Photo-generation profiles in deeply-etched, two-dimensional patterns in interdigitated back contact solar cells

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Interdigitated back contact (IBC) crystalline silicon solar cell model has been developed by using SILVACO in order to achieve design optimization in non-conventional device configurations. The SILVACO software was employed to evaluate performance of IBC solar cell as a function of texture while keeping identical semiconductor process parameters including doping of emitter, BSF and FSF. Based on the period of the pyramidal texturing, the textured surface can be distributed uniformly throughout the solar cell as exhibited by the 40-μm period pattern for which the incident is uniformly and deeply penetrated inside the IBC solar cell. Therefore, efficiency of the IBC solar cell is boosted to 23.31% in comparison with 22.36% from planar IBC solar cell. The photo-generation profile for planar surface is not uniformly and deeply distributed throughout the IBC solar cell but for P40D20 the distribution of incident photons well distributed and penetrates deeper into IBC solar cell which leads to improved IBC solar cell performance. For IBC solar cells with periods larger than 40 μm, performance is degraded due to formation of shadows within the solar cell located at grooves of pyramid. These shadows effectively reduce number of photons and therefore degrade solar cell performance. Hence, the texturization process can boost solar cell performance only if appropriate parameters are chosen otherwise reduced performance can result due to enhanced shadow effects inside the solar cell even though the front surface has no metallic contacts to physically block light.

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1. Introduction

Photogeneration referes to a process in which a photon incident on the surface of a semiconductor, in this case silicon wafer in solar cell configuration, is absorbed by the semiconductor as it passes through it in a straight line determined by internal scattering conditions. The photon is absorbed its energy (E_p) is equal or greater than bandgap energy of silicon. When a photon absorption takes place, an electron-hole pair is generated. The free electron from the electron-hole pair results in a flow of current through the cell when the load is applied. Electron-hole pairs must be seperated in order to ensure that photogenerated current flows through the external circuit. When the front surface of the silicon is planar, surface reflection is higher such that a significant percentage of incident photons are lost due to reflection back to the air. Therefore, in order to minimise reflection losses, planar surface is subjected to texturization either in random or periodic pattern.

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Surface texturing plays a critical role in IBC or conventional solar cells as it improves the efficiency efficiency of the cell through reduced reflection and enhanced internal scattering. Random texturing on (100) orientation Si wafers is carried out by etching in a mixture of potassium hydroxide, KOH and 2-propanaol isopropyl alcohol (IPA) solution [1]. Specifically-designed textured surfaces boost the solar cell performance through lower reflectance, enhanced light trapping, and increased short circuit current [2]. Therefore, in crystalline Si solar cell, surface texturing plays a crucial role in enhancing performance by increasing absorption [3]. In addition, photo-carrier generation is maximized when solar cell surface is appropriately textured.

Internal scattering of light after transmission into the solar cell is important as it influences the electron-hole pair generation. The pyramidal textured is preferred since it increases the optical path length of light which increases the probability of photo-generation. Light management is controlled by nature of the textured silicon surface to facilitate light trapping and anti-reflection characteristics [4-6]. Photogeneration in the solar cell illustrates the flow of photogenerated charge carriers. There have been very few studies of photogeneration profiles inside textured IBC solar cells.

Hence, his study focuses on the variation of photo-generation profiles as a function of texturization processes. For all computational work reported here, SILVACO software has been employed. In essence, this paper describes the internal scattering of the transmitted light inside an IBC silicon solar cell.

2. Simulation by SILVACO

SILVACO simulation parameters used for computational work have been summarized in Table 1. Figure 1 schematically describes the SILVACO TCAD software simulation processes for the IBC silicon solar cell. For solar cell simulations, SILVACO software uses TCAD tools known as Athena and Atlas. Athena is a fabrication process tool for physical solar cell construction in in 2D or 3D configurations. All the semiconductor process parameters including deposition, patterning, oxidation, diffusion, ion implantation, and etching ara available in Athena.

