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Analysis of Silicon Solar Cell Device Parameters using PC1D

Al Montazer Mandong[1*], Abdullah Üzüm[2]

Abstract

Analysis of the effects of various physical and electrical parameters in the overall efficiency of a solar cell is critical in designing a high efficiency solar cell. In this work, a computer simulation using PC1D was used to analyze the effects of the most substantial parameters in a silicon solar cell. Absorber layer, emitter layer, antireflection coating layer and back surface field layer were studied especially in terms of doping levels, thicknesses and the optimal values to for these parameters were simulated and obtained. The final simulated solar cells were validated using a measured data of an industrial scale fabricated solar cell with the same parameters and the measured result was in a good conformity with the simulation data. According the performed studies and achieved results, understanding and estimating the effects of these substantial parameters and obtaining their optimal values using a simulation software is both beneficial and the most practical way for designing a high efficiency solar cell structure.

Keywords: PC1D, solar cell, crystalline silicon, simulation, optimization

1. INTRODUCTION

The light energy radiated by the sun incident to the Earth's surface can provide an enormous amount of energy enough to meet the world's energy demands in present and in next generations [1]. Photovoltaic solar cells are one of the most effective options to efficiently harness sunlight by absorbing photons and converting them to a usable electrical energy.

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Improving the efficiency of solar cells can significantly contribute to the total generated photovoltaic energy worldwide. A published report from Fraunhofer Institute shows that the solar cell industry is dominated by crystalline silicon (c-Si) solar cells with a global market share of 93% [2]. Currently, the highest confirmed efficiency for mono-crystalline and multi-crystalline are 26.7% and 21.9%, respectively [3-5]. Further improving the efficiency of solar cell requires in depth knowledge of the fundamental working principles of semiconductors. One way to understand the effects for altering physical and electrical properties of each material on the device performance is through an accurate simulation software. Simulation softwares can predict the output behavior of the device with different material properties such as thickness of composing layers, doping levels, etc. Also, they combine both mathematical and experimental data in predicting output behavior of a solar cell. Numerous simulation softwares are available for solar cells such as Silvaco TCAD, Sentaurus TCAD, AFORS-HET and PC1D [6-8]. Sentaurus TCAD is one of the most versatile solar cell simulation software which can predict up to sub-90nm processes with atomic level accuracy [9]. However, its steep price is a major drawback. As an open-source alternative, PC1D can also simulate widely used solar cells such as silicon and germanium. PC1D was created by researchers from Photovoltaics Special Research Centre at University of New South Wales which is a world-renowned institution in solar cell research [8]. Numerous parameters such as temperature, doping levels, parasitic resistance, back surface fields, recombination, carrier lifetime and others can be modified in order to understand their effects on the overall performance of the device. PC1D can provide results including current-voltage (I-V) curves, short circuit current (J_{sc}), open circuit voltage (V_{oc}), etc. in a graphical format. These results can be analyzed and considered in the planning process of the fabrication of an actual device.

Various researchers used PC1D to simulate various types of solar cells before conducting experiment to verify the feasibility of their projects. Sepeai et.al used PC1D to simulate bifacial solar cell [10] while Meenakhshi et.al simulated multi-junction solar cells [11]. Belarbi et.al and Chuan et.al studied silicon solar cells using PC1D [12, 13]. But no validation was presented using a commercial/experimentally fabricated solar cell to verify the simulation software's accuracy and reliability.

In this work, the effects of the most important parameters such as device thickness, doping levels, emitter thickness, back surface field thickness, doping level and antireflection coating on the solar cell performance were studied for crystalline silicon solar cells. PC1D was used in simulating and analyzing performance by modifying device parameters. The result shows the importance of analyzing and obtaining the optimum value of each parameter to obtain the maximum possible device efficiency. Finally, the simulated device with optimized parameters was validated by comparing the results to an industrial scale fabricated solar cell with identical physical and electrical parameters which is other remarkable part of this work.

