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ON THE PERFORMANCE LIMITS FOR MONO CRYSTALLINE SILICON SOLAR CELLS: A COMPARATIVE STUDY

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Abstract

In this study the solar cell parameters depending on the electrical and physical properties of a semiconductor material were simulated and optimized with high accuracy and with a short simulation time. To obtain highly efficient solar cells in theory, later on for practical applications, Personal Computer One Dimensional (PC1D) software simulation program was used. The parameters were the thickness of emitter and absorber layers, type of absorber layer, doping profile, antireflective coating (ARC) materials and surface texturing. The results observed with the optimized parameters were compared and verified with the experimental results in the literature.

Keywords: Silicon Solar Cells, Photovoltaic Systems, PC1D Simulation, Antireflective Coating, Doping, Texturing

MONOKRİSTAL SİLİSYUM GÜNEŞ PİLLERİNİN PERFORMANS LİMİTLERİ ÜZERİNE: KARŞILAŞTIRMALI BİR ÇALIŞMA

Özet

Bu çalışmada, yarı iletken bir malzemenin elektriksel ve fiziksel özelliklerine bağlı olarak güneş pili parametreleri yüksek doğrulukta ve kısa bir simülasyon süresi ile simüle edilmiş ve optimize edilmiştir. Teoride yüksek verimli güneş pilleri elde etmek için, daha sonra pratik uygulamalar için, Kişisel Bilgisayar Tek Boyutlu (PC1D) yazılım simülasyon programı kullanılmıştır. Parametreler, yayıcı ve emici tabakaların kalınlığı, emici tabakanın tipi, doping profili, yansıma önleyici kaplama (ARC) malzemeleri ve yüzey şekli etkisi olarak belirlenmiştir. Optimize edilmiş parametrelerle gözlemlenen sonuçlar literatürdeki deneysel sonuçlarla karşılaştırılarak doğrulanmıştır.

Anahtar Kelimeler: Silisyum Güneş Pili, Fotovoltaik Sistemler, PC1D Simülasyon, Yansıma Önleyici Kaplama, Yüzey Tekstüre Etme

Cite

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1. Introduction

Nowadays the main source of energy is fossil fuels such as coal, oil, or natural gas. However, the most critical problem is that these resources are finite, and they are non-renewable. Increasing demand also gives rise to sustainability economic problems since the price of electrical energy is also increasing rapidly, so the researchers focus on finding out renewable and clean energy sources which have the ability to solve aforementioned problems without any harm to nature [1]. Renewable, clean and cheap energy sources are becoming more important day by day to fulfill the future energy requirements. Considering the global warming and environmental pollution issues, the demand for developing and improving cheap, clean, sustainable, and renewable energy fields have increased rapidly over the past decade. The alternative and free energy sources for the environmentally harmless ones include wind, hydroelectric, geothermal and solar.

Direct sunlight can be converted into electricity with solar cells based on photovoltaic (PV) principles. When the incident light strikes the surface of the solar cell, electrons are excited from the valence band to the conduction band leaving behind holes, thus creating electron-hole pairs, which are collected by the contacts and generate electricity. PV applications have increased significantly over the last years [2, 3]. Due to high potential of PV technology (PVT), the industry of the solar cell has grown with a fascinating rate of more than 30% per year over the last decade [4]. The solar cell revolution based on semiconductor materials, and the most common semiconductor material is silicon (Si). Si is stable, abundant and non-toxic element which makes it more advantageous for PV applications when compared to other semiconductors [5].

The basic structure of the solar cell consists of positive (p-type) and negative layer (n- type) which is called p-n junction. To decrease reflection and enhance optical performance Antireflective coating (ARC) is applied on top surface. In Figure 1Figure, the schematic of a crystalline Si (c-Si) based solar cell used in simulations is shown.