All of the simulation of electrical, optical and thermal responses of the IBC solar cell, synthesized from the Athena model, are facilitated by Atlas. Atlas displays results in form of graphical plots such as photogeneration, doping profile, IV curve, and electric potentials.

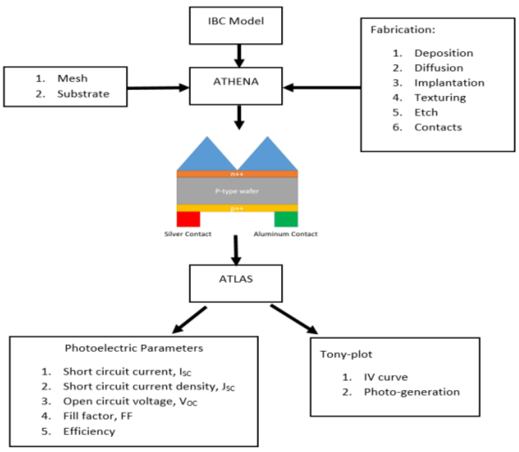


Fig. 1. SILVACO TCAD modelling process for IBC silicon solar cell.

Fig. 2 illustrates the configuration of the IBC silicon solar cell chosen for the SILVACO software to generate and evaluate the photoelectrical performance. This configuration was created with Athena and evalated by Atlas. The period (P) refers to the unit distance between two pyramids either from peak to peak or groove to groove. The depth (D) of the pyramid is measured from peak to peak or groove to groove of the pyramidal. The depth (D) of the pyramid is determined from base of pyramidal to the peak.

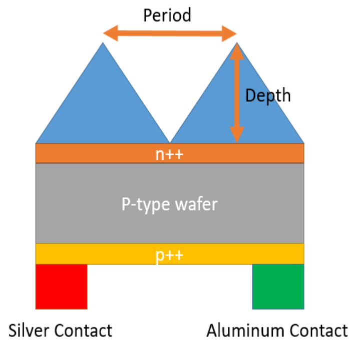


Fig. 2. Configuration of IBC silicon solar cell.

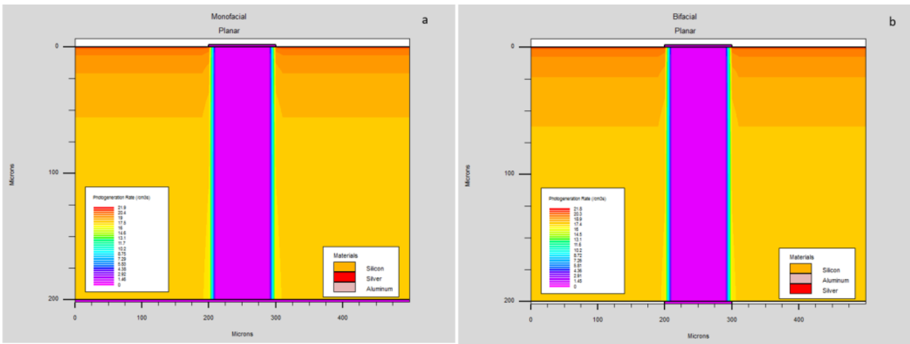
Table 1. IBC silicon solar cell parameter model.

IBC Parameter	Value	and
	unit	
Wafer	Silicon p-type	
Wafer doped	Boron	
Pitch size	500 μm	
Resistivity	2 Ω-cm	
Doping material	Phosphorous	
Front surface field	Phosphorous	
Back surface doping	Boron	
Band gap	1.124 eV	
Emitter doping concentration	1x 10^{18} cm^{-3}	
FSF doping concentration	1x 10^{18} cm^{-3}	
BSF doping concentration	$1x10^{18}$ cm^{-3}	
Diffusion time	20 min	
Diffusion temperature	900°C	
Textured period (P)	20-100 μm	
Textured depth (D)	20 μm	
Minority carrier lifetime	1000 μs	
Front surface recombination	1000 cm/s	
Rear surface recombination	1000 cm/s	

