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1-D Simulation Studies for the Optimization of i- layer Thickness in a-Si:H Solar cell

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Abstract

This paper illustrates and explores the use of 1-D simulation techniques using SCAPS for the study of solar cell characteristics of a p-i-n photovoltaic cell structure devised using hydrogenated amorphous silicon. Dependence of solar cell parameters such as J-V characteristics, Fill Factor, efficiency and spectral response with respect to i- layer thickness have been studied with the help of simulations. The technique provides a way to optimize the solar cell structure to achieve maximum efficiency, and provides an alternative tool for solar cell researchers for obtaining insight into operation and design of photovoltaic cells.

Keywords: a-Si:H PV cells, SCAPS, J_{SC}, V_{OC}, i- layer thickness, Fill Factor, Quantum Efficiency, spectral response.

INTRODUCTION

Solar cells fabricated using hydrogenated amorphous Silicon (a-Si:H) in a p-i-n (p type-intrinsic- n type) structure are second generation heteroface solar cells (Okamoto et. al., 1980) which offer low manufacturing costs. Further, they also offer larger absorption coefficient than the photovoltaic (PV) cells made using crystalline semiconductor, across majority of visible spectrum (Carlson and Wronski, 1976), thus reducing the volume of material necessary to capture light thereby further decreasing the manufacturing cost (Kirkpatrick et. al., 2015). One of the designing criterions to improve the efficiency of the a-Si:H PV cells is to optimize the thickness of the i- layer of the p-i-n structure. Simulation studies of PV cells cater this need by providing a way to study the solar cell characteristics over a wide range of structural and external parameters. Numerical modeling is increasingly used to obtain insight into the details of the physical operation of thin-film solar cells (Mohamed et. al., 2012). An open source electrical solar cell simulation programme SCAPS (Solar Cell Capacitance Simulator) [Burgelman et. al., 2000] version 3.3.05 is used to study the effect of i-layer thickness on J-V characteristics along with the fill factor (FF) and the efficiency (η) of the a-Si:H PV cell. The dependence of quantum efficiency (QE) on wavelength of the incident light is also reported over the range of i-layer thickness under study. The solar cell structure considered for the simulation is one dimensional (1-D).

METHODOLOGY

The 1-D model of the solar cell chosen in SCAPS, as shown in Figure (1), is based upon (Schropp and Zeeman., 1998) and the ratio of p:i:n layer thicknesses is initialized to 9:100:20 nm. The i-layer thickness (ILT) is used as batching parameter for the calculations whereas; the p-layer and n-layer thicknesses are held constant. This is justified since, the device performance of a-Si:H cell is negligibly impacted by quasi-neutral region transport, provided the i-layer is much thicker than the p- and n- layers (Kirkpatrick et. al., 2015). The p-layer should be as thin as possible to assure penetration of maximum amount of light to the following layers. The input parameters of the p-i-n structure used are as mentioned in table (1). The ambient temperature is set to be 300 K for all the batches of the simulation. The solar spectrum used for illumination purpose is standard AM 1.5G with incident radiation power of 1000 W/m^2, which refers to Air Mass 1.5 corresponding to a solar zenith angle of 48.2°. The cell is illuminated from left (the p-layer of the cell) as shown in Figure (1). The wavelength range chosen for the analysis of spectral response is from 300 nm to 900 nm. The ILT is varied from 100 nm to 5000 nm with logarithmic increments. The short circuit current density (J_{SC}), open circuit voltage (V_{OC}), fill factor (FF), efficiency (η) and the peak of the incident radiation (λ_{max}) corresponding to maximum %QE are determined for every batch using standard routines available in SCAPS.

