Investigation of light trapping mechanism of Silicon solar cell performance utilizing Silvaco TCAD

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Abstract. In this project, an investigation on the effect of difference shapes of the top surface silicon (Si) solar cell as an antireflective (AR) layer was carried out. Texturing the top surface of silicon solar cell helps to reduce light reflection from the solar cell. The different surface texturing which is planar structure, columnar structure and pyramid structure was created and simulated using Athena process simulator by SILVACO TCAD tools. The structures were then loaded into ATLAS device simulator to extract the electrical performance parameters of the solar cell. The results showed that the planar, pyramid and columnar structures of the Si solar cells exhibited efficiency of 2.04%, 2.18% and 2.39% respectively. The short circuit current, Isc, open circuit voltage, Voc and the maximum power, Pmax for the columnar structures are 2.35444 nA, 0.366605 V and 0.630363 nW respectively. The columnar structures exhibited better performances compared to the other structures indicating the columnar structure is good in trapping the light and efficiently collecting the current carrier at the electrode.

1. Introduction

Solar cell converts solar energy to electrical energy. Silicon-based solar cell is among the most used solar cell in industry. Solar cell needs to absorb huge amount of the energy from the sun for efficient photon conversion. Normally, plane and rougher surface produce different amount of electricity due to their different surface morphologies. The main obstacle in having high efficiency of the Si solar cell performance is the amount of reflection from the top surface [1,2]. One of the techniques to prevent the light reflection is by texturing the top surface. By surface texturization, it can help to trap more sunlight. Texturization process is the ability to gain the path length of the light through the active absorbing surface layer [3].

Light reflection happen on types of surfaces between two mediums that have distinct refraction indices. It is occur when two refraction indices are nearer, reflected light will be lesser [4]. Nonetheless, silicon solar cell has low conversion efficiency. This is because silicon has refractive index of 3.5 which indicate that it can rise up approximately to 35% reflection of light. Material of refractive index has link with reflection. This hinders the optimum of electron-hole from being generated [5, 6].

There are several techniques for improving light trapping in silicon solar cell. Among them are using anti-reflecting coating (ARC) layer and surface texturing (also as antireflective layer). The existence of new coating layer can enhance the performance and efficiency of the solar cell. According to A. Lennie et.al, addition of double layer anti-reflecting coating of silicon dioxide (SiO₂) and silicon nitrate (Si₃N₄), the efficiency can increase to 37.76% with average fill factor of 0.76 from bulk Si solar cell [7]. Surface texturing can be done through many techniques. Among the methods are implantation, wet and dry
etching but the most popular is anisotropic wet etching [3].

F. Jahanshah et.al reported that implantation during fabrication process affected the solar cell conversion efficiency, this is because the p-n junction depends on the annealing temperature [8]. By changing the period of the annealing, the depth of groove would affect the efficiency. For industrial solar cell texturing, the standard process is by using wet etching of alkaline solution [1]. In this work, Technology Computer Aided Design (TCAD) tool that capable for simulating the fabrication and characteristic of the semiconductor device, SILVACO software [9] was utilized to investigate effect of surface texturing of the Silicon solar cell. The objective is to obtain the different shape of top surfaces silicon solar cell and analyse their structural and electrical performances for optimum efficiency.

2. Methodology

In this work, SILVACO TCAD software which consist of ATHENA Process and ATLAS Device simulator tools was used to fabricate the textured silicon solar cell. The simulation was carried out to find the optimum texturing size and shapes which can be reference for future fabrication. According to A. Lennie et.al, ATHENA provided simulation modules with user-friendly environment and it has ability to produce a 2D structure and cross section for 1D structure [8]. While, ATLAS tools help to simulate and extract the performance data from the current-voltage (I-V) characteristic, spectral response (SR), maximum power (P\text{max}), fill factor (FF), open circuit voltage (V\text{o}c), short circuit current (I\text{sc}) and efficiency ($\eta$) of the solar cell.

There were three structures created which are planar, pyramid and columnar structure. The three structures were created by using ATHENA process simulation tools. Etching process command was used to texture the top surface of the silicon solar cell [9]. To view the planar, pyramid and columnar structures created in Athena, TONYPLOT tools were used. After the structures were created and viewed, ATLAS device simulation tools were used to bias the solar cell and extract the solar cell performance data. The extracted data of each structure was compared and analysed. Figure 1 shows the flowchart summarizing the project flow showing the Athena process simulation and the ATLAS device simulation. Solar cell created was in the form of a n-p junction.