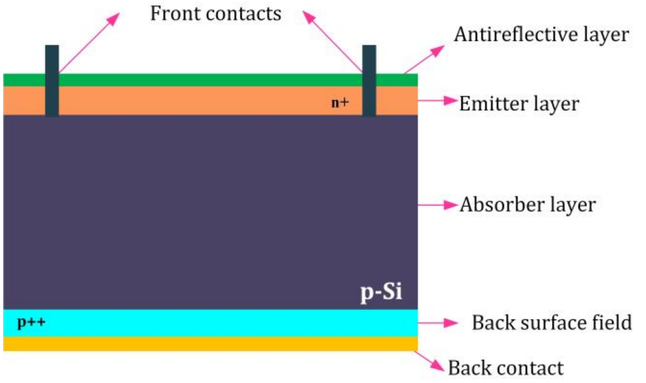

Figure 1. Schematic of c-Si based solar cell

PVs based on Si are the most common types providing highly efficient conversion of sunlight into electricity with low cost.

Over the last few years, the PVT has become increasingly interested in n-type Si wafer based solar cells due to their high efficiency potential [6]. A major part of the PV market today consists of monocrystalline (mono-Si) and poly-crystalline (poly-Si) wafer-based solar cells. Mono-Si wafers have the potential to produce highly efficient solar cells due to their perfect crystalline structure [7]. Mono-Si solar cells can be produced by Czochralski (CZ) or Float zone (FZ) methods afterwards sliced into 200-300 micrometers (μm) thick Si wafers. In comparison, multi-crystalline wafer-based solar cells are less expensive than mono-Si wafer-based solar cells, but are less efficient [8]. The maximum efficiency of Si solar cells is limited by the intrinsic properties of Si, such as bandgap energy (Eg) (Eg for Si = 1.12 eV) and the properties of the charge carrier generation and recombination [9, 10].

In this study, simulations were performed to examine the influence of various electrical and physical parameters on the performance of a mono crystalline Si solar cell by using Personal Computer One Dimensional (PC1D) software simulation program. Despite the fact that there are many other free and commercial software programs for simulating specific devices, for this study PC1D was selected [11, 12]. This program was developed in Australia at the University of South Wales in Sydney. PC1D can simulate the behavior of PV structures based on semiconductor materials with respect to one-dimensional simulations. It provides short simulation times with high accuracy. PC1D program has libraries' files with all parameters of the semiconductor materials used in PVT such as, GaAs, a-Si, AlGaAs, Si, InP, and Ge. The files of the solar spectrum are also available in this software. All required parameters of the solar cells can be defined during the simulation easily to obtain better performances. Depending on the demands of the researchers and companies, one can easily optimize the parameters.

2. Theoretical Study

In this part, we focus on examining the effects of wafer thickness, doping density of the emitter and absorber layers, surface area, junction depth, different ARC layers, and surface texturing on the performance of wafer-based c-Si solar cells. The effects of these parameters on open circuit voltage (V_{oc}), short circuit current density (J_{sc}), maximum power (P_{max}), and efficiency of c-Si solar cell were investigated.

2.1. The effect of wafer thickness:

The main goal of companies and researchers dealing with solar energy is to reduce production cost as much as possible, while maintaining the performance of the PV system at a desirable level. The highest cost of a solar cell production comes from wafer prices. In order to solve this problem there are many studies aiming to decrease the thickness of the wafer [13]. There is large interest in designing c-Si solar cells with active layer thickness of a few μm to reduce the cost of PV solar cells. While trying to reduce the cost, the effect of thickness changes the optical and electrical performances of the cells [14]. In this study the effect of wafer thickness on the performance of c-Si solar cell has been investigated.

Figure 2 shows the current-voltage (I-V) curves of the c-Si solar cell with different wafer thicknesses ranging between 100-500 μm. The doping density of the absorber layer in this example was taken as 1x1016 cm-3, whereas the surface area was taken as 1 cm2, which means that the current and current density values will be the same. It is observed that the Jsc increased from 38.3 mA/cm2 to ~40.2 mA/cm2, whereas the Voc decreased from 742 mV to 682 mV by increasing the wafer thickness from 100-500 μm. To get results close to real cell values, with standard test condition, the spectrum AM 1.5 G was used with 25 °C (300 K) process temperature.

