasis on photovoltaic devices. Initially developed at Sandia National Labs by Dr. Paul Basore and his colleagues, it was further refined by Dr. Don Clugston at the University of New South Wales, Australia. PC1D employs the drift-diffusion model and runs on all 32-bit MS Windows operating systems.

This program has gained popularity for its user-friendly interface, data input/output versatility, and comprehensive parameterization, allowing for accurate modeling of solar cells. It can accurately model common semiconductor materials like silicon (Si) and gallium arsenide (GaAs).

3. **Program Description:** PC1D is a standalone program that requires only one file, PC1D.EXE, to run. Additional files, such as PC1D.HLP for on-screen help, material parameters, standardized solar spectra, and example problems, are provided and can be copied to the directory of choice.

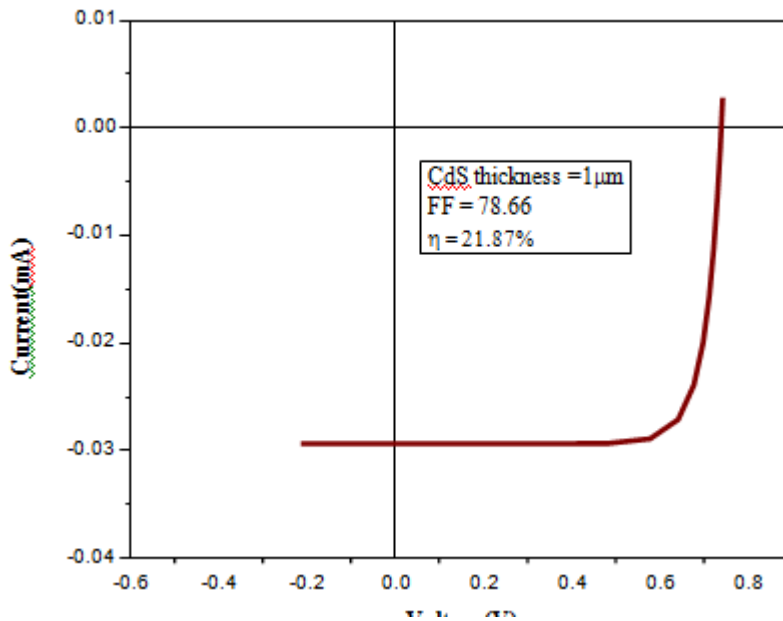
#### 4. Key PC1D Options

- **Device Menu**
  - **Region Manager:** Allows manipulation of region numbers in the device, which can be made of different materials with various parameters.
  - **Region Parameters:** Provides details on the current region, enabling examination and modification of thickness, material, doping, and recombination parameters.
  - **Device Parameters:** Allows for changes to device parameters as a whole, including area, surface texture, surface charge, external circuit contact locations, and optical reflectance.