2. METHODS

The most widely used structure of the silicon solar cell in industry is shown on Figure 1. Understanding the effects of various physical and electrical parameters of each layer is important for achieving high conversion efficiencies. PC1D simulation software was used to study the effects of various device parameters on each layer and achieve the highest possible conversion efficiency.

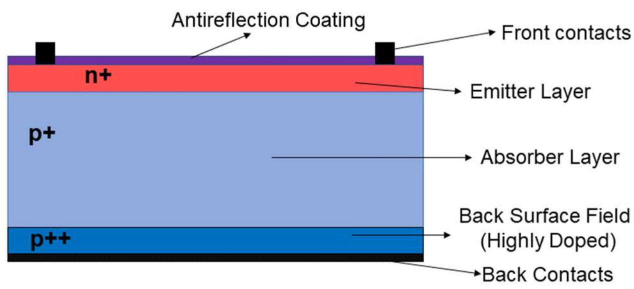


Figure 1. Basic structure of a conventional silicon solar cell with selective emitter

Front contact and back contacts collect mobile charge carriers while the absorber, emitter, and back surface field are responsible in generation and transportation of charge carriers. Antireflection coating minimizes the reflection on the surface of the solar cell and maximizes the light transmission and absorption in order to generate more current. Silicon nitride antireflection coating with refractive index of 1.873 was used in order to minimize reflectance on wavelengths with high spectral irradiance and provide a good surface passivation [14]. Table 1 shows the standard device parameters of the solar cell in this study.

Table 1. Solar cell device parameters using PC1D

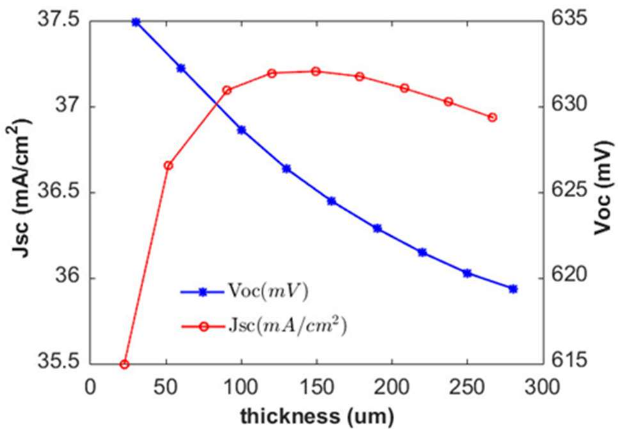
Front surface texture depth	3 μm
Internal optical reflectance	Enabled
Shunt Resistance	50000 Ω
Emitter Sheet Resistance	71.85 Ω/sq
Thickness (Absorber Layer)	180 μm
Intrinsic concentration @300k	1×10^{10} cm^{-3}
Front diffusion (N-type)	2×10^{20} cm^{-3} peak
Rear diffusion (P-type)	3×10^{18} cm^{-3} peak
Front SRV	2×10^{5} cm/s
Rear SRV	1×10^{7} cm/s
Bulk recombination	$\tau_n = \tau_p = 30$ μs
Temperature	25°C
Device Area	1 cm^2

2.1. Effects of Absorber Layer Thickness on Solar Cell Performance

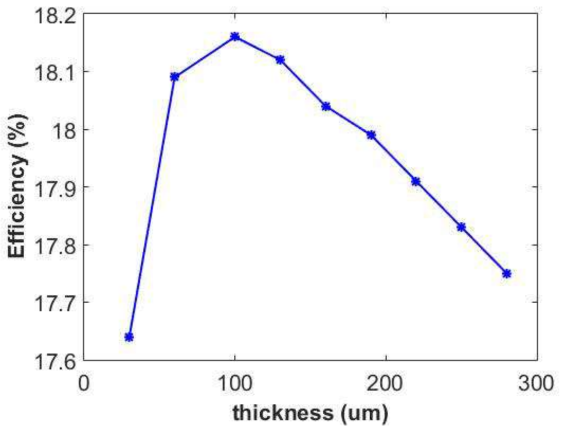
One key factor in establishing the feasibility of fabricating a photovoltaic device is the cost of semiconductor materials [14]. Careful selection of materials with optimum thickness is important factor in minimizing expenses while maximizing device efficiency. The absorber layer is the thickest part of commercial silicon solar cells which absorbs light and generates mobile charge carriers that are transported to and collected by the contacts in order to generate electricity [15]. A thicker absorber layer does not mean higher efficiency due to conflicting effects on V_{oc} and J_{sc}. A solar cell with varying absorber layer thickness was studied in this section. Table 2 shows the result of the varying silicon bulk thickness on the device performance. Figure 2 shows the effect of absorber layer thickness on V_{oc}, J_{sc} (Figure 2a) and efficiency (Figure 2b). 'T_{bulk}', 'FF' and 'η' stands for 'bulk thickness', 'fill factor' and 'conversion efficiency', respectively.