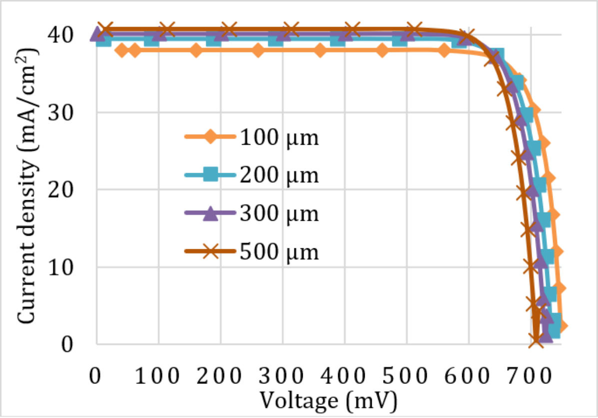

Figure 2. I-V curves of c-Si solar cells with 100, 200, 300 and 500 μm wafer thicknesses.

When the thickness is increased, the absorption of the incident light increased, and vice versa. The result does not mean that it is preferable to design a solar cell with high thickness of absorber layer. The high thickness negatively affects optical and electrical properties of a solar cell, in addition to the increase of cost. If the absorber layer gets thicker, it is known that electron-hole pairs will not be able to reach to contacts. The longer the path for electron-hole pairs, the higher the probability that they recombine, which will end up with low efficiency [7, 14, 15].

To summarize thickness impact, it can be said that the J_{sc} increases with increasing the thickness until it reaches to a specific thickness value, and the V_{oc} decreases with increasing the wafer thickness. This is expected because the recombination increases with increasing the bulk thickness which leads to lower V_{oc}, and therefore lower efficiency.

2.2. The effect of emitter layer thickness:

In this part, the effect of emitter layer thickness in p-type c-Si wafer on the performance of c-Si solar cell was investigated. When the thickness of emitter layer of the p-type wafer was increased from 0.3 µm to 0.7 µm, the Jsc and Voc decreased rapidly as shown in Figure 3, thus leading to lower device efficiency value, as tabulated in Table 1. The thickness of the emitter layer should be carefully optimized to absorb most of the incoming light and end up with high efficiency.

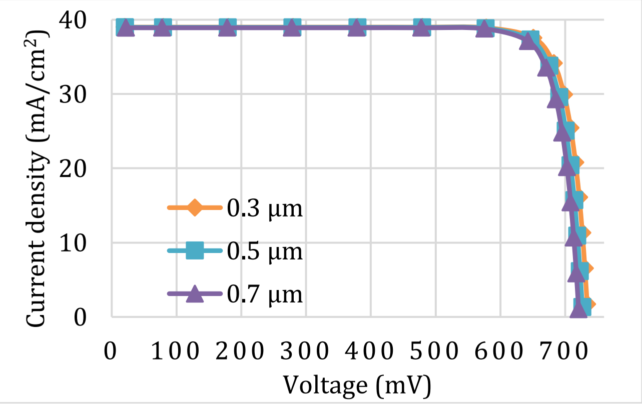

Figure 3. I-V curves of c-Si solar cells with 0.3, 0.5 and 0.7 µm emitter layer thicknesses.

The doping density for emitter layer was defined as $1x10^{16} cm^{-3}$. The thickness of the wafer was taken as 100 µm and the bulk recombination lifetime of the electrons and holes was assumed to be 250 µs. The efficiency decreased when the emitter thickness increased by 0.2 µm. This decrease was related to the incident light hardly penetrating the thicker layer, thus ending up with decrease in electron-hole pair generation. The highest efficiency with about 24.5% was obtained from 0.3 µm, whereas the efficiency (ŋ) of c-Si solar cell with 0.5 µm and 0.7 µm emitter thickness was about 24.1% and 23.8%, respectively as shown in Table 1. The thinner the emitter layer is, the larger the probability of the generated electron-hole pairs to reach the contacts.

Table 1. The effect of the emitter layer thickness on the device performance of c-Si solar cell.

Emitter thickness (µm)	J_{sc} (mA/cm²)	V_{oc} (mV)	P_{max} (mW)	Fill Factor (FF)	ŋ (%)
0.3	39	735	24.5	0.85	24.5
0.5	39	727	24.1	0.85	24.1
0.7	38.9	721	23.8	0.85	23.8

2.3. The effect of doping density of the emitter layer:

The doping density of the emitter layer was taken as 1x1015 cm-3 for low doping, and 1x1019 cm-3 for high doping. Increasing the doping density of the emitter layer from 1x1015 to 1x1019 cm-3 led to a decrease of the efficiency of the c-Si solar cell as represented in Table 2.