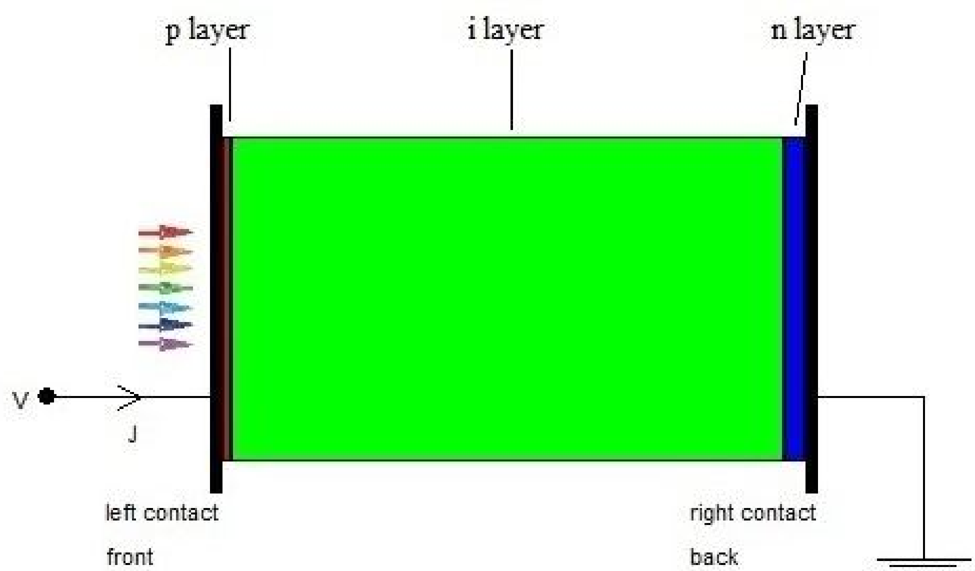

Figure 1: 1-D p-i-n structure used for simulation

Table 1: The input parameters used in the simulation

Parameter	value
Bandgap (eV)	1.8
Electron affinity (eV)	3.9
Dielectric permittivity (Relative)	11.9
N_C (cm^{-3})	1.0 X 10^{20}
N_V (cm^{-3})	1.0 X 10^{20}
Electron thermal velocity (cm/s)	1.0 X 10^{6}
Hole thermal velocity (cm/s)	1.0 X 10^{6}
Electron mobility (cm2/Vs)	20.0
Hole mobility (cm2/Vs)	5.0

SIMULATIONS AND DISCUSSION

Figure (2) illustrates the J-V characteristics for an ILT value of 1.00 μm. The magnitude of short circuit current density is 17.44 mA/cm^2 and the open circuit voltage is 1.085 V. The % FF value of 49.0 is recorded and the PV cell efficiency of 9.3 % is observed. The extrapolated values of parameters are considered wherever necessary for all the batches. The variation in J_{SC} and V_{OC} with respect to ILT is displayed in figure (3). It is evident that the maximum of J_{SC} occurs for the p:i:n ratio 9:1000:20 nm (i.e. for an ILT of 1.00 μm) whereas the open circuit voltage decreases rapidly with increase in the ILT and eventually saturates to a value of 0.95 volt. This decay in V_{OC} is exponential, and follows the logistic equation:

$$V_{OC} = 0.91 + \frac{36.9}{1+(\frac{ILT}{0.035})^{1.55}} \quad \text{.................................} \quad (1)$$

The fall in V_{OC} with increase in ILT can possibly be attributed to associated increase in defect densities, which affect the electric field and carrier collection (Mohamed et. al., 2012). The Fill Factor (FF) - which is a characteristic property of the quality of a PV cell - varies with ILT as shown in figure (3). The maximum value of FF equal to 49% corresponds to p:i:n ratio of 9:1000:20 nm, which is same as that for the maximum short circuit current value.