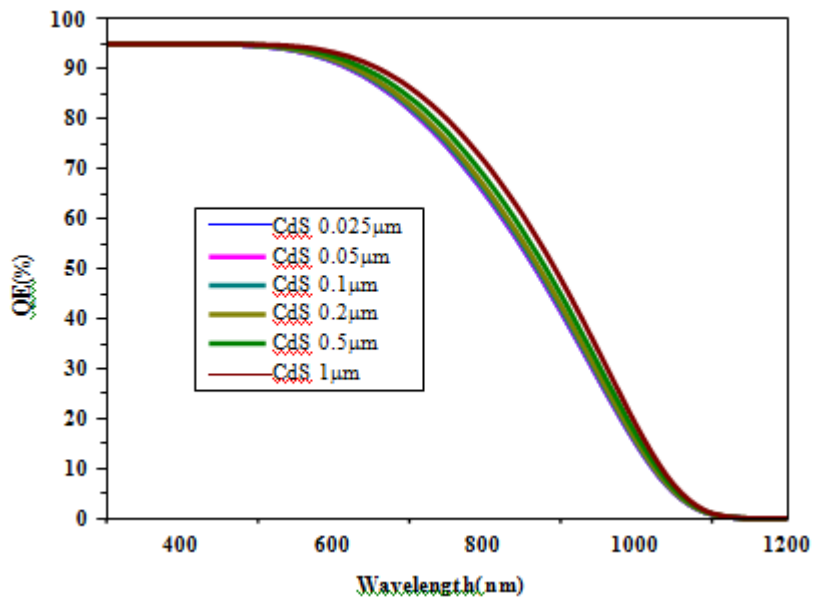
- **Device Files:** Enables the creation, retrieval, and storage of device files (.DEV), containing all device information without excitation or numerical solution data.
  - **Excitation Menu**
    - **Mode:** Controls whether excitation is applied in steady-state or transient mode.
    - **Temperature:** Sets the device temperature in Kelvin or degrees Celsius, impacting carrier mobilities, surface recombination, optical absorption, and more.
    - **Base/Collector Source Circuits:** Specifies Thevenin-equivalent circuits for the base and collector, active if contacts have been enabled.
    - **Photo Generation:** Allows the introduction of photo generation via primary or secondary light source illumination or external file input.
    - **Excitation Files:** Creates, retrieves, or stores binary files containing parameters to define excitation, which can be used with various devices.
  - **Graph Menu Commands**
    - **Spatial Graphs:** Controls graphs displaying spatial information.
    - **Temporal Graphs:** Manages graphs displaying temporal information.
    - **Defined Graph:** Specifies x and y functions for any graph from a selection of 75 functions, offering detailed insight into device operation.
    - **Auxiliary Graph:** Deals with spatial function and position within the device, data can be viewed using the Auxiliary selection.
    - **Experimental:** Opens a dialog box for data selection from external files, which can be viewed on user-defined graphs.
    - **Previous and Next History Graph:** After simulation, up to 100 interactive graphs are saved and can be viewed for result comparison.
5. **Improving CdS/CdTe Solar Cell Efficiency:** The following sections describe how variations in the thickness of CdS and CdTe layers impact the efficiency of CdS/CdTe solar cells using PC1D simulator.
6. **Variation of CdS Thickness:** The study investigates the impact of window layer (CdS) thickness on cell performance.

**Table 1: Performance values for different CdS thickness values**

CdTe ( $\mu\text{m}$ )	CdS ( $\mu\text{m}$ )	Voc (V)	Isc (mA)	FF (%)	H (%)
3	0.025	0.754	28.6	85.04	21.52
3	0.05	0.752	28.6	84.65	21.50
3	0.1	0.751	28.7	84.02	21.54
3	0.2	0.748	28.9	82.86	21.60
3	0.5	0.74	29.3	80.27	21.68
3	1	0.729	30	78.66	21.87



**Figure 10:** I-V characteristics of CdTe/CdS solar cell with CdS thickness 1  $\mu\text{m}$



**Figure 11:** QE-Wavelength curve of CdTe/CdS solar cell with different CdS thickness

Our observations about the impact of CdS thickness on efficiency and the role of CdS as a window layer in CdTe solar cells are insightful. Here's a summary of your observations:

- **Effect of CdS Thickness:** Increasing the thickness of the CdS layer in CdTe solar cells leads to an increase in efficiency. This is likely because thinner CdS layers allow more carriers generated in the CdTe layer to be collected and contribute to the photocurrent.

- **Optical Transmission:** To maintain above-gap optical transmission, it is preferable to use thin CdS layers, typically in the range of 50 - 100 nm. This thickness ensures that a significant portion of incident light can penetrate the CdS layer and reach the CdTe layer for conversion.
- **Homogeneity:** CdTe layers in the range of 1-10  $\mu\text{m}$  thickness provide homogeneity in the solar cell structure, which is essential for consistent and efficient performance.
- **Challenges with CdS Substitution:** Substituting CdS as the window layer in CdTe solar cells can be challenging. CdS has been found to form an excellent hetero-junction with CdTe, which is crucial for efficient charge separation and collection.

Improvement through Nano-Crystalline CdS: One potential avenue for improving CdS as a window layer is by making it nano-crystalline and introducing oxygen. This process can lead to a larger bandgap in CdS, reducing absorption losses in the CdS layer and potentially enhancing overall cell performance.

