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Study of the Effect of Absorber Layer Thickness on the Efficiency of a Perovskite Solar Cell (FTO/TiO_2/$MAPbI_3$/Spiro-OMeTAD) Using the SCAPS-1D Simulation Program

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Abstract

This study investigated the effect of methylammonium lead iodide ($MAPbI_3$) perovskite absorber-layer thickness on the photovoltaic performance of a solar cell through numerical simulation using the SCAPS-1D program. The simulated device comprised a four-layer architecture consisting of fluorine-doped tin oxide (FTO) as the transparent conductive oxide, titanium dioxide (TiO_2) as the electron transport layer, $MAPbI_3$ as the absorber layer, and Spiro-OMeTAD as the hole transport layer, configured as FTO/TiO_2/$MAPbI_3$/Spiro-OMeTAD. The $MAPbI_3$ absorber thickness was systematically varied from 200 to 2000 nm at intervals of 200 nm to evaluate its influence on device performance. Simulations were conducted under AM1.5G illumination at an intensity of 1000 mW/cm^2 and a temperature of 300 K. For each absorber thickness, the key photovoltaic parameters investigated were short-circuit current density (Jsc), open-circuit voltage (Voc), fill factor (FF), and power conversion efficiency (PCE). The simulation results demonstrated a nonlinear relationship between $MAPbI_3$ absorber thickness and solar-cell power conversion efficiency. Among the investigated thicknesses, an absorber thickness of approximately 800 nm produced the optimum photovoltaic performance. At this thickness, photon absorption was maximized while recombination and charge-transport resistance were minimized, resulting in the highest simulated device performance. The optimized cell achieved a short-circuit current density of 22.173 mA/cm^2, an open-circuit voltage of 1.082 V, a fill factor of 74.989%, and a power conversion efficiency of 24.24%. These findings demonstrate that optimization of $MAPbI_3$ absorber-layer thickness is a critical parameter for achieving high-efficiency perovskite solar-cell performance.

Keywords
Perovskite,
Thickness optimization,
Absorber layer,
Solar cell,
SCAPS-1D program
Nigeria.

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INTRODUCTION

Solar cells are important as they are regarded as a clean and environmentally friendly energy source which causes almost no pollution and are regarded as a strong candidate to replace the traditional energy sources of organic nature (Green et al., 2014). Perovskite solar cells (PSCs) have seen significant advances in efficiencies over the last few years, with power conversion efficiencies rising from around (3%) in (2009) to over (26%) in (2024), close to the efficiencies of monocrystalline silicon cells which took decades to reach such efficiencies [NREL, 2024]. This fast progress is largely due to the structural and electronic properties of the hybrid perovskite family of compounds, especially methylammonium lead iodide ($MAPbI_3$).

These properties include also a bandgap (≈ 1.5–1.6 eV) appropriate for absorbing the solar spectrum, as well as a very high absorption coefficient, which enables the utilization of nanometric films with very small thickness (a few hundred nanometers) to absorb most of the solar spectrum. It also possesses excellent charge carrier mobility and flexibility in chemical composition that allows tuning of the electronic and optical properties (Jeong et al., 2023; Hossain et al., 2022). The performance of perovskite solar cells is closely related to the thickness of the absorber layer, because the absorber layer is the key part in the absorption of the light spectrum, the generation of electron-hole pairs and the short-circuit current (Jsc) of the solar cell. But the performance does not necessarily improve with high thickness; a high increase in thickness can also increase the number of defects inside the layer and recombination rates, which can decrease the open-circuit voltage (Voc) and fill factor (FF) (El-Amine et al., 2024).

Thus, it is important to find the optimal thickness by balancing the absorption of the incident light spectrum and losses due to internal resistance and defects. In this context, the computation of the numerical simulation of solar cells becomes important and essential in order to evaluate the performance of a solar cell ideally and accurately without the experimental fabrication and commercial marketing processes. In this context, the use of a specialized computational numerical simulation using a software program like SCAPS-1D becomes important and essential to evaluate the performance of a solar cell ideally and accurately before experimental fabrication and commercialization process. The SCAPS-1D program is based on the numerical solution of Poisson's equation, the continuity equations for the electron and hole, and the transport of current due to drift and diffusion, enabling one to investigate the impact of the layer thickness, defects, charge transport, energy levels and interfaces on the performance of a cell with high accuracy (Ghaithan et al., 2025).

The simulation program SCAPS-1D can be used for testing the solar cell under various conditions and the optimum parameters of the layers can be obtained without any expensive fabrication steps. Moreover, it would save researcher's time and effort to get the optimized performance of the solar cell. With this, our aim in this research was to investigate how much the performance of

the solar cell with the layer structure (FTO/TiO2/MAPbI3/Spiro-OMeTAD) is affected by the thickness of the MAPbI3 absorber layer in the range (200–2000 nm) and finding the optimum thickness corresponding to the highest power conversion efficiency of the solar cell by using simulation program SCAPS-1D.

The solar cell variation of short circuit current, open circuit voltage and variation in fill factor and power conversion efficiency of the solar cell over a wide range of absorber layer thickness has been analysed by the research.

Also, we compared the results with the latest published scientific journal articles to make the results more reliable and to be able to interpret the physical behavior of the solar cell outputs in relation to the change in the thickness of the absorber layer.