Table 2. Device performance depending on absorber thickness

T_{bulk} (μm)	J_{sc} (mA/cm^2)	V_{oc} (mV)	FF (%)	η (%)
30	35.50	635.0	78.25	17.64
60	36.66	632.3	78.06	18.09
100	37.10	628.7	77.86	18.16
130	37.20	626.4	77.76	18.12
160	37.21	624.5	77.64	18.04
190	37.18	622.9	77.66	17.99
220	37.11	621.5	77.65	17.91
250	37.03	620.3	77.62	17.83
280	36.94	619.4	77.56	17.75



(a)



(b)

Figure 2. (a) V_{oc} and J_{sc} as function of bulk thickness, (b) Effect of thickness on efficiency

The J_{sc} is directly proportional to the thickness until bulk thickness of 160μm then reverses after that while the value of the V_{oc} is inversely proportional from 30 to 280μm. The total efficiency of the device is slowly reduced as the device gets thicker more than 100μm. The device with 100μm thickness has the best efficiency of all, but due to difficulty in handling a very thin device and other physical constraints such as bowing effect of standard aluminum back surface field, manufacturers often use device with more than 150μm thickness. Properties including durability, stability, and handling harsh weather conditions should also be considered in manufacturing processes.

2.2. Effects of Emitter Doping Concentration on Device Performance

Large portion of light are absorbed at the surface of the solar cell which results to high generation rate. Doping concentration and the thickness of the emitter should be carefully designed in order to absorb most of incoming light. High doping concentration in these layers can result to a lower overall efficiency due to decreased light transmission, absorption and higher recombination rate [17]. But high enough concentration is also needed in order to aid the drift transport mechanism and achieve lower sheet resistance. Table 3 shows the result of varying doping concentrations on the sheet resistance and overall performance of the device. Figure 3 presents the effect of emitter doping concentration on emitter sheet resistance and V_{oc}. 'C_{dop}' and 'R_{sht}' stands for the 'doping concentration' and 'sheet resistance', respectively.

Table 3.
Influence of emitter doping concentrations on sheet resistance and device performance

C_{dop} (cm^{-3})	J_{sc} (mA/cm^2)	V_{oc} (mV)	FF (%)	R_{sht} (Ω/sq)	η (%)
2×10^{16}	37.52	625.9	77.73	79650	18.25
2×10^{17}	37.52	631.5	77.78	7852	18.43
2×10^{18}	37.52	631.7	77.79	1751	18.44
2×10^{19}	37.49	630.5	77.80	421.7	18.40
2×10^{20}	37.22	623.6	77.70	71.85	18.03
2×10^{21}	34.33	604.3	77.48	8.7	16.08

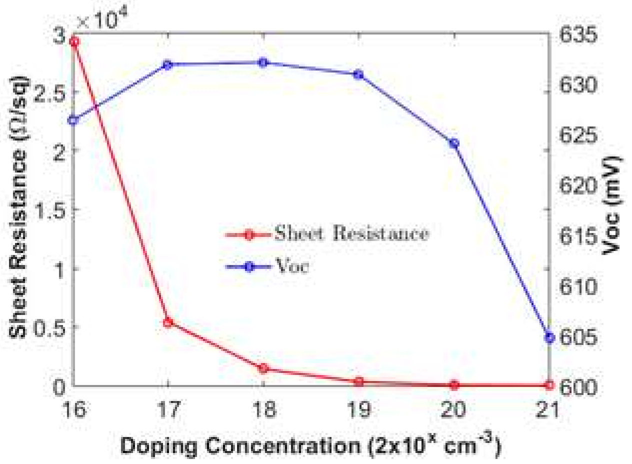


Figure 3. Effect of emitter doping concentration on emitter sheet resistance and on V_{oc}