![Figure 1. Process of creating solar cell and device simulation.](image-url)
In the Athena process fabrication, firstly, the area of the project was set at 10µm width × 10µm length respectively. Mesh definition was set for the region created for better accuracy of the simulation. The fine mesh was defined at the active area region of the solar cell. Next, the silicon wafer of p-type (100) orientation was initialized as the substrate. The p-type region was doped with boron dose of $1 \times 10^{14}$ cm$^{-3}$. After that, the n-type layer was formed by implanting phosphorus of $1 \times 10^{17}$ cm$^{-3}$. The n-type dopant was then drive-in at 900°C for 300 minutes to drive the dopant deeper into the junction. For the textured surface, the location of x-axis and y-axis point was set to etch the region to form the pyramid and columnar structures as illustrated in Figure 1. The thickness of the textured surface was 0.5µm depth and 1µm width. The planar structure remained as bulk silicon. After the creation of the three structures were completed, contact were deposited at the bottom and top of the silicon solar cell. Both metal contacts were using aluminium. The top contact was set as cathode electrode while for the bottom contact was set as anode electrode. Figure 2 shows three structures of the silicon solar cell created using ATHENA tool.

![Figure 2. Three different structures a) planar b) pyramid and c) columnar shapes.](image)

The three structures constructed in ATHENA were then loaded to ATLAS device simulator tools. In ATLAS there are four main sections need to be defined such as the specification of structures, materials models used, selection of numerical method, solution specification setting and analysis of the result. Table 1 summarizes the function used in ATLAS tool. The electrical parameters simulated in
ATLAS are I-V characteristic and spectral response. Figure 3 shows the statement for solution specification to bias the device and get the I-V characteristics.

| COMMAND | FUNCTION |
|---------|----------|
| Doping, Region, Electrode and Mesh | Specification of Structures |
| Interface, Models, Contact and Material Method | Specification of Material Models |
| Save, Load, Log and Solve | Selection of Numerical Method |
| TONYPLOT and extract | Specification of Solution |

Table 1. The statement used in the ATLAS tool [10].

```plaintext
models conmob fldmob consrh
solve init
solve b1 =0
log outfile=darki-vplanar.log
solve vcathode=-0.01 vstep=-0.01
vfinal=-1*$open_circuit_voltage name=cathode
log off
solve init
solve b1=1
log outfile=lighti-vplanar.log
solve vcathode=-0.01 vstep=-0.01 vfinal=-1*$open_circuit_voltage name=cathode b1=1
log off
tonyplot darki-vplanar.log
tonyplot lighti-vplanar.log
```

Figure 3. Commands to bias the solar cell for its I-V Characteristics.

The performance parameters for the silicon solar cell constructed were extracted by the ATLAS tool. The plotted data for device performances (I-V and spectral response) graphs in Tonyplot were then exported and replotted using OriginPro 8.5 software.

3. Result and Discussion

Figure 4 shows the images of the silicon solar cell structures that were created in ATHENA Process simulation. The contour images show the distribution of the net doping concentration in the structures. The resultant junction depth after the drive-in process was 1.06386µm extracted by the ATLAS tool. The depth was similar for all the structures. Figure 5 shows the spectral response curve of the three structures. The spectral response is a measure of the ratio of current generated by the silicon solar cell to the incident power. At the visible spectrum, the three structures of silicon solar cell exhibited response at the wavelength of 400nm to 1000nm [9]. The three structures showed peak values at the same wavelength of 650nm with generated current of 3.3 to 3.8 x 10^8 A respectively. This indicated the response of the devices towards the broad visible spectrum.
Figure 4. a) Planar Structure, b) Pyramid and c) Columnar structures with net doping contour.

Figure 5. Spectral response for the three structures.
Figure 6a and Figure 6b shows graph of internal quantum efficiency (IQE) and External quantum efficiency (EQE). EQE is referring to the efficiency of the cell which include the optical loss experienced by the cell such as from transmission and reflection. While IQE is referring to the efficiency where photon which are not reflected or transmitted out of the cell can generate collectable carriers [10]. For the IQE and EQE, the cell starts to respond indicating by the increase of the peak intensity at the range of 300nm to 650nm wavelength. After 650nm the peak starts to decrease until 1000nm. The columnar solar cell has the highest peak intensity than pyramid and planar solar cell. Theoretically, IQE must be higher than EQE to indicate the good absorption of photon at the active layer of the solar cell. Specifically, the columnar structure showed the higher peak value of 0.9 for IQE at 600nm whereby pyramid and planar contributed to 0.86 and 0.85 peak values respectively. While, for EQE, again the columnar structure exhibited the highest peak value of 0.78 at 600 nm wavelength than the two others structures of pyramid with 0.7 and planar with 0.68 peak values.