Our analysis provides valuable insights into the design and optimization of CdTe solar cells, highlighting the delicate balance between CdS thickness and optical properties in achieving high efficiency. Additionally, exploring innovative approaches like nano-crystalline CdS demonstrates a commitment to improving the technology's performance and sustainability.

**Table 2: Parameters for CdTe and CdS films required for modeling**

Parameter	CdTe	CdS
Thickness ( $\mu\text{m}$ )	1-8	0.025
Bandgap (eV)	1.5	2.4
Electron affinity (eV)	3.9	4
Dielectric permittivity (relative)	9.4	10
Electron mobility ( $\text{cm}^2/\text{V}\cdot\text{s}$ )	500	350
Hole mobility ( $\text{cm}^2/\text{V}\cdot\text{s}$ )	60	50
Electron thermal velocity (cm/s)	1.00E+7	1.00E+7
Hole thermal velocity (cm/s)	1.00E+7	1.00E+7
Electron density ( $\text{cm}^{-3}$ )	-	1.00E+15
Hole density ( $\text{cm}^{-3}$ )	1.00E+17	-
Light Intensity ( $\text{W}/\text{cm}^2$ )	0.1	

Table 2 provides essential properties of CdTe and CdS thin films used in the simulation of CdS/CdTe solar cells, along with considerations for potential improvements in cell performance. Here's a summary:

- **Donor Concentration:** The donor concentration considered in the simulation is  $1 \times 10^{17} \text{ cm}^{-3}$ . However, it's noted that this value strongly depends on the deposition

method. Using a higher donor concentration, such as  $1 \times 10^{18} \text{ cm}^{-3}$  through doping processes, may lead to better results, especially in terms of open circuit voltage (Voc).

- **Electron Diffusion Length:** The electron diffusion length is estimated to be around 3-4  $\mu\text{m}$  for the given donor concentration. However, literature reports suggest that this value can vary between 1 and 8  $\mu\text{m}$  under different laboratory conditions and deposition techniques for CdTe.
- **Carrier Concentration:** The carrier concentration for the majority carrier is currently at  $1 \times 10^{15} \text{ cm}^{-3}$ . Increasing this value to  $1 \times 10^{16} \text{ cm}^{-3}$  is expected to result in a higher built-in voltage.

These considerations indicate that optimizing the material properties, particularly donor concentration and carrier concentration, can have a significant impact on the performance of CdS/CdTe solar cells, potentially leading to improvements in key parameters like open circuit voltage and overall efficiency.

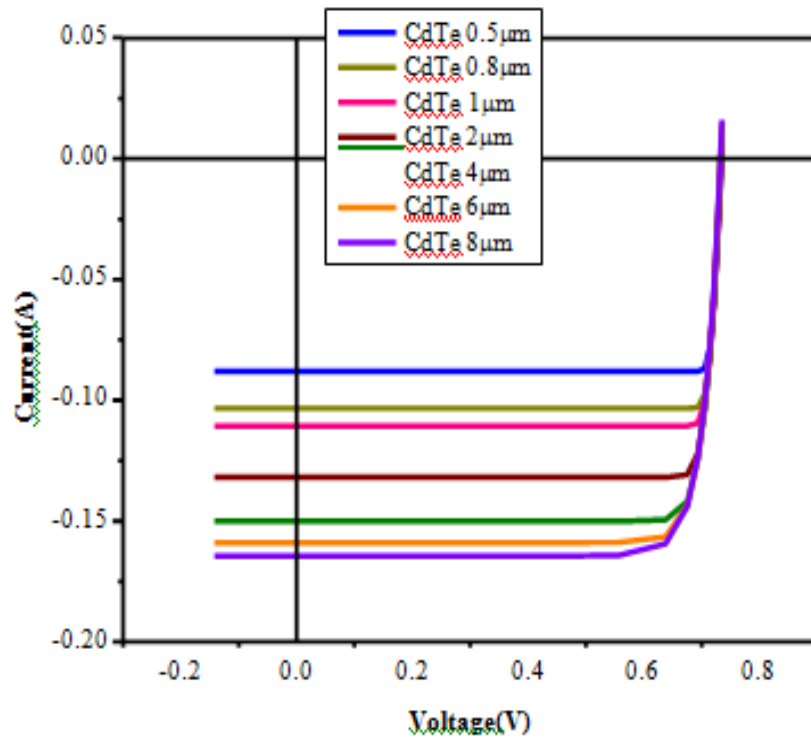
7. **Investigating the Influence of CdTe Thickness:** One crucial aspect we must examine is the effect of varying the thickness of the CdTe absorber layer on the overall performance of the solar cell. While there is a desire to minimize material costs by reducing layer thickness, it's essential to consider that doing so could potentially lead to a decline in cell performance.

