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A simulation study on the performance characteristics of 3D crystalline silicon (c-Si) solar cells.

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A Simulation Study on the Performance Characteristics of 3D Crystalline Silicon (c-Si) Solar Cells

Sani Mohammed Lawal[1] , Shima Valizadeh[2] , Nazila Fough[1]

[1]School of Engineering, Robert Gordon University, United Kingdom.
[2]Department of Theoretical Physics and Nano Physics, Faculty of Physics, Alzahra University, Iran.

***Abstract*— One of the most popular materials used is the wafer-based crystalline silicon (c-Si) solar cells that are dominant in the technology of the global PV market. In this paper, a 3D finite element method in COMSOL Multiphysics was used to simulate a crystalline silicon solar cell to investigate the impact absorber layer while keeping the electron and hole transport layer constant. The Variation of the c-Si_absorber layer thickness has influenced variation of output results based on the changed in the absorber layer. An efficiency of 25% at a temperature of 300K with a minimum short circuit current density of 18mA/cm^2 and a maximum short circuit current of 36.2mA/cm^2, where a power output of 9.5mW/cm^2 and 19.4mW/cm^2 respectively**

Keywords—Finite Element Method, Crystalline Silicon Solar Cells, Electron, Absorber, Hole Transport Layer.

I. INTRODUCTION

Photovoltaic (PV) solar cell technology represents a promising option for harnessing renewable energy by utilizing semiconductor materials. The performance of solar cells is highly dependent on their characteristics and the materials used. Solar cells are integral to photovoltaic systems; however, their effectiveness varies based on the quantity and nature of their application [1]. The power conversion efficiency (PCE) of solar cells is a key factor that determines the effectiveness of PV technology and its competitiveness in the market. Among the various materials available, wafer-based crystalline silicon (c-Si) solar cells are among the most popular and dominant in the global PV market [1]. Despite their widespread use, the high production costs of c-Si wafers remain a significant barrier to further development. Recent research has explored combining c-Si with thin-film technologies to reduce these costs, showing promising results [2]. In addition to c-Si, researchers are investigating various alternative solar cell materials and combinations. For example, studies have explored different materials and configurations to enhance performance and reduce costs [3][4]. Another critical area of research focuses on optimizing the efficiency of solar cells using diverse materials, as highlighted in recent studies [1-5]. The aim of this study is to investigate the impact of absorber layer in c-Si while keeping the electron and hole transport layer constant. In a recent study the performance of a basic silicon solar cell was tested based on layer thickness variation to determine the optimal values. It has been determined that as the base layer thickness increases, short circuit current increases whereas open circuit voltage and maximum power reduces [4]

II. PROPOSED METHOD

In the study, simulations were conducted using COMSOL Multiphysics. The model wizard was selected, and a 3D space dimension was employed for the simulation. The Semiconductor Module, a key component of the physics interfaces in COMSOL, was utilized. This module encompasses three dependent variables: electric potentials, electron solutions, and hole solutions [6]. To ensure the most accurate results, a stationary study type was chosen as the most appropriate for this work. Input parameters were carefully set, as detailed in Table 1, and the geometry of the model was defined and assigned within the COMSOL Multiphysics environment [6].

Table 1: Selected Parameters of the Solar Cell

Parameter	Value/Size
Front Metal Contact width	1E-6 m
Back Metal Contact width	2E-5 m
Acceptor Doping	1E17[1/cm^3]
Donor Doping	1e19[1/cm^3]
Intrinsic Layer	1E16[1/cm^3]
Model in Temperature	293.15[K]
Bang Gap	1.12[V]
Electron mobility	1450[cm^2/(V*s)]
Hole mobility	500[cm^2/(V*s)]
Electron affinity	4.05[V]

The COMSOL Multiphysics software uses the Finite Element Method to solve continuity equations as shown in Eq. (1) while simulating solar cells to find the current density distribution[6]

$$-\nabla.(\sigma\nabla V - J) = Q \qquad (1)$$

Where:
V– The electric potential,
J – The current density,
Q – The generated current, and
σ – The conductivity of the material
The semiconductor module contains all the necessary partial differential equations (PDE) which govern the electronic transportation mechanism in the semiconductor material.
The generation rate contributes in terms of reflecting the absorption behaviors, which added to the built-in of the current densities output in form user-defined generation while the recombination techniques are being considered within the Shockley-Read-Hall (SRH) under the trap assisted recombination.
The photo-generation rate can be expressed as.

$$G(x) = \int_0^{\alpha} \alpha(\lambda)\, \phi(\lambda) \exp(-\alpha(\lambda)\, x)\, d\lambda \qquad (2)$$

Where:
x – The depth into the solar cell from the surface
λ– The wavelength
$\alpha(\lambda)$ – The Absorption coefficient

$$\alpha(\lambda) = \frac{4\pi}{\lambda} K(\lambda) \qquad (3)$$

Where:
$K(\lambda)$ – The extinction coefficient
$\phi(\lambda)$ – The incident photons flux, as in:

$$\phi(\lambda) = \frac{\lambda}{hc} F(\lambda) \qquad (4)$$

$F(\lambda)$ – The spectral irradiance, at approximated value of AM 1.5 Spectrum[7]. One-diode model system is used to represent the solar cell as in Fig. 1.