PREVIOUS STUDIES

In the last twenty years, there has been a significant rise in research investigating the effect of absorber layer thickness in perovskite solar cells with the help of various computer numerical simulation software programs, rather than experiment, to reduce the time and effort spent on experiments, and to achieve the maximum efficiency of the solar cells. One of the most advanced research methods that can be used for cell modeling is the calculation of the effects of the external parameters (like light spectrum and temperature) and internal parameters (like cell layer thickness, defects, and resistances) on the outputs of the solar cell, with high accuracy, using SCAPS-1D program. This section highlights some of the key studies in the recent past that relate to the subject of the current research, and emphasizes the methodology employed, the most significant findings of those studies, and the significance of the findings for the current research topic.

First Study

Although this study is not very recent, it is considered a fundamental and important reference in the simulation of the $MAPbI_3$ absorber layer. The results show that both low and high value of thickness results in a significant reduction of light absorbed falling on the solar cell and high value of the thickness results in high resistance within the layer. These findings are consistent with most of the later studies that supported the idea of the optimum thickness (Mandadapu et al., 2017).

Second Study

This group has performed numerical simulation to compare the performances of both FA and MA perovskite cells and found the thickness of the absorber layer to be in the range of (500 - 800 nm) to be the optimum range for the cells. To evaluate the influence of defects in the absorber layer and the interface defects the study employed the SCAPS program and it was found that the leakage current across the interface between electron transport layer (ETL) and perovskite increased with increasing thickness of the absorber layer, due to increase in depletion region of the absorber layer (Karthick et al., 2020).

Third Study

The optical properties and structural stability of $MAPbI_3$ perovskite films were investigated in this work, but the results demonstrated that as the thickness of the films increases, the grain structure and size changes, affecting the charge transport properties, and also increasing the chances of bulk defects. This is the reason for the reduction of the fill factor (FF) and the open circuit voltage (Voc) with increasing thickness at large thickness, and is consistent with the numerical models demonstrating the best performance at a moderate thickness (Jeong et al., 2023).

Fourth Study

The researchers have used a hybrid experimental and computer simulation approach to study the effect of the thickness of the $CH_3NH_3PbI_3$ absorber layer on the photovoltaic performance of the solar cell. It was found that the short-circuit current undergoes significant enhancement as the thickness of the absorber layer increases up to around (800 nm), but after that thickness, short-circuit current increases due to an increase in Shockley-Read-Hall (SRH) recombination within the absorber layer and a decrease in the open-circuit voltage.

The study showed that the best thickness range is between (700-900 nm) which was recommended by many theoretical models over the last few years and reinforced the need to control the thickness during fabrication, as this is necessary to achieve the best results when using the thin film (El-Amine et al., 2024).

Fifth Study

The objective of this study is to analyse the performance of a $CH_3NH_3PbI_3$ perovskite solar cell with the help of simulation software SCAPS-1D. The study also involved changing the thickness of the absorber layer (200–1200 nm), and a gradual relationship between the thickness change of the absorber layer and the improvement of the absorption was confirmed up to a certain thickness, after which it was demonstrated that the performance was in a state of optical saturation that prevents further increase in short-circuit current. A decreasing trend in the open-circuit voltage (Voc) was also found with thickness increment which could be attributed to the higher probability of recombination (Ghaithan et al., 2025).

SCAPS-1D SIMULATION PROGRAM

One of the most popular numerical simulation programs used to study layered-structure solar cells like PV thin films, thin silicon, and perovskite solar cells is the SCAPS-1D (Solar Cell Capacitance Simulator) program. The program is unique because it is able to accurately numerically represent, in terms of physical phenomena, charge transport, charge recombination, defect properties and the influence of temperature. SCAPS-1D is a simulation tool developed at the Ghent University in Belgium, and is one of the leading software packages for comprehensive solar cell simulation (Burgelman et al., 2000).

Basic Working Mechanism of the SCAPS-1D Program:

The SCAPS-1D program relies on solving three primary equations solved simultaneously in one dimension, namely:

Poisson's equation

The distribution of electric potential within the layers, depending on the distribution of free charges and the permittivity of each layer of the solar cell [Niemegeers et al., 2013]:

$\nabla\cdot(\varepsilon\nabla\psi) = -q(p - n + N_D^+ - N_A^-) \pm q N_t$ …… (1)

Where:

The symbol ψ stands for potential, ε for permittivity, n for electron concentration, p for hole concentration, ND for doping concentration, NA for doping concentration and Nt for defect concentration.

This is the basic relationship between the electric charges and the resulting electric field and is crucial to determine the band structure and the electric field distribution inside the solar cell (Karthick et al., 2020).

Continuity equations for electrons and holes:

The equations for the generation, recombination and transport of electrons and holes in the solar cell are:

For electrons:

$\partial n/\partial t = (1/q)\nabla\cdot Jn + Gn - Rn$…… (2)

For holes:

$\partial p/\partial t = -(1/q)\nabla\cdot Jp + Gp - Rp$…… (3)

Where:

- Jn, Jp: electron and hole current densities

- Rn: recombination rate of the electrons and holes

- Rn, Rp: electron and hole recombination rates [Hossain et al., 2024]

Drift-diffusion equation:

The program is based on a drift diffusion model of the movement of charge carriers due to the electric field (drift) and the concentration gradient (diffusion): [Chen et al., 2024]

$Jn = qn\mu nE + qDn\nabla n$…… (4)

$Jp = qp\mu pE - qDp\nabla p$…… (5)

Where:

The mobility of the electron and hole are denoted by μn and μp respectively.