Device thickness of 150□m was used and emitter doping concentration 2×10^{20} cm^{-3} due to its low sheet resistance. The thickness of the emitter layer can also have a huge impact on the sheet resistance and overall performance of the device. Table 4 shows the device performance with varying emitter thickness. 'T_{emt}' stands for the 'emitter thickness'.

Table 4.
Effect of emitter thickness on device performance

T_{emt} (μm)	J_{sc} (mA/cm^2)	V_{oc} (mV)	FF (%)	R_{sht} (Ω/sq)	η (%)
0.1	36.95	619.7	78.76	71.85	18.03
0.2	36.15	617.0	78.68	35.93	17.55
0.3	34.91	615.3	78.83	23.95	16.93
0.4	33.43	614.3	79.01	17.96	16.23
0.5	31.88	613.6	79.18	14.37	15.49
0.6	30.39	613.0	79.39	11.98	14.79
0.7	29.04	612.5	79.49	10.26	14.14

The J_{sc} and V_{oc} decreases at as the emitter thickness increases while the sheet resistance decreases in value. Lower emitter sheet resistance is desirable in a device, but there are certain drawbacks in having thick emitter. Light hardly penetrates a highly doped and thick emitter layer which affects the generation of charge carrier thus resulting to a lower device efficiency.

2.3. Effect of Back Surface Field Concentration on Device Performance

Back surface field (BSF) is an important part of a modern solar cell which consists of heavily doped layer at the rear of the solar cell. An electric field will be induced to the junction of low and highly doped region which acts as a barrier for minority mobile charge carriers and reduce the recombination at the rear layers of the solar cell [18]. Table 5 shows the result of simulation of varying doping concentration of BSF on sheet resistance and overall device performance. The effects of BSF doping concentration on the overall device performance is shown in Figure 4.

Table 5. Device performance on varying BSF doping concentrations

C_{BSF} (cm^{-3})	J_{sc} (mA/cm^2)	V_{oc} (mV)	FF (%)	R_{sht} (Ω/sq)	η (%)
3×10^{17}	36.72	619.1	77.67	166	17.65
3×10^{18}	37.52	631.7	77.77	36.13	18.44
3×10^{19}	37.11	633.1	77.88	7.175	18.29
3×10^{20}	35.57	626.3	77.81	0.984	17.33
2×10^{21}	35.01	620.7	77.85	0.161	16.92

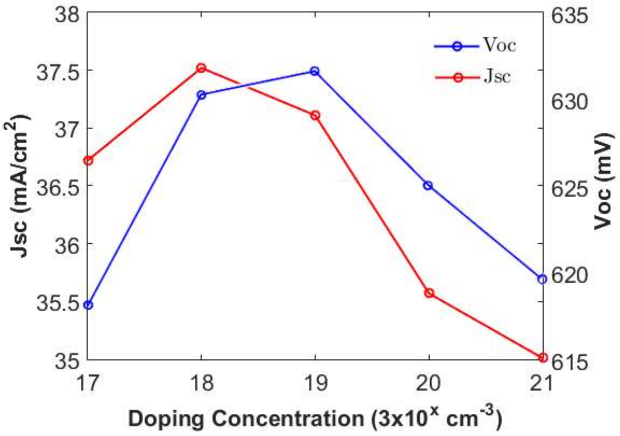


Figure 4. Effects of doping concentration on J_{sc} and V_{oc}

Solar cell with doping concentration of 3×10^{18} cm^{-3} has the highest recorded efficiency. Doping concentration has considerable effect on open circuit voltage of the device from 3×10^{17} to 3×10^{18} cm^{-3}, but after 3×10^{19} cm^{-3} concentration, V_{oc} saturates and then decreases gradually. Similarly, the value of J_{sc} also increases until the doping concentration of 3×10^{18} cm^{-3} but also gradually decreases over higher doping concentrations.