Table 2. The effect of doping density of the emitter layer on the performance of c-Si solar cells.

Doping density of the emitter (cm^{-3})	J_{sc} (mA/cm²)	V_{oc} (mV)	P_{max} (mW)	Fill Factor (FF)	ŋ (%)
$1x10^{15}$	38.1	748	23.9	0.84	24
$1x10^{19}$	17.53	657	9.6	0.83	9.6

As shown in Figure 4, the Jsc values decreased from 38.1 mA/cm2 to 17.53 mA/cm2, and Voc decreased from 748 mV to 657 mV by increasing doping density of the emitter layer from 1x1015 cm-3 (for low concentration) to 1x1019 cm-3 (for high concentration), respectively. It can be seen that the efficiency decreases with increasing doping density, and the reason for this is the decrease in the mobility of the electrons and holes. The mobility of the charged carriers (electrons & holes) is inversely proportional to the doping density [16]. Our results agree with the ones reported in the literature.

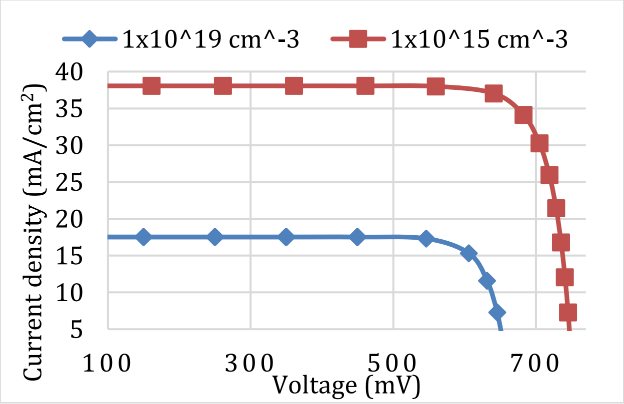

Figure 4. I-V curves of c-Si solar cells with $1x10^{15}$ and $1x10^{19} cm^{-3}$ doping densities of the emitter layers

The studies showed that the efficiency decreased with increased doping density, and this is because defect

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generation rate (recombination) strongly increases with increasing the doping density [13, 17-19].

The doping density and the thickness of the emitter layer should be optimized carefully to maximize the absorption of the incident light and drift transport mechanism [20]. As explained in Table 2, the efficiency decreased with the increase in doping density. This is related to the decrease in the amount of absorbed light, and high recombination rate.

The emitter layer thickness increases with the increase in doping density. The emitter layer thickness was set between 1.2 to 2.75 µm by PC1D with the increase in the doping density from $1x10^{17}$ to $1x10^{20}$ cm^{-3} (Table 3). Higher doping density (because of Coulomb scattering) leads to reduced values of the mobility. Hence, the doping density of the emitter and absorber layers should be carefully optimized to obtain highly efficient solar cells [20].

2.4. The effect of doping density of the absorber layer:

The effect of the doping density of the emitter on the performance of c-Si solar cell was discussed in section 2.3. To create p-n junction, we need two different layers (emitter & absorber layers). Here, we study the influence of the doping density of the absorber layer on the performance of the c-Si solar cell. The obtained results of the I-V curves are shown in Figure 5.

When the doping density of the absorber layer is increased from $1x10^{15}$ cm^{-3} to $1x10^{19}$cm^{-3}, the J_{sc} and V_{oc} values decreased from 38.1 to 31.7 mA/cm^2, and 748 to 683 mV, respectively. The doping density for the emitter was kept at $1x10^{16}$ cm^{-3} for both cases. When the number of impurities is increased, the mobility of the charged carriers (electrons & holes) decreases, consequently the performance of Si solar cell decreases [21]. Experimentally, the maximum efficiency, for absorber doping concentration $2x10^{15}$ cm^{-3}, was found to be 22.1% [22]. The values of the performance parameters for low and high-doped absorber layers can be seen in Table 4.

2.5. The effect of junction depth:

The junction depth is the most crucial parameter affecting the performance of a c-Si solar cell, so it must be optimized very carefully to obtain the maximum efficiency.