- Dn, DP: electron and hole diffusion rates

This model is particularly appropriate for hybrid materials like ($MAPbI_3$), a material with a balance of balanced charge transport between electrons and holes, and mixed conductivity (Chen et al., 2025).

Physical Models Used in the SCAPS Program:

Recombination models

The SCAPS program supports three main mechanisms:

First - Radiative recombination:

This is called direct electron-hole recombination where an electron and a hole combine to release a photon with energy hv = Eg. This type is especially significant

under high absorption coefficient and relatively fast radiative lifetime in materials with direct bandgap like $MAPbI_3$ (Jeong et al., 2023). It is represented by the mathematical relation:

$R_{rad} = B (n p - ni^2)$ ..... (6)

Where:

- B: radiative recombination coefficient. The concentration of intrinsic carriers is ni.

Second - Shockley–Read–Hall (SRH) recombination:

This is the most important mechanism in perovskite materials and is dependent upon the presence of intermediate energy levels (trap states) within the bandgap due to crystal lattice defects (vacancies, impurities, dislocations). It is provided by the following relationship:

$RSRH = (np - ni^2) / [\tau p (n + n_1) + \tau n (p + p_1)]$ ..... (7)

Where:

- τn, τp: carrier lifetimes (inverse of defect density Nt)

- n_1, p_1: Parameters that are dependent of the position of the defects in the bandgap.

The importance of this mechanism is further enhanced in the thick, low quality films in which the bulk defect density increases. As the number of defects increases in the crystal lattice which can capture carriers, the more the recombination process will increase (Chen et al., 2025).

Third - Auger recombination:

Its presence is seen at high carrier concentrations, and these mechanisms all contribute to the values of Voc, Jsc and FF. This process takes place when the concentration of carriers is very high, like when cells are subjected to strong illumination, and an electron and a hole recombine, thereby transferring its energy to a third carrier (electron or hole) that is pushed to a higher energy level, and later releases its energy by thermal diffusion. It is determined by the formula:

$RAuger = (Cn n + Cp p) (np - ni^2)$ ..... (8)

The Auger coefficients are Cn and Cp for the electrons and holes respectively. This type is not significant in normal illumination conditions, but is significant at high thickness where the carrier concentration becomes high in some places (Ghaithan et al., 2025).

Optical absorption model:

It is possible to put in and use a default model supplied by SCAPS or an absorption coefficient file. This feature becomes important when it comes to studying the role of the absorber layer thickness on the generation of charges.

Defects:

The SCAPS program can accept input on:

- Defects within the bulk of the layers (bulk traps)

- Defects at the interfaces: absorber layer/electron transport layer (ETL/absorber) and absorber layer/hole transport layer (absorber/HTL)

- Surface defects of the transparent conductive oxide layers

Band alignment:

The program can be used to calculate:
The distribution of the valence band maximum (VBM)

The distribution of the conduction band minimum (CBM) is shown here.

This affects the transport of electrons and holes across the electron and hole transport layers ETL and HTL.

Advantages of the SCAPS simulation program:

- Easy-to-use interface for researchers in the field of solar cells.
- Applicable to hybrid materials and multiple layers (up to seven layers possible).

Accurately enters spectral data and defects.

- High accuracy in results and stable in numerical solutions.

- Applied throughout the world in the study of perovskite solar cells.

Although the program is beneficial, there are some limitations in its operation; Chemical reaction processes and degradation over time under natural environmental conditions like humidity and temperature are not simulated (Rafieipour & Abdi, 2023). Furthermore, the program is dependent on the accuracy of the inputs for each layer of the solar cell and this is the most important factor in the accuracy of the results (Yousfi, A., 2025).

Application of the SCAPS Program in Solar Cell Simulation:

The following structure was designed for a standard n-i-p perovskite solar cell:
Anode: Fluorine doped transparent conductive oxide layer (TCO).

Electron transport (ET): Titanium dioxide (TiO_2).

Absorber layer (Perovskite): e.g. Methylammonium lead iodide ($MAPbI_3$)

Hole transport layer (HTL): Spiro-OMeTAD

Anode: metal (silver).

The materials were chosen for the following reasons:

- Transparent in visible and ultra-violet spectrum, has high conductivity, widely used in industry, FTO.

- $MAPbI_3$: low cost, good chemical stability with respect to TiO_2.

- $MAPbI_3$: great absorption properties, a bandgap of ~1.55 eV, ease of preparation.

- Spiro-OMeTAD: one of the most common hole transport materials in high-efficiency perovskite cells.

Simulation Parameters in SCAPS:

The electrical and optical properties of the materials for the layers in the solar cell were inputted manually into the SCAPS-1D program. These parameters were the bandgap, carrier mobility, absorption coefficient, doping concentration (ND, NA), defect parameters (Nt, Et, σn, σp), relative permittivity and other parameters as shown in Table (1)