Doping concentration with the highest efficiency was selected and simulated with various thicknesses of BSF. The effects of BSF thickness on the overall device performance is shown on Table 6. The effects of BSF thickness on the V_{oc} and J_{sc} is shown in Figure 5. 'T_{BSF}' stands for the 'BSF thickness'.

Table 6. Device performance of varying BSF thickness

T_{BSF} (μm)	J_{sc} (mA/cm^2)	V_{oc} (mV)	FF (%)	R_{sht} (Ω/sq)	η (%)
5	37.52	631.7	77.77	36.13	18.44
10	37.57	635.3	77.78	18.07	18.57
15	37.52	636.9	77.81	12.04	18.60
20	37.44	638.2	77.87	9.033	18.61
25	37.36	639.1	77.91	7.226	18.61
30	37.36	640.0	77.96	6.022	18.64
35	37.29	640.6	77.97	5.162	18.62
40	37.20	641.4	78.02	4.516	18.61

BSF thickness also has an observable effect on the overall efficiency. As seen on Table 6, a BSF with 30μm thickness produces the highest efficiency.

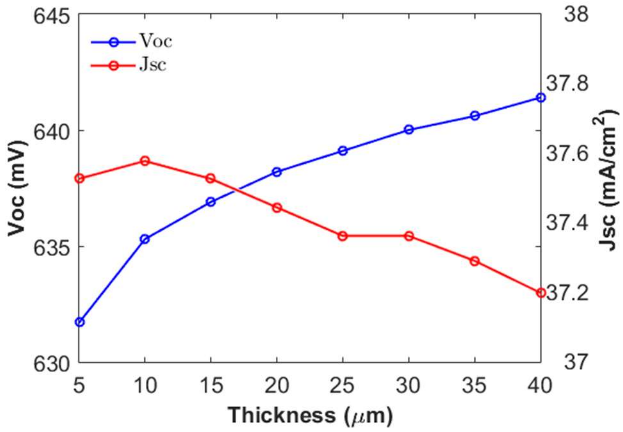


Figure 5. Effect of BSF thickness on J_{sc} and V_{oc}

The value of V_{oc} increases with increasing BSF thickness while the value of J_{sc} is slightly decreasing as the BSF becomes thicker. In addition, the value of the sheet resistance is also inversely proportional with the doping concentration and the thickness of the BSF layer. Higher doping concentration results to a lower resistance but there will be a tradeoff due to significant rise in recombination rate which decreases the collection probability.

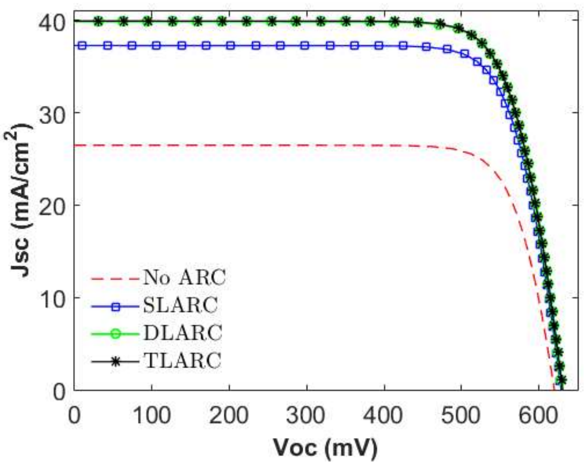
2.4. Effect of Antireflection Coating on Device Performance

Antireflection Coating (ARC) is an integral part of high efficiency solar cells. Thin layer of dielectric material is deposited at the surface of solar cell in order to reduce the total reflectance of incoming light and maximize transmission to generate more charge carriers [16]. ARCs that are used in modern solar cell is composed of single, double or multi-layered dielectric materials with different refractive indices which are stacked one after another. In order to understand the effects of ARC on the device performance, bare silicon, single layer ARC, double layer ARC and triple layer ARC applied silicon surfaces were simulated.