In this part of the study, the optimum junction depth, which can lead to maximum efficiency, is studied. At the end of the simulation studies, it was found that the junction depth has significant effect on Isc and Voc values as demonstrated in Figure 6.

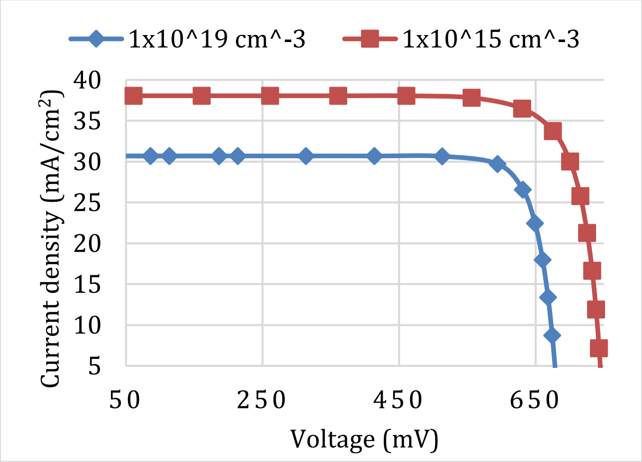

Figure 5. I-V curves of c-Si solar cells with $1x10^{15}$ and $1x10^{19}$ cm^{-3} doping densities of the absorber layers.

The Jsc and Voc are reduced from ~39.4 mA/cm2 to ~35.2 mA/cm2, and from 720 mV to 670 mV with the increase in the junction depth from 0.1 µm to 2.1 µm, respectively.

In this part of the simulation, the p-type doping density was taken as 1x1016 cm-3. From Figure 7 it can be seen that when the junction depth was increased from 0.1 µm to 2.1 µm, Jsc and Voc reduced by 11% and 7%, respectively.

In summary, the efficiency decreased from 23.8% to about 19.9% with the increase in junction depth from 0.1 µm to 2.1 µm because of lower electron-hole pair generation. In previous work, it was shown that the efficiency decreased from 16.4% to 10.35% for junction depth of 0.1 µm and 2 µm, respectively [23].

2.6. Comparison between n- and p-type absorber layers:

In this section of the study, the differences between n-type and p-type absorber layer types were investigated and simulated with PC1D. The performances for both layers are depicted in Figure 8.

Table 3. The effect of doping density for emitter layer on the sheet resistance and device performance parameters.

Doping density of the emitter layer (cm^{-3})	Sheet resistance (Ω/sq)	Emitter thickness (µm)	J_{sc} (mA/cm^2)	V_{oc} (mV)	P_{max} (mW)	Fill Factor (FF)	η (%)
$1x10^{17}$	3282	1.2	37.8	753	23.9	0.836	~24
$1x10^{18}$	512.7	1.82	37.8	752	23.9	0.837	~24
$1x10^{19}$	108	2.33	37.7	739	23.5	0.84	23.5
$1x10^{20}$	19.96	2.75	33.8	675	19.2	0.842	19.2

Table 4. The effect of doping density of the absorber layer on the performance of c-Si solar cell.

Doping density of the absorber (cm^{-3})	J_{sc} (mA/cm^2)	V_{oc} (mV)	P_{max} (mW)	Fill Factor (FF)	ŋ (%)
$1x10^{15}$	38.1	748	23.9	0.84	~24
$1x10^{19}$	31.7	683	18.1	0.81	18.1

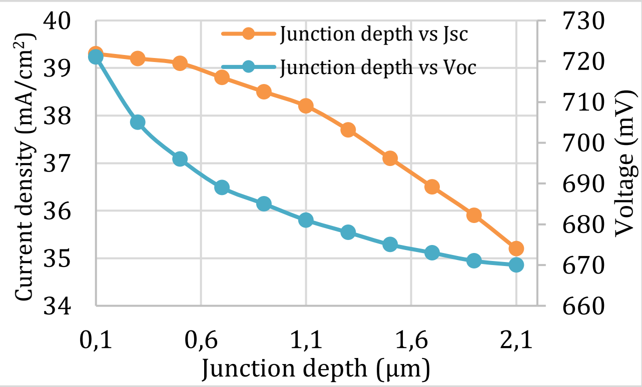

Figure 6. The effect of junction depth (0.1- 2.1 µm) on I_{sc} and V_{oc}.