Table (1) Parameters of the solar cell layers

Parameters	Spiro-OMeTAD	$MAPbI_3$	TiO_2	FTO
Thickness (nm)	50	200-2000	50	100
Band gap (eV)	2.25	1.55	3.2	4.0
Electron affinity (eV)	3.65	3.9	4.9	4.5
Dielectric permittivity (relative)	14	6.5	9	10
CB. effective density of states ($1/cm^3$)	7.50E+17	2.2E+18	1.00E+21	1.20E+20
V.B. effective density of states ($1/cm^3$)	1.5E+19	1.8E+19	2.00E+20	7.80E+20
Electron thermal velocity (cm/s)	1.000E+7	1.00E+7	1.000E+7	1.00E+7
Hole thermal velocity (cm/s)	1.000E+7	1.00E+7	1.000E+7	1.00E+7
Electron Mobility (cm^2/Vs)	1.0E-4	20	10	20
Hole Mobility (cm^2/Vs)	2.0E-3	20	1.0E-4	10
Shallow uniform donor density, N_D ($1/cm^3$)	0	0	1.00E+19	1.00E+19
Shallow uniform acceptor density N_A ($1/cm^3$)	1.00E+19	1.00E+15	0	0
Defect type	Single Acceptor	Single Acceptor	Single Donor	Single Donor
Capture Cross Section Electrons (cm^2)	1.00E-12	1.00E-17	1.00E-15	1.00E-15
Capture Cross Section Hole (cm^2)	1.00E-15	1.00E-12	1.00E-15	1.00E-12
Nt ($1/cm^3$)	2.00E+14	1.00E+15	1.00E+14	1.00E+15

The values of these parameters that were manually entered into the simulation program were based on data published in scientific research (Mandadapu et al., 2017; Chouhan, et al., 2018; Karthick et al., 2020).

SIMULATION PLAN

The thickness of the perovskite absorber layer ($MAPbI_3$) was changed systematically from (200–2000 nm) and (200 nm) intervals, and all the other parameters of the other layers were kept fixed for every thickness value.

The thickness range was chosen to include the common experimental and theoretical range for $MAPbI_3$ material in the published literature and research, where the optimal thickness ranges between (200–2000 nm) according to previous studies (Karthick et al., 2020; Singh & Ravindra, 2024).

The other parameters of all the layers were maintained constant to assess the effect of

thickness variation, only keeping the studied parameter to find its direct effect on the output. Later studies are possible for combined effects with defect density, temperature and mobility. Thicknesses are also high in this range to examine saturation effects and bulk losses.

The current-voltage (J-V) curves and the solar cell outputs of this structure, such as the short circuit current (Jsc), the open circuit voltage (Voc), the fill factor (FF) and the power conversion efficiency (PCE) were recorded under the SCAPS program.

All calculations were performed under standard test conditions of (300K), (1000W/m^2) and (AM1.5G) for the irradiation spectrum which are the standard conditions used to evaluate the performance of solar cells, so as to be compared with the results of published works.

RESULTES AND DISCUSSION

The values obtained from the numerical simulation are valid only if the assumptions made and the simulation parameters used in the computer program are valid, so that in some cases it is possible that the values of the efficiencies may differ slightly from those published experimentally. The overall effect of the thickness of the absorber layer, however, is reliable and corresponds to the physical behavior of perovskite solar cells.

Analysis of the Effect of Varying the Absorber Layer Thickness on the Short-Circuit Current (Jsc)

It is observed from the figure (1) that, as the thickness of the absorber layer increases the short circuit current (Jsc) increases up to (800 nm) because, the increased thickness of the absorber layer results in the increased number of photons absorbed and electron-hole pairs generated in a larger volume of the absorber material. At this thickness, the increase rate starts to decrease because the absorption approaches saturation because most of the absorbable photons are absorbed in the front part of the absorbable layer. The reason for the increase is attributed to the improvement of optical absorption of photons with this amount of thickness (El-Amine et al., 2024).

This change can be understood with the help of three related physical mechanisms:

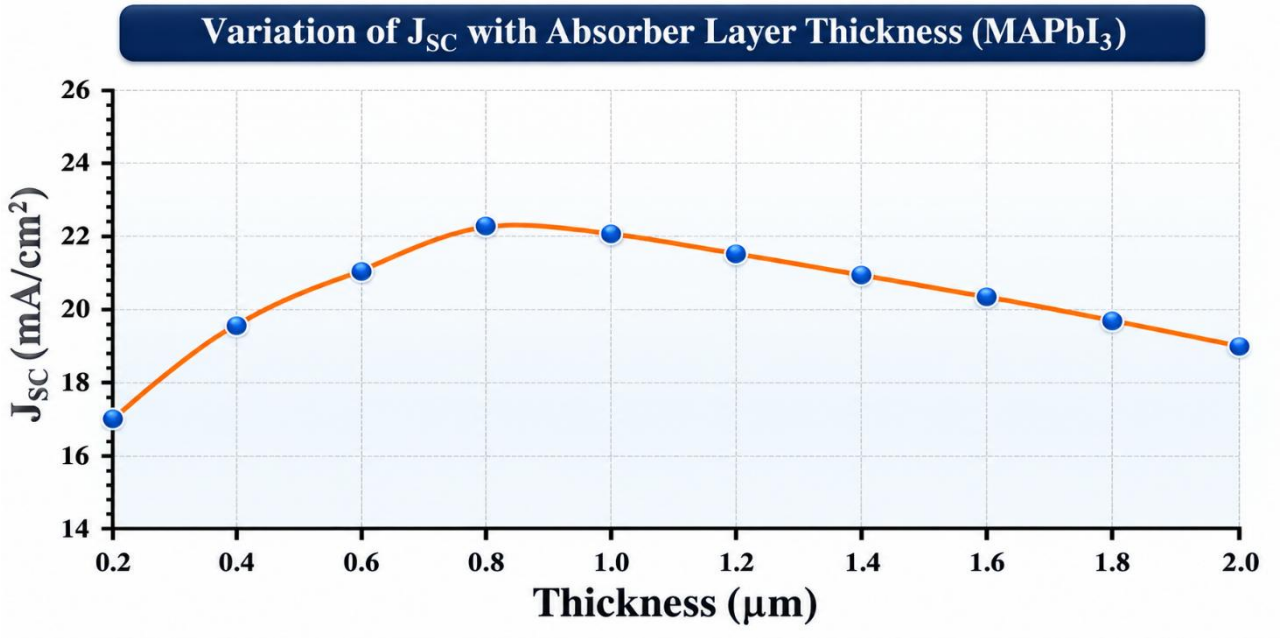

Figure (1): Effect of thickness on short-circuit current

First: Optical Absorption Mechanism

For small thickness (less than 300 nm), the light path traveled by photons inside the absorber layer is short, and the incident photons are not completely absorbed, particularly in the red part of the solar spectrum that falls on the solar cell. The Beer-Lambert Law states that the intensity of the light reaching the end of the absorber layer thickness d is related to the following equation:

I = I₀ e^{-ad} ..... (9)

Thus, as the thickness increases the total number of photons absorbed approaches the saturation level (Olyaeefar et al., 2020).

If the thickness of absorber layer is raised to (800 nm), the absorption is more than (95%) for most of the solar spectrum (excluding infrared radiation) as the energy of the absorbed radiation is greater than the band gap of the absorber material (1.55 eV).

Second: Generation and Collection Mechanism:

As the thickness of the absorber layer increases, the volume of the absorber layer increases, which means that the number of absorbed photons becomes greater, and the number of electron-hole pairs generated becomes greater. But the increased thickness also means an increased mean distance between the transport interfaces (ETL/Perovskite interface for electrons and Perovskite/HTL interface for holes). If this distance is larger than the carrier diffusion length (LD), a significant number of these carriers will recombine before they are collected, thereby decreasing the current (Ghaithan et al., 2025).

The range of carrier diffusion lengths varies depending on the crystal quality and defect density for $MAPbI_3$ material (Jeong et al., 2023).

Third: Thickness-Dependent Recombination:

At very large thicknesses, the bulk defect density increases due to the increase in the total number of defect sites in the larger volume of the absorber layer. The probability of Shockley-Read-Hall (SRH) recombination also increases in proportion to the thickness. This leads to a reduction in the number of carriers capable of reaching the electrodes, and thus a decrease in the short- The thickness dependence of the bulk defect density at very high thicknesses is a result of the higher total number of defect sites in the absorber layer. In addition, the Shockley-Read-Hall (SRH) recombination process also increases with thickness. Also, Shockley-Read-Hall (SRH) recombination increases with thickness. The carriers that can reach the electrodes are reduced, which results in the short-circuit current decreasing (Son et al., 2024; Chen et al., 2025).

This result is in good agreement with the previous studies. El-Amine (2024) reported the saturation of the short circuit current is about (800 nm) and absorption efficiency is more than (90%). Ghaithan et al., (2025) demonstrated similar trend of a rise, reaching a saturation level and then decreasing gradually with time. In comparison, the maximum value of short-circuit current (22.17 mA/cm^2) obtained is in the range of published experimental and theoretical reported range for $MAPbI_3$ perovskite cells.

Analysis of the Effect of Thickness on the Open-Circuit Voltage (Voc):

With increase in thickness up to (800 nm), an increase in open circuit voltage (Voc) was observed. After that, it starts to go down. This is believed to be due to the defects which increases the likelihood of the recombination of charge carriers before they arrive at the charge conducting electrodes thus reducing the open circuit voltage (Ghaithan et al., 2025).

The open-circuit voltage is approximately given by the relationship:

$$V_{oc} = (n k_B T / q) \ln (J_{sc} / J_0 + 1) \quad \text{(10)}$$

In the above, J_0 represents the reverse saturation current, which is directly proportional to the recombination rates. Hence, Voc is observed as a function of the balance between the photocurrent (Jsc) and reverse saturation current [Ouslimane, 2021].

It can be seen from figure (2):

The first increase in the open-circuit voltage is found in the thickness range (200–800 nm).

For small and medium thicknesses, the value of Jsc also shows a significant increase, but the value of the saturation current J_0 is relatively low because of the quality of the absorber layer and its low defect content. This results in net increase in Voc as per above equation (Datta et al., 2024).

Furthermore, the uniform electric field throughout the depletion region due to increasing thickness to a certain level, enhances charge separation and reduce

charge recombination (El-Amine et al., 2024).

Second: The decrease in Voc at large thicknesses (> 800 nm):

There are two primary reasons that the reverse saturation current J_0 rises significantly at large thicknesses: increase in bulk recombination. The larger volume has an effective defect density that leads to a higher SRH recombination rate (Ghaithan et al., 2025).

Besides, the electric field, away from the interfaces (in the middle of the thick layer) will be reduced, causing a reduction in the carrier drift speed, thereby enhancing the chance of carrier recombination before they arrive at the interface [Karthick et al., 2020].

The highest Voc obtained thus far in the research is relatively high (1.082 V) at the thickness (800 nm) which is realistic for high-quality $MAPbI_3$ perovskite cells.

Research has shown that the Voc of $MAPbI_3$ perovskite cells usually fall within (0.9–1.15 V), which is influenced by the fabrication quality and the density of defect [NREL, 2024].