TiO_2 with refractive index of 2.116 and thickness of 67nm was used as single layer ARC (SLARC). MgF_2 and ZnS with refractive indices of 1.39 and 2.371 with thickness of 107nm and 60.5nm respectively was used as double layer ARC (DLARC). MgF_2, SiO_2, TiO_2 with refractive indices of 1.39, 1.48 and 2.453 with thickness of 80nm, 30nm and 60nm was used as triple layer ARC (TLARC). The device performances of each device were given in Table 7. Figure 6a shows the I-V curve of solar cell with and without ARC while Figure 6b shows the reflectance spectra of a device with and without ARC.

Table 7.
Device performance with varying layers of ARC

ARC	J_{sc} (mA/cm^2)	V_{oc} (mV)	FF (%)	□ (%)
None	26.50	619.8	79.79	13.1
SLARC	37.30	628.8	78.88	18.5
DLARC	39.90	630.6	78.56	19.77
TLARC	39.96	630.6	78.53	19.79



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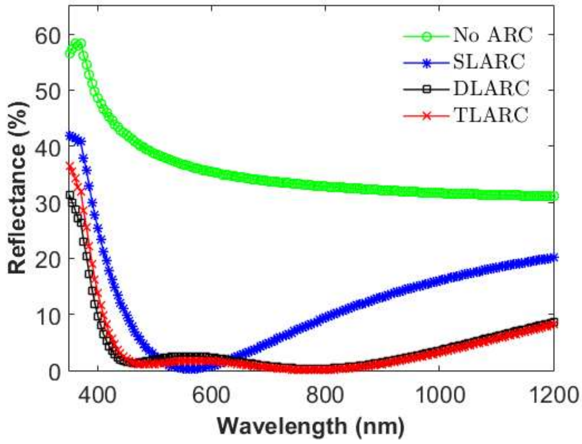

(b)

Figure 6. (a) I-V curve of device with and without ARC, (b) Reflectance spectra of device with and without ARC

2.5. Comparison of Optimal Simulated Solar Cell with a Fabricated Solar Cell

In order to validate simulation data, a simulated device with identical parameters was compared to the measurements of actual solar cell in real application conditions. Table 8 presents the comparison of electrical parameters of simulated solar cell with a real solar cell.

Table 8.
Comparison of electrical parameters of optimal simulated solar cell with a fabricated cell

Data type	J_{sc} (mA/cm^2)	V_{oc} (mV)	FF (%)	□ (%)	Pseudo □ (%)
Real Cell	36.6	617.0	78.30	17.7	18.48
Simulated Cell	37.3	628.8	78.88	18.5	-

According to Table 8, one can observe that the simulation results can predict the actual cell results in a good agreement. Overall, the simulated results were slightly higher than that of the parameters of real cell. Emitter doping of the real cell was 5×10^{20} cm^{-3} where the simulated optimal emitter doping was 2×10^{20} cm^{-3} for a homogenous emitter while the emitter depths of the cells were 0.6□m and 0.1□m, respectively.

Slightly higher performance of simulated cell can be considered in an acceptable range due to lesser recombination losses. On the other hand, the pseudo efficiency of the real cell was measured as 18.48% by Suns-V_{oc} measurement tool which shows the potential efficiency of the cell precisely estimated by the simulation when excluding resistive losses.

3. CONCLUSION

This study highlights the importance of using PC1D simulation software in analyzing and obtaining the optimum values of each device parameter in order to achieve the maximum conversion efficiency. Nonetheless, device properties such as durability, stability, handling harsh weather conditions, and manufacturing process limitations should also be considered when using simulation softwares. Finally, this paper shows the potential of integrating simulation softwares such as PC1D as a practical alternative in research and development stage of fabricating crystalline silicon solar cells due to its accuracy and reliability.

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