Indeed, optimizing the thickness of the CdTe absorber layer in CdS/CdTe solar cells is a critical factor in achieving the right balance between cost and performance. As we have mentioned, increasing the thickness of the absorber layer can enhance short-circuit current and efficiency, but there are practical limitations due to cost considerations.

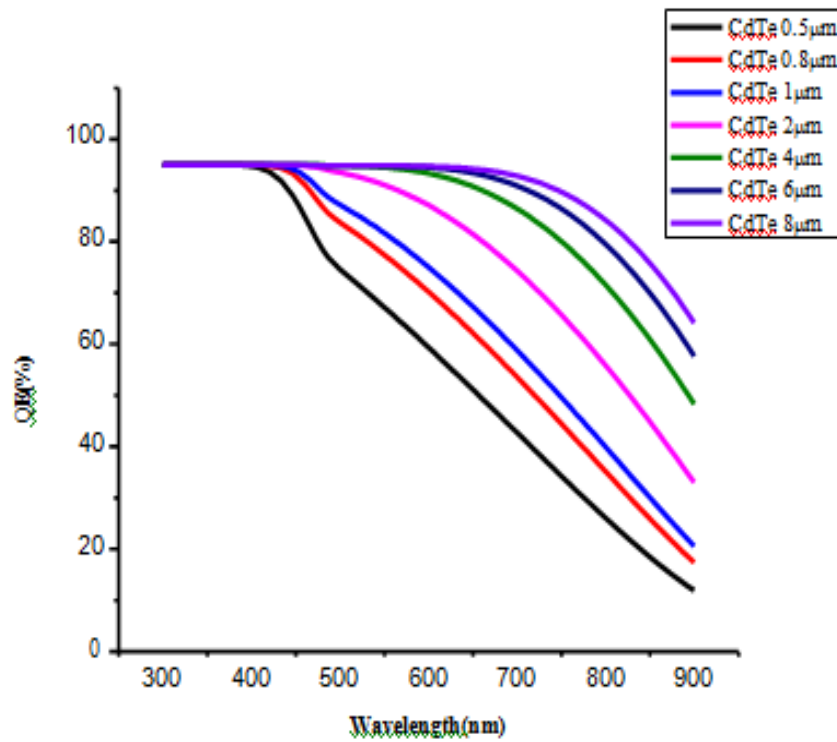
**Table 3: Performance Values for Different CdTe Thickness Values**

CdTe (um)	CdS (nm)	Voc (V)	Isc (A)	FF (%)	$\eta$ (%)
0.5	35	0.7774	0.088	81.5438	11.157
0.8	35	0.7716	0.1034	84.2355	13.4412
1	35	0.7688	0.1106	82.7013	14.0641
1.5	35	0.7634	0.1234	84.5524	15.9303
2	35	0.7591	0.1319	83.5962	16.7402
2.5	35	0.7554	0.1382	81.8486	17.0894
3	35	0.7522	0.143	84.4595	18.1697
3.5	35	0.7493	0.1469	84.5602	18.6154
4	35	0.7467	0.1501	84.3869	18.9161
5	35	0.7422	0.1552	83.4243	19.2192
6	35	0.7385	0.159	82.4265	19.3573
7	35	0.7352	0.162	81.4971	19.413
8	35	0.7323	0.1644	84.4466	20.3331