In other similar studies, the voltage of the open circuit reached (1.05–1.12 V) at the optimum thickness [El-Amine et al., 2024; Ghaithan et al., 2025]. The decrease after the thickness (800 nm) is consistent with what was documented by Mandadapu et al. (2017) and Chen et al. (2025).

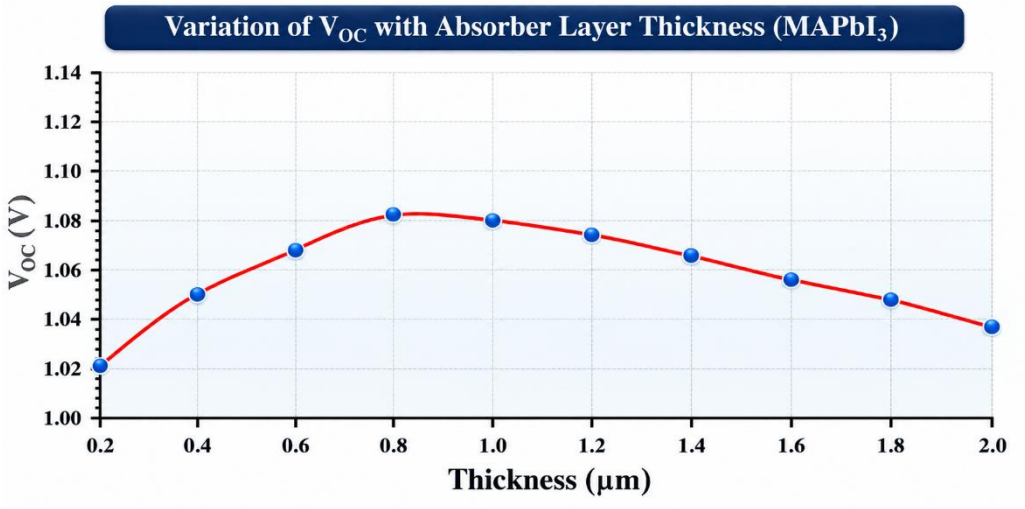

Figure (2): Effect of thickness on open-circuit voltag

Analysis of the Effect of Varying Thickness on the Fill Factor (FF)

The fill factor (FF) increased with thickness from (72.13%) at (200 nm) to a maximum value of (74.99%) at (800 nm) before it started decreasing with increasing thickness in a near linear fashion reaching a value of (67.81%) at (2000 nm). In very thick cells (>1500 nm), the series resistance is large enough to impact the fill factor even though the open-circuit voltage (Voc) and short-circuit current (Jsc) are relatively high [Ouslimane et al., 2021]. The recombination mechanisms are more significant under high voltage (close to Voc). The fill factor Son et al., (2024) is reduced further due to the accumulation of carriers in some areas of the layer, particularly in the electrically neutral areas, resulting in increased radiative and Auger recombination at large thicknesses. Figure (3) shows the effect of thickness on the fill factor (FF).

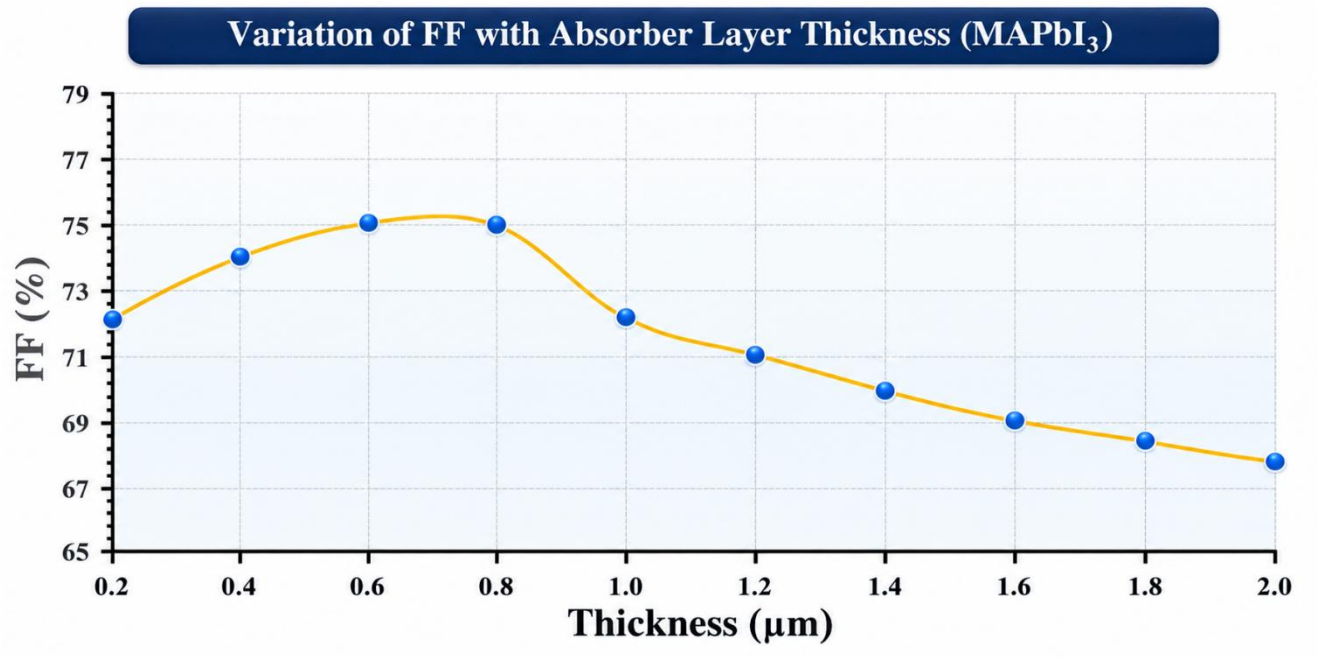

Figure (3): Effect of thickness on fill factor

The fill factor FF of the simulated and experimental PBCs achieved in this research (67–75%) is within the usual range of reported fill factors of simulated and experimental $MAPbI_3$ perovskite cells (Mandadapu et al., 2017; Karthick et al., 2020). As seen in the decreasing thickness (800 nm), the result is consistent with the study conducted by Sławek et al. (2021) which reported that FF decreases by (1–2%) per (200 nm) change in thickness.