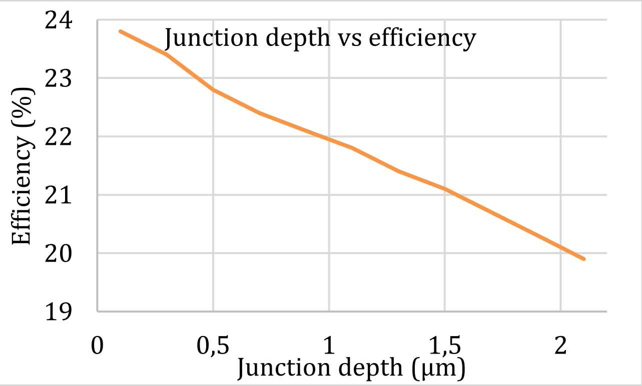

Figure 7. Junction depth versus efficiency of c-Si solar cell.

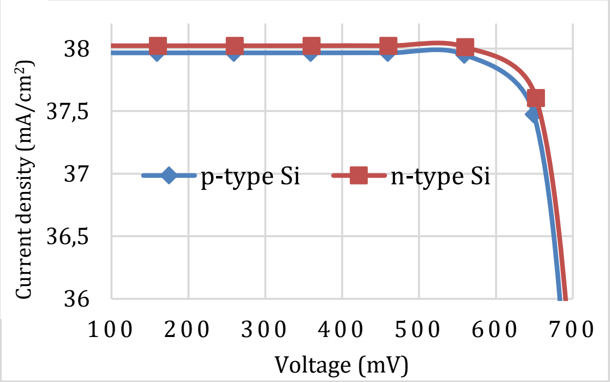

Figure 8. I-V curves of c-Si solar cells with n- and p-type absorber layers

The parameters such as doping density, thickness and solar spectrum were kept the same during p- and n-type solar cells simulations. The thickness of the absorber layer was taken as 180 µm, whereas the doping density of the absorber layer was defined as $1x10^{17}cm^{-3}$. The device area was 1 cm^2 for both n-and p-type wafers. The J_{sc} and V_{oc} values for p-type c-Si solar cell were 38 mA/cm^2 and 757 mV, while the J_{sc} and V_{oc} for n-type c-Si solar cell with the same parameters were 38.2 mA/cm^2 and 762 mV, respectively. The efficiency of the cell with n-type wafer was 25%, whereas the efficiency of the cell with p-type wafer was approximately 24.7%, as reported in Table 5.

Table 5. The performance of n- and p-type c-Si solar cells.

Wafer type	J_{sc} (mA/cm^2)	V_{oc} (mV)	P_{max} (mW)	Fill Factor (FF)	ŋ (%)
n-type	38.2	762	25	0.86	25
p-type	38	757	24.7	0.84	24.7

A major difference was observed in the minority carrier lifetime which ended up with low FF values for p-type cells [24]. N-type Si solar cell has lower tendency to metallic impurities, this is one of the major reasons why it ends up with higher efficiency values when compared with p-type Si solar cells. Cell efficiencies above 23% were reported with n-type Si in recent studies [25, 26].

2.7. Saw damage removed and textured Si surfaces:

When sunlight hits the surface of Si, there are three possibilities for the interaction: it may be reflected back, be absorbed, or be transmitted according to the wavelength of the light. It is very important to keep the reflected light as small as possible and the absorption amount as high as possible to end up with highly efficient solar cells. One of the most important parameters to reduce the reflected light and to increase the absorption of the light is surface texturization [26]. If the performance of Si-wafer-based solar cells has to be well above 25%, it is inevitable to apply new methods and implement them alongside with the traditional ones. The currently used methods are surface passivation, ARC and texturing the front surface and the rear side of the cells [27].

In this part of the study, the effect of surface texturing on the performance of c-Si solar cell was studied and compared with saw damage removed (in other words non-textured, bare) c-Si solar cell by using PC1D software program [28]. In Figure 9 the I-V curves of saw damage removed and textured c-Si solar cell are shown.