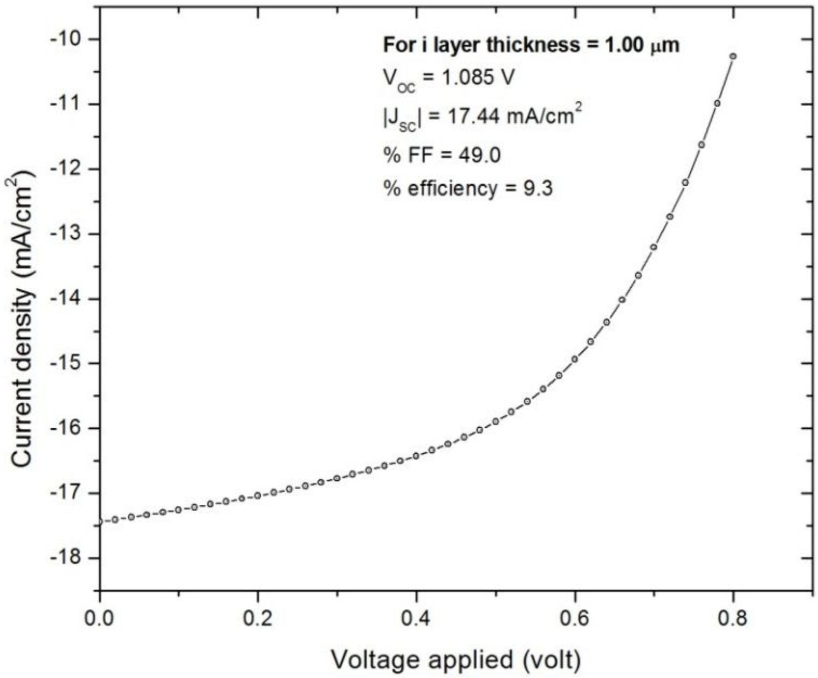

Figure 2: J-V characteristics for ILT = 1000 nm

The efficiency (η) of a solar cell is the resultant outcome of J_{SC}, V_{OC} and FF given by the equation, where P_{in} is the input power applied to the solar cell:

$$\eta = \frac{J_{SC}\, V_{OC}}{P_{in}} FF \qquad \text{……………………………………..….. (2)}$$

The efficiency values over the specified range of ILT are also described in figure (3). It is observed that maximum efficiency of 11.9% is achieved for an i-layer thickness of 300 nm. Here, the optimized i-layer thickness is significantly reduced compared with other finings- 500 nm (Mohamed et. al., 2012), 600 nm (Myong et. al., 2004), 700 nm (Hamakawa et. al., 1980) and 840 nm (Pathak et. al., 2012), respectively. Though the J_{SC} and FF values show maxima at ILT = 1000nm, since, efficiency is a collective effect of parameters mentioned in equation (2), η_{max} occurs at ILT = 300 nm.

The spectral response of the a-Si:H cells have also been studied. As illustrated in figure (4), for ILT value of 100 nm and 150 nm the QE peaks at 408 nm and 443 nm respectively. The same for all other batches are plotted in figure (5) and (6). It is observed that, the maximum %QE peak shift towards higher wavelengths with increase in the i-layer thickness. This shift in the wavelength is higher for smaller ILT values (0.1~ 1 μm) as compared to higher values (1~4 μm).