3. Simulation results and discussion

Photogeneration plots from the SILVACO were generated from the Tony-plot which represents the photogenerated charge carriers within the solar cell. Fig. 3 plots the photogeneration inside monofacial (Fig. 3-a) and bifacial (Fig. 3-b) silicon solar cells based on design and simulation programs in SILVACO. The yellow in the Fig. 3 manifest the intensity of photogenerated charge carriers inside the IBC silicon solar cell. The intensity of photogenerated charge carriers is varied by the incident photon intensity penetrate inside the solar cell. The straight purple band extending from front surface to the rear side of the solar cell represents the shadow effect from the contact. Shadow effect reduces solar cell performance due to loss of sunlight.

Shadowing losses on screen-printed front contacts are estimated in 8 to 10% range which are relatively large [7]. Therefore, smaller front contact grid design can reduce shadow losses if it can maintain low series resistance [8]. Shadow losses are eliminated in IBC solar cells by formation of both positive and negative contacts on the rear side [9]. Hence, this method came to be known as back contact solar cell. The interdigitated back contact (IBC) represents the highest efficiency solar cell without shadow loses as shown in Fig. 4(a).



(a) *(b)*

Fig. 3. Photo-generation in (a) monofacial and (b) bifacial silicon solar cell.

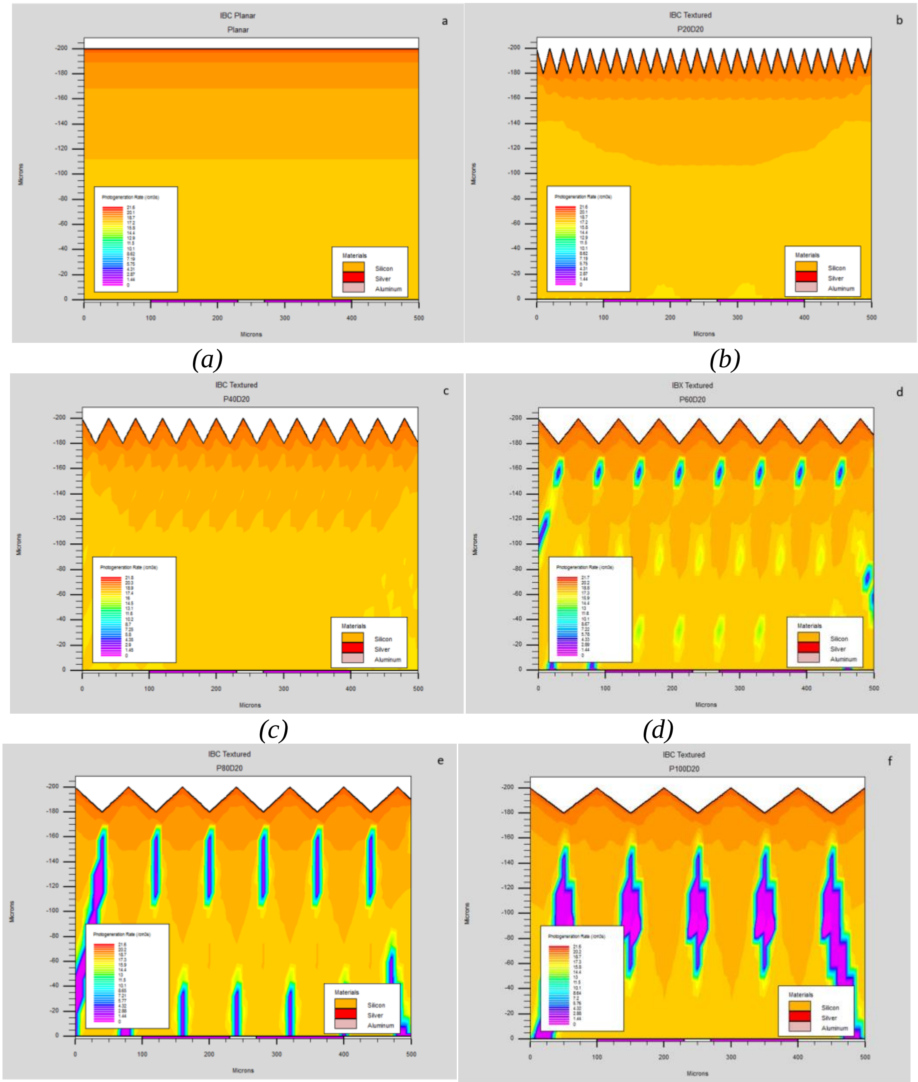
Fig. 4 plots distribution of photo-generation rates inside (a) planar, (b) P20D20, (c) P40D20, (d) P60D20, (e) P80D20, and (f) P100D20 IBC solar cells. These period and depth was explained as shown in fig. 2. From the simulation results, the distribution of photo-generation profiles inside the planar surface solar cell remain close to the top of the solar cell. This means that less solar radiation is extracted at the rear solar cell which leads to reduced performance in comparison with textured IBC solar cell.