The depth of the front surface texture was defined as 3 µm, and the angle of the pyramid texture was 54.7°. This angle occurs as a result of the orientation and atomic density of Si atom, in other words that is the natural tendency of Si [29, 30].

From the saw damage removed Si surface, the obtained J_{sc} value was ~27.6 mA/cm^2 and V_{oc} of about 722 mV, while the J_{sc} and V_{oc} values obtained from textured Si surface were ~36.1 mA/cm^2 and 731 mV, respectively.

16.6% efficiency was obtained from saw damage removed Si surface, while the efficiency obtained from the textured Si surface was about 21.8%. An improvement was also obtained for absorption with texturing during fabrication of the cells. The published results proved that our results are consistent with the experimental data [7, 31]. The improvement obtained with pyramid texturing lead to a significant enhancement in the efficiency of the cells [31]. The reflection of the light in the saw damage removed surface decreased rapidly from ~35% to ~15% after texturing the surface as shown in Figure 10, which led to an increase of the absorbed light [32- 34]. The lowest light reflection that was obtained from saw damage removed (bare) Si surface was ~35%, while the lowest reflection obtained from textured Si surface was ~13%.

2.8. The impact of different ARC layers:

In this part of the study, different ARC layers have been simulated for c-Si solar cells with PC1D software program. To enhance the performance of a solar cell with ARC coating, there are some critical parameters that should be optimized carefully. Those parameters are the thickness, refractive index of the ARC layer, and the material selection for the coating. With the appropriate combination of this three factors, the reflectivity can be minimized [35]. It was found that the optimum thickness of the ARC layer depends upon the refractive index and wavelength for reducing the reflectivity [21, 36-38]. The solar flux is maximized at 600 nm, for that reason the wavelength was set to 600 nm during our simulations.

The thickness of the ARC layer (d_1) which results in minimum reflectivity was calculated with:

$$d_1 = \lambda_0 / 4n_1 \qquad (1)$$

where λ_0 is the wavelength of the incident light (600 nm) and n_1 is the refractive index of ARC material for 600 nm wavelength.

The uncoated c-Si surface was used as a reference cell during the analyses. It was found that J_{sc} value was most affected parameter during the use of different ARC materials. When silicon nitride (Si_3N_4) was used as an ARC layer, the J_{sc} increased by about 36.6% and this was the highest J_{sc} value obtained.

The V_{oc} and FF increased by about 2% and 5%, respectively during the application of different ARC materials. The highest efficiency value of 14.4% was obtained when Si_3N_4 with a refractive index of 2 and 75 nm thickness were used as tabulated in Table 6. To better understand the results, the reflectivity plot obtained at this thickness range is shown in Figure 11. By optimizing the refractive index and thickness of ARC layer, the reflectivity is reduced in the range of 600 nm wavelength, so the light absorption increases leading to higher efficiency. In Figure 11, it can be seen that the lowest reflectivity was achieved for c-Si solar cell coated with Si_3N_4 ARC layer.

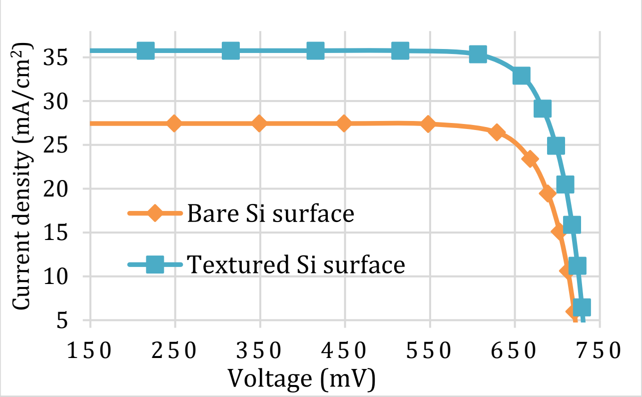

Figure 9. I-V curves of saw damage removed and textured c-Si solar cell observed with PC1D.