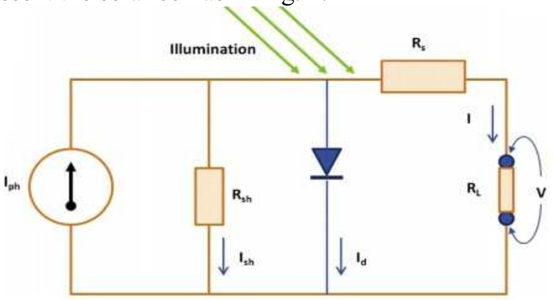

Fig 1. PV Cell Equivalent Circuit[8]

The overall current passing through the load resistance RL, can be describe in equations (5) & (6)[8] where I_{ph} represent the photo-generated current and I_d represent the diode current respectively.

$$= I_{ph} - I_d \qquad (5)$$

$$= I_{Ph-} \ I_O \left[\exp\left[\frac{V}{nVT}\right] - 1\right] - \frac{V_j}{R_{sh}} \qquad (6)$$

The solar cell's physical domain is modelled based on three-dimensional (3D) form and divided geometry into five different domains: front contact, c-Si_n_layer, absorber layer, c-Si_p_layer, and back contact respectively as shown in figure 2. The domains were meshed at different predefined element sizes ranging from normal to extra fine finite elements for optimal output with input power of 100 mW/cm^2

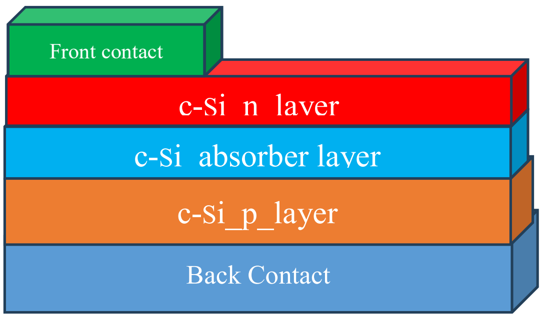

Fig 2. Schematic view of the Simulated c-Si Solar Cell

III. RESULTS AND DISCUSSION

In this work, we have demonstrated a 3-D optoelectronic model that can be used to show the impact behaviours of absorber layer in a 3-D solar cell. The simulation was carried out under AM1.5G illumination spectrum.

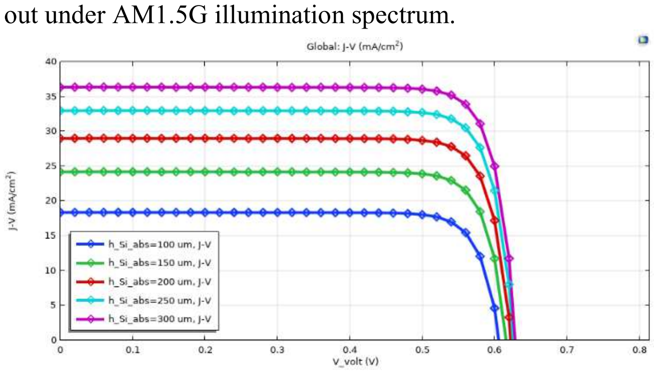

Fig 1,Impact of absorber layer on short circuit current density

The study has shown the influence of the absorber layer of the c-Si solar cell while keeping the electron transport layers (ETL) and the hole transport layer (HTL) constant. The thickness absorber layer was varied from 100 um to 300 um as indicated in fig 3 and fig 4 while keeping the electron transport layer at a constant value of 20 um. Simulated results show an efficiency of 25% at a temperature of 300K. These proposed values in the solar cell structure can be used or validated through the experimental processes.

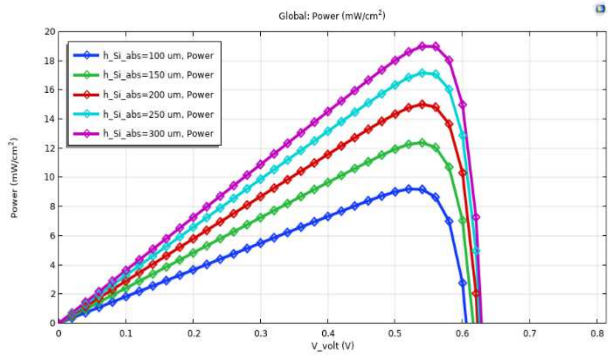

Fig 4. Impact of absorber layer on power output of the solar cell

V. CONCLUSION

In conclusion, the impact of the absorber layer has been studied on the output current density as indicated in fig. 3 and it also shows increase in the thickness of the c-Si_absorber layer also, while keeping electron transport layer (ETL) and hole transport layer (HTL) constant. The study shows that the absorber layer of the solar cell has great influence on the short circuit current density and the power output of the solar cell as indicated in fig 3 and fig 4. The Variation of the c-Si_absorber layer thickness has influenced variation of output results based on the changed in the absorber layer. An efficiency of 25% at a temperature of 300K with a minimum short circuit current density of 18mA/cm^2 and a maximum short circuit current of 36.2mA/cm^2, where a power output of 9.5mW/cm^2 and 19.4mW/cm^2 respectively.

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