Analysis of the Effect of Thickness on the Power Conversion Efficiency (PCE):

The cell efficiency is in the shape of a curve and is known as the power conversion efficiency (PCE) and is based on the collective behavior of the cell outputs, which are the short circuit current Jsc, the open circuit voltage Voc and the fill factor FF. With thickness the efficiency rises quickly until it peaks at this thickness in this simulation, and then decreases from this thickness. If the thickness exceeds the optimum, recombination problems and high resistance occur, but if it is below the optimum, it is not possible to utilize the entire spectrum falling on the solar cell.

It's easy to see that a simple equation can describe the relationship between PCE and the other outputs:

PCE = (Jsc × Voc × FF) / Pin……. (11)

At the point of pin (Ouslimane, 2021; Son et al., 2024) is the intensity of the illumination of the incident beam.

When the product of the three is maximized, it is at (800 nm) (where Voc and FF are at their maximum) while Jsc is at its optimum, thus the optimum product is at the optimum thickness of the absorber layer thickness.

The optimum absorber layer thickness can be explained as a compromise between three competing processes:

Optical absorption:

It is lacking at low thickness but almost complete at high thickness.

Bulk recombination:

It is low for thin thicknesses, and very high for thick thicknesses.

Series resistance:

It is low when the thickness is small, and high when the thickness is large.

From observing the results of the solar cell simulation in Figure (4), it is evident that the solar cell efficiency was at its maximum value (PCE = 24.24%) at the absorber layer thickness of (800 nm). As the thickness of the absorber layer increases, the amount of light absorbed by the absorber layer also increases. Therefore, as the thickness of the absorber layer increases, so does the short-circuit current density (Jsc), which is the number of electron-hole pairs absorbed and generated by the absorber layer per unit area (Peijie Lin, 2014).

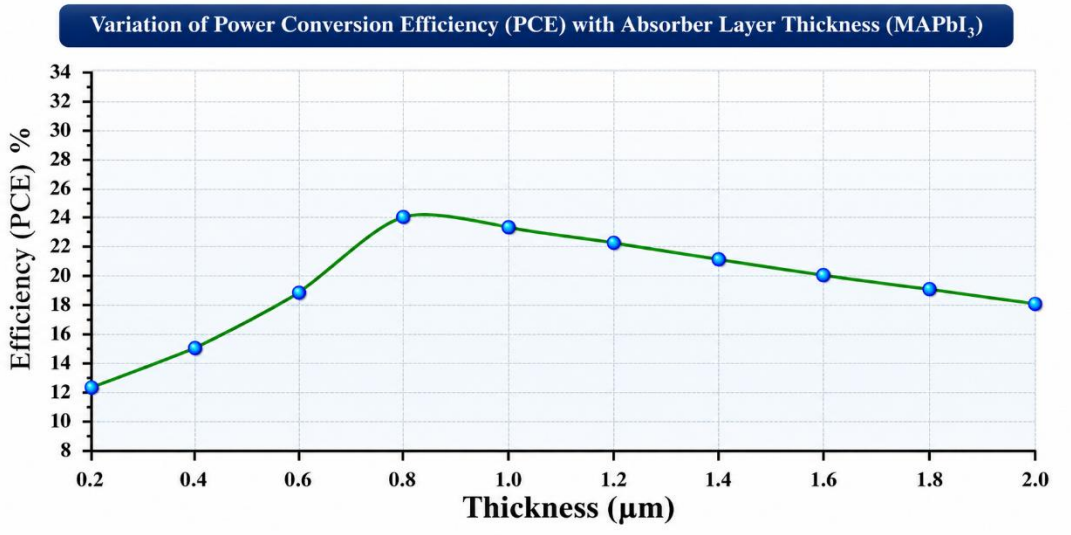

Figure (4): Effect of thickness on solar cell efficiency

It is important to note that charge recombination starts to cause losses in cell efficiencies beyond this thickness. The defect density and recombination rate increases with the thickness increase (Mahjabin S., et al., 2020). The efficiency of the cells starts to decrease because of the internal losses, which is already evident with some studies (Ouslimane, 2021; Sławek et al., 2021) and will continue to decrease if the thickness increases more. Other works have also indicated that for $MAPbI_3$ cells, absorber layer thicknesses in the range of (700–1000 nm) yield the optimal performance in terms of efficiency, since they allow for the optimal combination of effective absorption for the generation of electron-hole pairs with minimisation of the charge loss from recombination (Ouslimane, 2021).

The absorption of the incident light was low and efficiency was low when thickness was less than (800 nm). Similarly, the bigger thickness than (800 nm) result into increase of the recombination process, increase in internal resistance, and decrease in solar cell efficiency (Ouslimane et al., 2021; Singh and Ravindra, 2024).