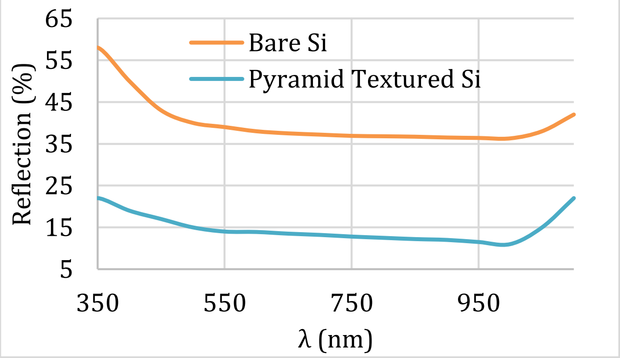

Figure 10. Wavelength versus reflection for saw damage removed and textured Si surfaces [31].

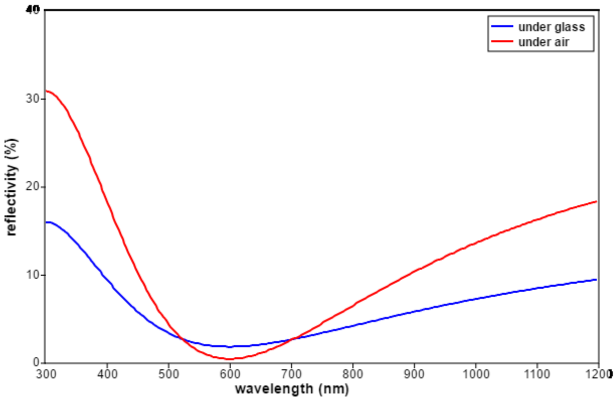

Figure 11. The reflectivity as a function of the wavelength of c-Si solar cell coated with Si_3N_4 ARC layer.

3. Conclusion

Using simulation, “inside” the device can be seen. Experimental measurements tell ***what*** happens, but not ***why*** it happens. In this study, a comparative analysis on the performance limits of c-Si solar cells was conducted using numerical experiments. The optimization of Si solar cell parameters both from electrical and optical view, by using trusted software simulation PC1D program, was done. The parameters that were optimized were the wafer thickness, the type of the absorber layer, doping concentration, surface texturing and ARC materials.

Table 6. The performance of c-Si solar cells with different ARC layers.

ARC material	Refractive index	ARC thickness (µm)	J_{sc} (mA/cm^2)	V_{oc} (mV)	P_{max} (mW)	Fill Factor (FF)	η (%)
Uncoated	-	Bare Si	20.2	610	9.8	0.79	9.8
MgF_2	1.38	108.7	24.9	617	12.7	0.83	12.7
SiO_2	1.46	102.74	25.7	618	13.1	0.82	13.1
Al_2O_3	1.76	85.23	27.2	619	14	0.83	14
Si_3N_4	2.00	75	27.6	621	14.4	0.84	14.4
ZnS	2.36	63.56	26.7	619	13.8	0.83	13.8
TiO_2	2.62	57.3	25.7	618	13.7	0.82	13.7

When the thickness values were taken in the range of 100 µm to 500 µm, it was observed that I_{sc} increased with increasing the absorber layer thickness, but when it reached to a critical value, V_{oc} diminished. The reason of that is because of the ascending of the recombination rate with increasing the bulk thickness.

With regard to the emitter layer thickness analysis, it was found that the efficiency increases as emitter layer thickness decreases. The reason of this inverse proportional behavior is because of the incident light's hardly penetrating to a thicker emitter layer ending up with lower electron-hole pair generation.

The impact of both emitter and absorber layers on the performance of a solar cell was also analyzed. It was observed that, the performance of c-Si solar cell was negatively affected with increasing doping density and this was because of the mobility of the charged carriers' (electrons & holes) decreasing with the increase in the doping density.

The difference between n-type and p-type Si wafers was simulated and analyzed. From the IV curves of n- type and p-type wafers, it was found that n-type wafers led to higher efficiency values when compared with p-type wafers.

The effect of surface texturing and different ARC layers was studied and compared with the bare Si surfaces as a reference. The reflection of the light from the surface of c-Si solar cell reduced by using these techniques and this leaded to higher cell performance.

Finally, a comprehensive simulation summary has been reported with various parameters, in terms of electrical, and optical approaches using PC1D program. The actual production for some of the parameters would be possible with the developed new devices and materials.

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