![Graph of Internal Quantum Efficiency](image1)

![Graph of External Quantum Efficiency](image2)

**Figure 6.** a) Internal quantum efficiency and b) External quantum efficiency for planar, Columnar and pyramid structures.

Figure 7a shows the I-V graph consisting of the light current and the dark currents for the three devices. The light currents were obtained after the exposure of light at the top surface of the cell device while the dark currents were measured when no light is exposed.

The dark currents rely on the superposition principle used in solar cell analysis. Specifically, the columnar structures has the highest light current than other two structures. The highest generating current produced was 2.35444 x 10^{-9} A for columnar solar cell whereby 2.14504 x 10^{-9}A and 2.03596 x 10^{-9}A for pyramid and planar structures respectively. Figure 7b shows the maximum power curve for the three structures. The maximum power, Pmax can be calculated by the equation below:

\[
P_{\text{max}} = FF \times I_{\text{sc}} \times V_{\text{oc}}
\]

whereby \(FF\) is fill factor, \(I_{\text{sc}}\) is short circuit current and \(V_{\text{oc}}\) is open circuit voltage which can be extracted from the I-V curve of the devices. The highest value of maximum power of 6.30363 x 10^{-10}W is obtained by the columnar structure. While pyramid and planar structures exhibited the maximum power value of 5.73109 x 10^{-10}W and 5.36498 x 10^{-10}W respectively.
Figure 7. a) Light and Dark Current- voltage characteristics and b) Maximum power of columnar, pyramid and planar structures.

Table 2 shows tabulated extracted solar cells performance parameters for the three structures. Columnar has the highest $I_{sc}$ of 2.35444nA, while pyramid and planar structures produced 2.14504nA and 2.03596nA respectively. Similarly for the $V_{oc}$, the columnar structure exhibited the highest $V_{oc}$ value than other two structures. The fill factor for the columnar is 0.730306, pyramid is 0.364423 and planar is 0.72635.

Table 2. Tabulated results of columnar, pyramid and planar structures.

| Parameters / Silicon solar cell | Simulated results | Experimental data by [1] |
|---------------------------------|-------------------|-------------------------|
|                                 | Isc (A)           | Voc (V)                 | Pmax (W)           | Fill Factor (FF) | Efficiency, $\eta$ (%) |
| Planar                          | 2.03596nA         | 0.362788                | 0.536498nA         | 0.72635          | 2.03827                |
| Pyramid                         | 2.14504nA         | 0.364423                | 0.573109nA         | 0.733155         | 2.17737                |
| Columnar                        | 2.354444nA        | 0.366605                | 0.630363nA         | 0.730306         | 2.39489                |
| As-grown Si                     | 14.55m            | 0.37                    | 3.71m              | 0.6887           | 3.70                   |
| PS layer                        | 28.81m            | 0.57                    | 13.23m             | 0.8059           | 13.23                  |
| Pyramid texturing               | 27.70m            | 0.53                    | 11.37m             | 0.7743           | 11.36                  |

The simulated data in this work were compared to the experimental data by Khaldun et al [1]. It is showed that the simulation results exhibited similar trend to the fabricated work by [1] whereby the columnar structure produces the best response to the light exposure. The lower values of efficiency in the simulation result probably due to the simulation was carried out at 2D and the textured surface was not optimized. The results showed that the pyramid texturing have higher reflection than porous surface or columnar surface [1]. According to Zamir et al, in real fabrication of solar cell, the pyramid structure are not the best one squared based tetrahedrons according to its base angle of 54.74°. This is because of the industry mostly processes in between 49° and 53°[11]. Figure 8 illustrated the texture surface of pyramid shape and plane substrate that may cause the light reflection back to surrounding due to the angle. Major factor for achieving higher efficiency of silicon solar cell is by reducing optical losses in the solar cell and one of the key features is by improving its absorption properties [12].
Figure 8. Illustration of the photon reflection at the pyramid structure and the flat surface.

4. Conclusion
In this work, the effect of different shapes (planar, columnar and pyramid structures) of the top surface silicon solar cell as an anti-reflective layer were investigated. The ATHENA and ATLAS tool of SILVACO TCAD was successful been utilized to obtain the three different structures and their device performances. The electrical performances of the silicon solar cell with the different surfaces texturing were analysed and compared. It is shown that the columnar textured surface of the silicon solar cell produces better solar cell performances than the pyramid and planar shapes. Columnar structure clearly reduces the light reflection and has the best performance of the silicon solar cell with efficiency of 2.39489% whereby pyramid and planar was 2.17737% and 2.03827% respectively.

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