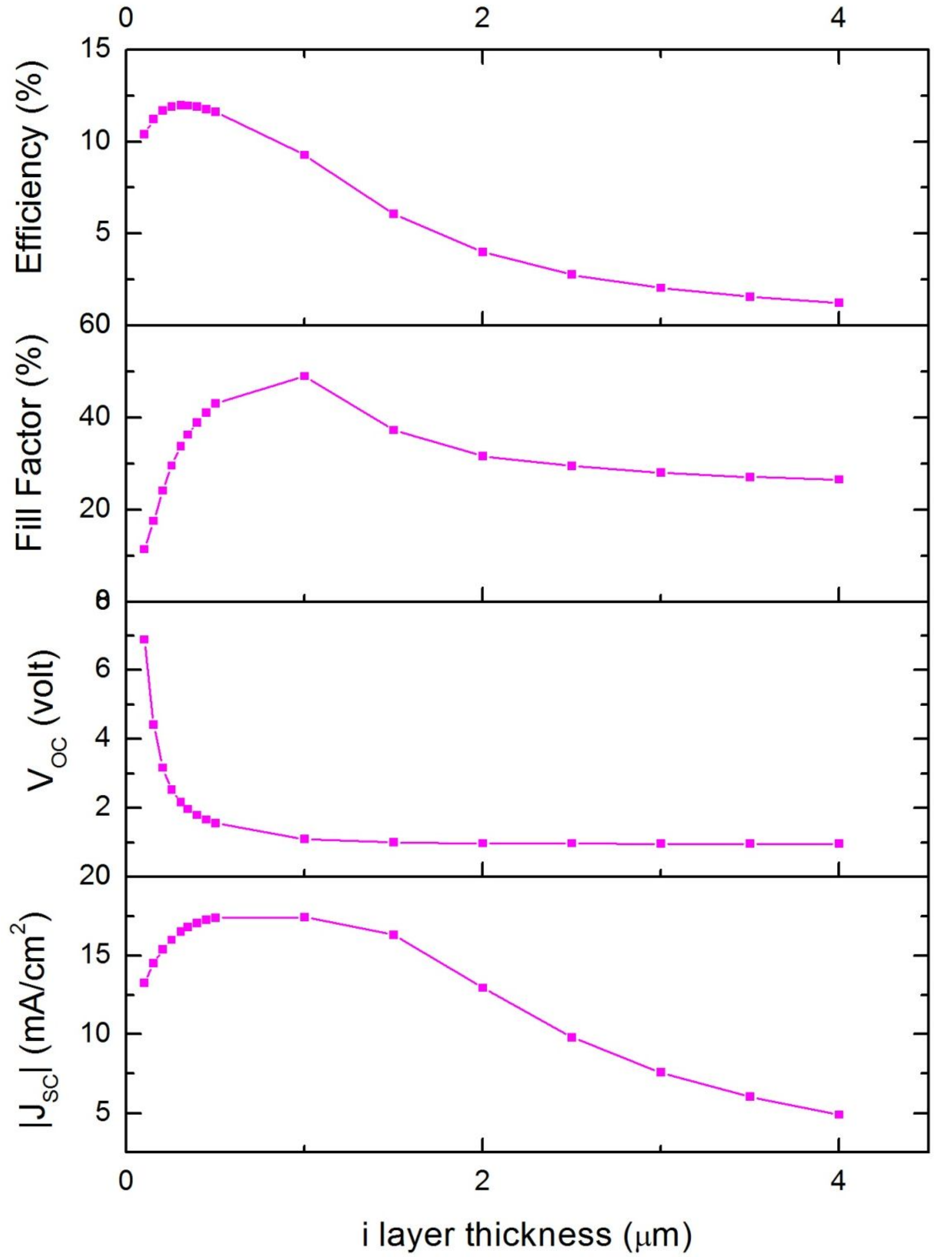

Figure 3: variation in $|J_{SC}|$, V_{OC}, %FF and efficiency for the entire batch