Photogeneration profiles of the P20D20 structure in Fig. 4 (b) shows less photogenerated carrier profile penetration deep into the solar cell in comparison with the planar surface. As a result, lesser number of photogenerated charge carriers are collected by the rear contacts. Photogenerated charge carriers for P20D20 configurations between -140 and -110 μm are not uniformly distributed throughout solar cell in comparison with planar surface. Therefore, for this configuration, IBC solar cell performance response would be lower than the planar cell.

In contrast, P60D20, P80D20 and P100D20 configurations exhibit patterns of photogenerated charge carriers extending deep inside the IBC solar cell. However, there are purple regions within the solar cell that result in performance poorer than P40D20. These purple regions illustrate shadow effects within the volume of the solar cell. All these shadow regions inside the solar cell are created at groove of the pyramid. Therefore, P80D20 and P100D20 exhibit far denser shadows inside the solar cell.

Therefore, P40D20 promotes far more extensive photogenerated charge carriers than P60D20, P80D20 and P100D20 because of the lack of shadow effect inside the solar cell. The photogenerated charge carriers for P40D20 is higher than P20D20. Consequently, this results in higher short circuit current density, J_{SC} for P40D20 than P20D20 as shown in Table 2.

The distribution of photogenerated on P100D20 shows deeper than other textured IBC solar cell. Nevertheless, the performance of the solar cell is far poorer than P40D20, P60D20 and P80D20. This is due to the fact that there are larger shadow areas in P100D20 than other textured IBC silicon solar cell. As the period of the pyramid is increased, the textured pyramid structure will be expanded throughout the solar cell which will produce lesser pyramidal textured on the surface of the IBC solar cell.



(a) (b) (c) (d) (e) (f)

Fig. 4. Photo-generation profiles inside IBC silicon solar cell for (a)planar and (b-f) textured configurations.

Table 2 details percentage improvement of photo-generation rates with textured surfaces with respect to planar IBC silicon solar cell. P20D20 exhibits less performance than planar which is -4.91% of the improvement of Jsc based on planar. This is due to reduced photogenerated charge carrier penetration through the solar cell than planar surface (Fig. 4-a). P40D20 exhibits the short circuit current density (J_{SC}) of all other types of textured IBC silicon solar cells. The percentage J_{SC} improvement based on the ratio of textured to planar shows small increments with respect to planar IBC solar cell. As the size of pyramidal texturing increased, the efficiency and *Jsc* are reduced. This is because of the surface area of the solar cell is effectively reduced and lesser amount of incident solar radiation is trapped by pyramid as its width increases.

Table. 2. Photo-electric performance of IBC silicon solar cell from SILVACO.