Comparison of the Results Obtained in This Simulation with Previous Simulation Studies

The findings of this study are mostly congruent with previous studies. One of such previous simulation study using SCAPS was conducted by Karthick et al., 2020 which they found the best thickness of the absorber layer $CH_3NH_3PbI_3$ is 800 nm for the best efficiency up to 20%. Thicknesses ranging (600–800 nm) were also found to be optimum in another study that used the GPVDM program, where thicknesses were found to be optimal for balancing the light absorption and charge transport (Mandadapu et al., 2017). As indicate in Table (2), this agreement between the findings of our study and the published studies brings the credibility of the SCAPS

program model used and the strength of the findings and conclusions. The experimental efficiencies of $MAPbI_3$ cells with a similar structure range between (13–23%), while the theoretical efficiency in this research (24.24%) is slightly higher than what is usual experimentally. This is typical since it is usually assumed in the numerical simulation that there will be no degradation, ideal interfaces, and less defects than can be practically created in an experiment.

Table (2) Comparison with previous studies

Study Optimal	Thickness (nm)	Efficiency %	Difference from this study
Mandadapu et al. (2017)	700	19.5	Lower by 4.74%
Karthick et al. (2020)	600–800	20.0	Lower by 4.14%
Ghaithan et al. (2025)	700	22.8	Lower by 1.44%

We assumed that all material parameters (carrier mobility, permittivity, defect density) are constant and do not change with changing thickness. However, in practice, such parameters may vary as a function of thickness for different layers because of changes in grain structure and crystallization quality in the layers (Jeong et al., 2023).

The simulation was carried out at a constant temperature (300 K). The spectrum selected for this study is AM1.5G which is a measure of the intensity of solar radiation incident on the solar cell per unit area with a value of (1000 W/m^2). In real applications, however, the solar cells get hot while operating under the sun (Teimouri and Kolahdouz, 2022), which impacts the performance. However, it has to be considered that SCAPS-1D is not a program that accounts for degradation, caused by heat, humidity or ultraviolet radiation, over time for materials.

There are also other reasons that led to achieving higher efficiency in this current study compared to the previous studies shown in Table (2), including:

1. Using a larger thickness range for the absorber layer (200-2000 nm) to accurately determine the optimum thickness.
2. The use of updated simulation parameters that take into account the latest developments in the quality of perovskite materials.
3. Optimization of defect and interface parameters using the latest experimental measurements.

CONCLUSION

After studying the effect of the absorber layer thickness on the outputs of the solar cell ($MAPbI_3$) while keeping the thickness of the other layers of the solar cell

constant, the following conclusions were reached:

The short-circuit current changes nonlinearly with the thickness of the $MAPbI_3$ absorber layer, with the short-circuit current increasing significantly between the thickness (800 nm) from (16.78–22.17 mA/cm^2), followed by a saturation stage after which it decreases slightly on increasing thickness.

The effect of thickness on the open-circuit voltage was noted: Voc has a maximum value (1.082V) at (800nm) and thereafter, the voltage decreases at higher thicknesses which results from the increase in recombination.

After increasing thickness (800 nm), it was found that the fill factor (FF) is decreased from (74.99%) at the optimum thickness to (67.81%) at the thickness (2000 nm).

As the thickness increased (from >800 nm), the efficiency of the solar cell started to decrease because the effective defect density increased, with an increasing number of defect sites with an increasing volume, bulk resistance increased and the diffusion distance increased. These all created degradation in the performance of the solar cell.

It was proven that the SCAPS-1D program has high accuracy in simulating the behavior of perovskite solar cells, as the research results showed great agreement with previous studies (experimental and theoretical) in terms of the optimal thickness range and the qualitative behavior of the solar cell layer parameters, which makes it a reliable tool for optimizing the design of solar cells before experimental fabrication.

It was clearly proven through this study that the thickness of the absorber layer ($MAPbI_3$) is important in improving the performance of perovskite solar cells. But the thickest is not the best – there is an optimum thickness range that maximises the power conversion efficiency of the solar cell. That's because it is important to balance the amount of light absorbed and current produced, with the amount that is lost from recombination of charge carriers and internal resistance. The findings could serve as valuable insights for engineers and researchers working on high-efficiency perovskite cells during the development and manufacturing process.

To achieve the following values, the optimum thickness of the absorber layer in the $MAPbI_3$ solar cell was calculated to be (800 nm):

- Short-circuit current (Jsc) = 22.173 mA/cm^2

- Open-circuit voltage (Voc) = 1.082 V

- Fill factor (FF) = 74.989%

Conversion efficiency of power (PCE) = 24.24 %

RECOMMENDATIONS

This study suggests that the thickness (800 nm) should be taken as an initial reference value in the fabrication process of PSCs, and the crystal quality and defect density should be improved during the deposition stage to ensure the achievement of this efficiency practically. The scope of the simulation is recommended to be expanded

in the future to study the effect of the interaction of thicknesses with other parameters such as: bulk defect density, operating temperature, the properties of the interfacial layers (ETL/HTL), in order to arrive at a more complete design that correlates thickness optimization with actual operating conditions.

LIMITATIONS OF THE STUDY

These results are obtained from a numerical simulation under ideal conditions (constant defect density and no consideration of the effect of the interface defects and dynamic thermal effects). In practice, this optimal value may vary slightly due to the assumptions made; in practice, other factors such as interface defects would also have an effect.

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