**Figure 13:** I-V characteristics of CdTe/CdS solar cell with CdTe thickness 0.5 – 8 μm



**Figure 14:** QE vs Wavelength curve of CdTe/CdS solar cell with CdTe thickness 0.5-8micron

Here are some key considerations

- 1. Cost vs. Efficiency:** Increasing the thickness of the CdTe absorber layer typically improves efficiency by allowing for more light absorption and carrier generation. However, this can also increase material costs. Finding the sweet spot where you get a significant efficiency boost without excessive cost is essential.
- 2. Optical Absorption:** The CdTe absorber layer needs to be thick enough to absorb a substantial portion of the incident sunlight. Extremely thin layers may limit light absorption, reducing the photocurrent and efficiency.
- 3. Carrier Collection:** A thicker CdTe layer provides more space for the generation and collection of charge carriers. This can improve both the short-circuit current and fill factor.
- 4. Deposition Method:** The choice of deposition method for CdTe can influence the optimal thickness. Different methods may have varying thickness requirements.
- 5. Homogeneity:** Ensuring uniformity and homogeneity in the CdTe layer's thickness is essential to maintain consistent and reliable cell performance.
- 6. Economic Considerations:** While thicker CdTe layers may improve performance, they also increase material costs. Careful economic analysis is required to determine the most cost-effective thickness.
- 7. Environmental Impact:** Consider the environmental impact of material usage and disposal. Thinner layers may be more environmentally friendly.

To optimize CdS/CdTe solar cell performance, it's crucial to conduct systematic experiments or simulations to identify the optimal CdTe thickness for your specific application, taking into account factors like cost, efficiency, and material availability. This optimization process can lead to the development of more efficient and cost-effective solar cells.

#### IV. CONCLUSION

Our conclusion summarizes the key findings and insights from our study on CdS/CdTe solar cells effectively. It highlights several important points:

- 1. Absorber Thickness Impact:** It is observed that the thickness of the CdTe absorber layer significantly affects cell performance. Thinner absorber layers may lead to performance limitations due to optical issues, interface effects, and back contact considerations.
- 2. Interface Defects:** It's worthy to note that introducing an acceptor defect between the window and absorber layer can potentially improve results, especially for ultra-thin absorber layers. This action could help mitigate the impact of increased interface defect density.
- 3. Back Contact Investigation:** There is a need for further investigation into the influence of the back contact, particularly for thinner cells. This aspect is crucial for understanding and optimizing cell performance.

- 4. Model Complexity:** It's highlighted that modeling CdTe-CdS devices requires a substantial number of parameters, approximately 50-100, to achieve accurate results. This complexity underscores the importance of considering various factors when optimizing cell performance.

In conclusion, our study provides valuable insights into the factors influencing CdS/CdTe solar cell performance, offering a foundation for further research and potential improvements in the design and efficiency of these solar cells.