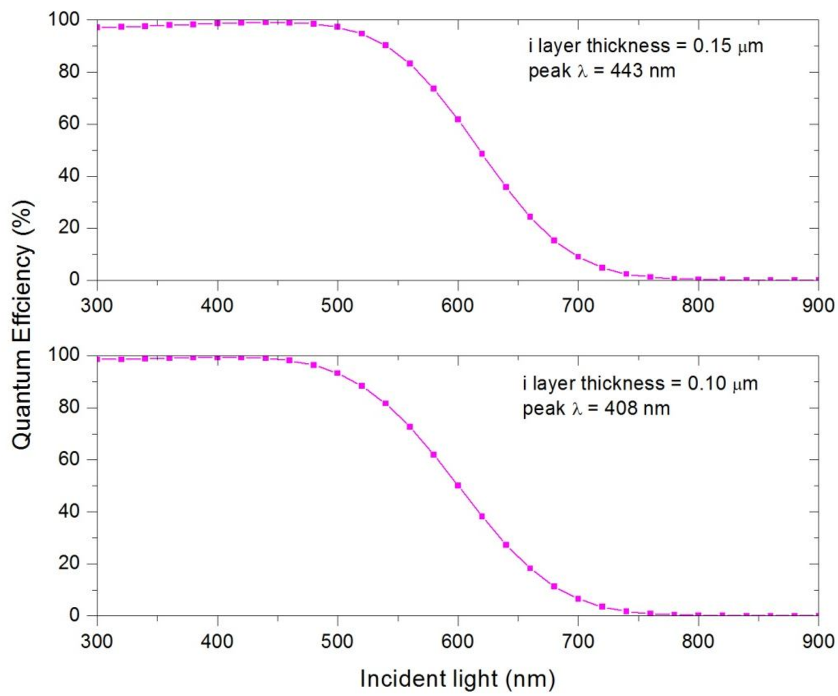

Figure 4: Spectral response for ILT = 100 nm and 150 nm

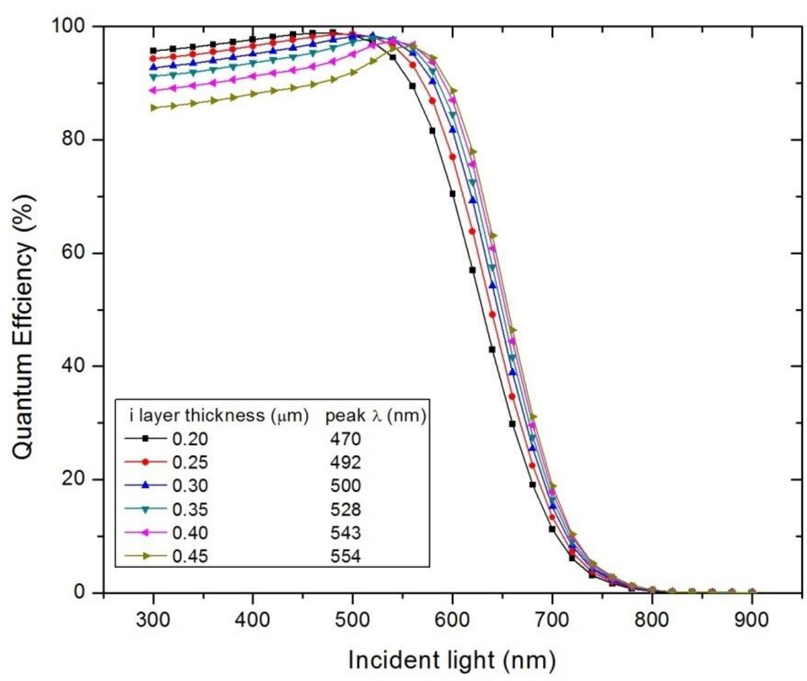

Figure 5: Spectral response for ILT = 0.2~0.45 micron

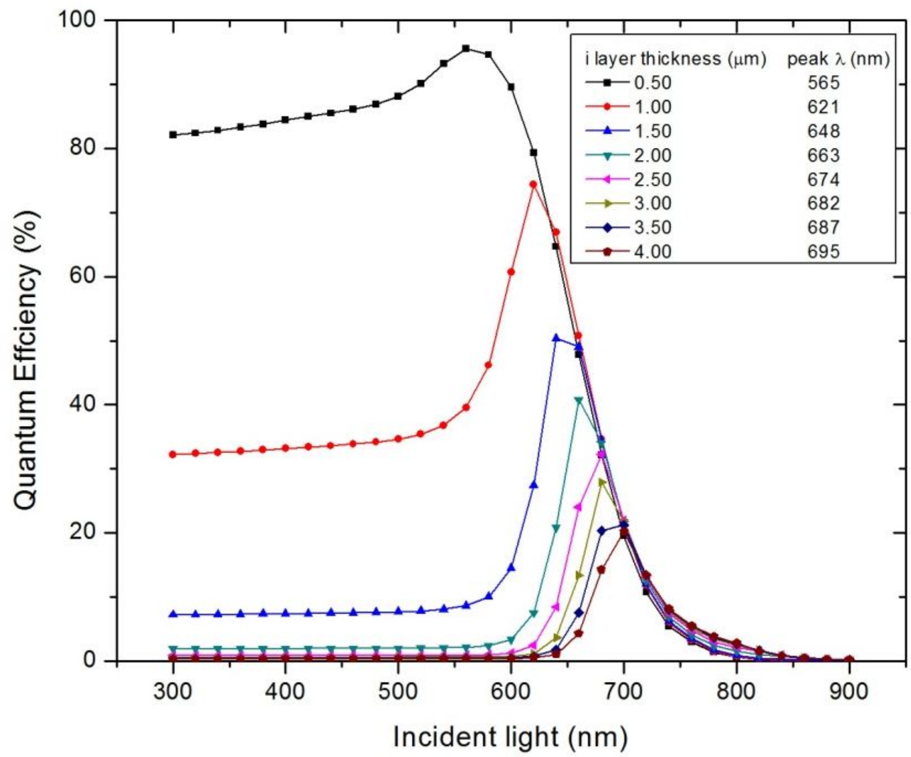

Figure 6: Spectral response for ILT = 0.5~4.00 micron

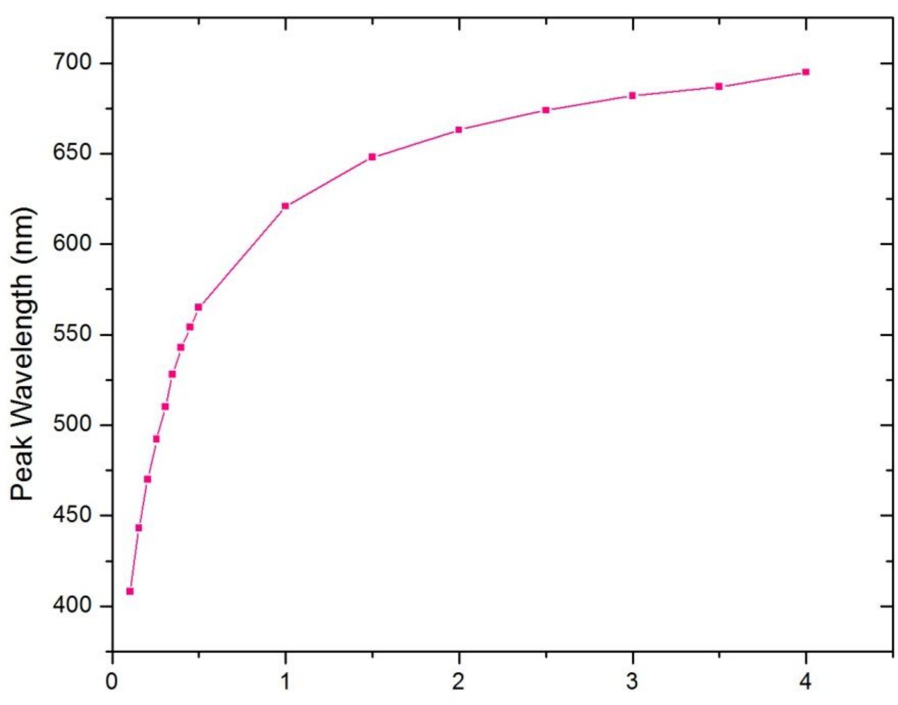

Figure 7: spectral response peak λ v/s ILT

The QE curves show that the cell has a good spectral response over the wavelength range of 400~650 nm which corresponds to i-layer thicknesses of 100~1000 nm. Further, for the ILT value corresponding to maximum efficiency (i. e. 300 nm), the spectral response peaks at a wavelength of 500 nm. It is to be noted that, the solar irradiance also peaks at 500 nm, assuming the Sun to be a blackbody with surface temperature of 5800 K (Dash E Julius, 1996). Thus, the ILT is optimized such that the PV cell offers maximum efficiency and maximum QE simultaneously. Beyond ILT of 1.5 micron, QE drops below 50% and the peak of the spectral response shifts above the wavelength 650 nm. This observation sets a limit on the thickness of the i-layer in the p-i-n structure.

CONCLUSION

An a-Si:H solar cell has been designed numerically and its properties are studied with the help of SCAPS simulations. The best efficiency of the simulated solar cell is 11.9% for an i-layer thickness of 300 nm, with V_{OC} = 2.15 volts, $|J_{SC}|$ = 16.49 mA/cm^2 and FF = 33.7%. Further, The i- layer thickness of 300 nm offers spectral response peak at 500 nm, which also overlaps with the peak of solar irradiance at the earth's surface. The QE curves show that the cell offers good spectral response over the range of 400~650 nm of incident radiation, making it a suitable candidate for PV cell manufacturing. The concept of numerical modeling or simulation of a solar cell is thus one of the best approaches to find out an optimized structure for maximizing their efficiency, thereby reducing the complexity, cost and time required for manufacturing PV cells.

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