IBC Silicon Solar Cell	V_{oc} (V)	J_{SC} (mA/cm^2)	% J_{SC} Improvement Textured/Planar	Efficiency (%)
Planar	0.7239	38.52	-	22.36
P20D20	0.7235	36.63	-4.91	21.26
P40D20	0.7267	39.95	3.71	23.31
P60D20	0.7266	39.84	3.43	23.23
P80D20	0.7264	39.74	3.17	23.17
P100D20	0.7261	39.34	0.02	22.93

Fig. 5 plots current-voltage (I-V) responses extracted from the SILVACO for planar and textured surfaces of IBC solar cell. The I-V plots illustrate that the planar surface IBC silicon solar cell is superior than P20D20. P40D20 structure results in the highest value of J_{SC}. Short circuit current density, J_{SC}, performance integrates the number of photons, spectrum of the incident light, optical properties, and the collection probability of the IBC silicon solar cell, all of which impact the output of solar cell. Optical improvement on solar cell by texturization with low reflectance which will enhance the photo-current generation that will contribute to increased J_{SC} [10].

Diffusion to create the emitter (p-n junction) is maybe the most significant stride in solar cell manufacturing [12]. Depend on experimental operation parameters like temperature, time, gas flow rate, structure, emitter doping concentration can be changed over a broad range. Thus, it is essential to appreciate its impact on efficiency. For simulations, the n-layer doping concentration was changed over six orders of magnitude from 5×10^{16} to 1×10^{22} cm^{-3}; these values are fine within empirically obtainable values.

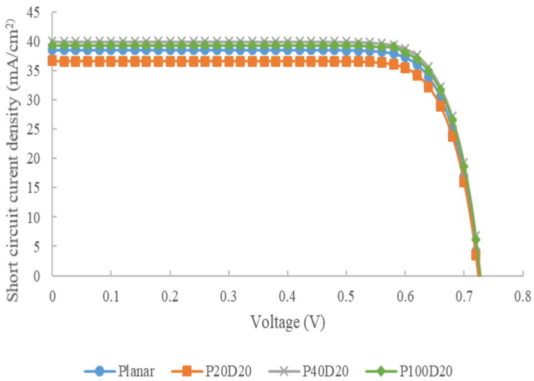


Fig. 4. Simulation of I-V response of planar and textured configurations investigated in this study.

As plotted in Fig. 5 and summarized in Table 2, the *Jsc*, *Voc*, and efficiency for planar surface is significantly lower than textured IBC solar cell. This is because of higher reflection losses in planar surface in comparison with textured surfaces. The reflection losses result in lesser photons collected by solar cell at the rear contact. The textured surface of IBC solar cell maximize the absorption of solar radiation as the incident radiation is trapped through increased optical path lengths. Therefore, incident sunlight is more effecively utilized in pyramidal textured IBC solar cell which results in increasing the minority carrier density originating from the flow of the minority carriers.

4. Conclusions

Modelling of planar and textured IBC solar cells has been successfully developed by using SILVACO software. This paper focused on optimization of the surface texturing with two-dimensional structures appropriate for IBC solar cell. IBC solar cell with no shadowing losses is inherently superior than monofacial and bifacial solar cells. Therefore, optimized texturization on the front surface can lead to significant performance gains. The model demonstrates that output efficiency of the IBC cell decreases as the period of pyramidal texturing increases. The efficiency of the planar IBC solar cell is 22.36% while for textured surface, the highest efficiency observed is around 23.31%.

By looking at P40D20 performance, the texturization impact on the IBC solar cell as a function of the period can be understood. As the period of the pyramidal texturization increases beyond 40 μm shadow effects will create lightless places at pyramid groove locations. Therefore, solar cell effectively sees less sunlight and therefore generates less electron-hole pairs. Hence, the period of the pyramidal textured plays a major role in creating photogenerated charge carriers since it will either enhance o reduce photogeneration inside the solar cell. Depth and uniform distribution of photo-generation leads to larger number of charge carriers collected by the contacts at the rear side. In summary, texturing of IBC solar cell contributes to improvement of optical properties of the solar cell with specific periods and depths of textured surface.

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