## REFERENCE

- [1] E. Colegrove et al., "High-Efficiency Polycrystalline CdS/CdTe Solar Cells on Buffered Commercial TCO-Coated Glass", *Journal of Electronic Materials*, Vol. 41, No. 10, pp. 2833-2837, May 2012
- [2] E.W. Jones et al., "Towards ultra-thin CdTe solar cells using MOCVD", Elsevier, *Thin Solid Films*, No.517 , pp. 2226–2230, 2009
- [3] C. Ferekides and J. Britt, "CdTe solar cells with efficiencies over 15%", Elsevier, *Solar Energy Materials & Solar Cells*, Vol No. 35, pp. 255-262, 1994
- [4] V. Plotnikov et al., "Thin-film CdTe cells: Reducing the CdTe", Elsevier, *Thin Solid Films* , No. 519, pp. 7134–7137, 2011
- [5] Alessio Bosio et al., "Polycrystalline CdTe thin films for photovoltaic applications", Elsevier, *Progress in Crystal Growth and Characterization of Materials*, No. 52, pp. 247- 279, Sept. 2006
- [6] Robert W. Birkmire and Brian E. McCandless, "CdTe thin film technology: Leading thin film PV into the future", Elsevier, *Current Opinion in Solid State and Materials Science*, No. 14, pp. 139–142, Aug. 2010
- [7] Clugston, D.A. and Basore, P.A., "PC1D Version 5: 32-bit Solar Cell Simulation on Personal Computers," 26th IEEE Photovoltaic Specialists Conference, Sept 1997.
- [8] Basore, P.A. and Clugston, D.A., "PC1D Version 4 for Windows: From Analysis to Design," 25th IEEE Photovoltaic Specialists Conf., May 1996
- [9] Basore, Rover, and Smith, "PC-1D Version 2: Enhanced Numerical Solar Cell Modeling," 20th IEEE Photovoltaic Specialists Conf., September 1988
- [10] Basore, P.A., "PC-1D Version 3: Improved Speed and Convergence," 22nd IEEE Photovoltaic Specialists Conf., October 1991
- [11] K. Omura et al., "Recent technical advances in thin-film CdS/CdTe solar cells", WREC, pp. 405-409, 2006
- [12] S. Banerjee, "High Efficiency CdTe/CdS Thin Film Solar Cell", *International Journal of Engineering Research and Technology*, ISSN: 2278-0181, Vol. 4, Issue 09, pp. 700-703, 2015
- [13] S. M. Sze, *Physics of Semiconductor Devices*, 2nd Edition, Wiley, 1981
- [14] S. Banerjee, "Dependence of Temperature of CdTe/CdS based solar cell performance", *International Journal of Electronics Engineering*, ISSN: 0973-7383, Vol. 10, Issue 2, pp.92-96, 2018.
- [15] S. Banerjee, "Performance Analysis of Cadmium Sulfide/Cadmium Telluride (CdS/CdTe) Thin Film Solar Cell using PC1D", *IEEE conference Devices for Integrated Circuit (DevIC)*, ISBN: 978-1-5090-4724-6, pp.189-195, 2017
- [16] Md. Irfan, S. Banerjee, H. Rza, A. Maji, (2023), "Optimization of Crystalline Silicon Solar Cell Parameters Using PC1D", *Advances in Data Science and Computing Technologies, ADSC 2022 Lecture Notes in Electrical Engineering*, Vol. 1056, pp.557-565, 2023 Springer, Singapore. DOI: 10.1007/978- 981-99-3656-4\_57
- [17] Koushik Sarkar, Sudipta Banerjee, A.K. Chakraborty and K.K. Ghosh, "Optimal Designing of Higher Efficiency Chalcogenide Thin Film Solar Cell", *Springer Proceedings in Physics*, ISBN: 978-981-10- 3908-9, pp 189-195, pp. 730-733, 2017
- [18] S. Banerjee, Y. K Ojha, K. Vikas, A. Kumar, "High Efficient CIGS based Thin Film Solar Cell Performance Optimization using PC1D", *International Research Journal of Engineering and Technology*, ISSN: 2395 -0056, Vol. 3, Issue 6, pp. 385-388, 2016.
- [19] K. Sarkar et al. (2017), Optimization of the window layer in CdTe solar cell, *IEEE Conference Published in 2017 4th International Conference on Opto-Electronics and Applied Optics (Optronix)*, DOI: 10.1109/OPTRONIX.2017.8350001
- [20] K. Sarkar et al. (2019), Effects of very thin CdS window layer on CdTe solar cell, Vol.-14, No.-3, *JMCMS*, DOI: 10.26782/jmcms.2019.06.00002

- [21] K. Sarkar, K. K Ghosh (2019), Effect of pinhole and its recovery in CdS/CdTe solar cell through fabrication Simulation, Nanomaterials and Energy, DOI: 10.1680/jnaen.19.00012
- [22] K. Sarkar, K. K Ghosh, N K Mandal (2018), Effect of TCO, BSF and Back contact Barrier on CdS/CdTe solar cell: Modeling and Simulation, JMCMS, DOI: 10.26782/jmcms.2018.04.00009

