Modeling of Bifacial Solar Cell on Partial Transparent Si Wafer by SILVACO Software

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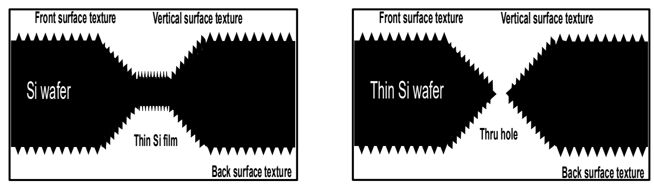
Abstract - Bifacial solar cells are future paradigm in increasing the energy yield of solar power due to ability of photon absorption from front and rear surface. The concern in this research is the amount of photon transmission to rear surface in order to enhance the bifacial solar cell efficiency. Partial transparent silicon wafer was proposed to drill hole array by using laser pulsed processing which allow photon transmission to rear side of Si wafer from front surface. In this simulation, phosphorus was doped into silicon (Si) wafer as selective emitter to produce npn junction. Current-Voltage (I-V) curve of bifacial solar cell on hole array Si wafer with phosphorus and boron emitter were simulated by using SILVACO Software. The pyramid texture on trench slope was form at the angle of 54.74º plane. The simulation was conducted in partially transparent Si wafer which thin Si film thickness was varied with the hole diameter of 45 µm. The efficiency obtained for the bifacial solar cell having 5 µm to 10 µm thickness were 18.4%-18.6%, and efficiency decrease to 8% when thin Si film is 2 µm and through-hole.

Keywords – Bifacial solar cell, Silvaco, simulation, transparency, current-voltage

I. INTRODUCTION

Bifacial solar cell is ideal future module in solar cell fabrication due to ability of this cell in increasing the capacity of energy yield through rear surface compared to conventional monofacial module[1]. The main objective in this research to determine ability of photon absorption through thin Si film in order to boost the bifacial solar cell efficiency. Backside irradiance are strongly non-uniform due to upper and lower cells do not receive the same amount of radiation[3]. Partially transparent Si wafer is proposed to increase the ability of backside irradiance. Laser pulsed processing is conducted to drill hole array to allow photon transmission to the rear side[4]. This process able to change morphology of the texturing wafer due to molten deposition[5] on the sidewall which can be etched to produce thin Si film (Fig 1A) and through hole (Fig 1B).



(A) (B)

Fig 1: Pulsed laser processing conducted producing thin film (A) which allow light transmission to rear surface, and in the extreme case, though hole can be produce through high ns-regime or etching by using alkaline solution on laser area. Through hole allow 100% light transmission.

According to Shockley and Quaisser, the theoretical efficiency limit of single junction silicon solar cell is about 33.7%[6] but commercial Si solar cells which are mainly screen printed reduce the efficiency between 14% to 17%[7]. This mechanism reduces due to intrinsic losses of Si material bandgap. Higher energy photons are converted to into lattice vibration (phonons), while lower energy photons, below the bandgap unable to generate electron-hole pair[8]. Therefore, hole array produced by laser process allow lower energy photon to react and filled the electron-hole pair on rear surface. In order to reduce the bandgap, the wafer thickness has been reduced to 200 µm from 630 µm and the thickness after etching is 160 µm[9]. By reducing the thickness, current-voltage *(I-V*) curve as well as efficiency will be improved. However, the thinner Si wafer may associate crack during wet-chemical process, mismatch expansion during high temperature diffusion and screen printed rapid thermal annealing[10][11].

Performance simulation and energy yield commonly can be calculated directly through commercial photovoltaic (PV) software, however the modeling of bifacial solar cell is quite challenging due to variable illumination conditions on front and rear surface which depend on different parameters, such as percentage of diffuse radiation in the solar spectrum, ground reflectance, module elevation angle, orientation and tilt angle[12]. In order to study the performance of bifacial solar cell on partial transparent Si wafer, the numerical study on bifacial cell is performed using TCAD Silvaco software. The basic parameters of the modeling focusing on thickness, doping concentration, the relation with photovoltaic parameters and external quantum efficiency which investigated comprehensively[13]. TCAD Silvaco software provides 2D and 3D simulation of semiconductor devices using two-simulation modules which are Athena (process simulation and structure)[14] and Atlas (electrical characteristics)[15]. The simulation is widely used to characterize the *I-V* characteristics of solar cell by the using of two currents that produce in the open-circuit voltage (V_{oc}).

$$V_{oc} = V_t \ln\left(1 + \frac{I_L}{I_S}\right) \tag{1}$$

Where I_S is reverse saturation current, while V_t is thermal voltage.

The output current and output voltage produce *I-V* curve and its describe the energy conversion in existing of irradiance and temperature. The *I-V* curve range is span from maximum possible current, where the short-circuit current, I_{sc} at zero volts while the open-circuit voltage, V_{oc} at zero current[16]. Fig 2 shows the I-*V* curve for solar cell where the output power can be calculated by the intersection of the characteristics of the solar cell with the respective area based on equation (2).

$$P = VI \tag{2}$$

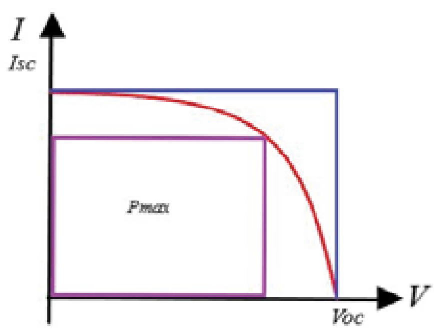


Fig 2: Maximum power rectangle (P_{max}) is shows in *I-V* curve for solar cell[17].

The knee of the curve called as maximum output power point, P_{max} which corresponding with maximum current, I_{max} and maximum voltage, V_{max}. This two values will form rectangle under the curve.

Next indication that able to examine by using *I-V* curve is fill factor, FF which is essentially quality measurement of the solar cell. It can be defining as the ratio of P_{max} from the solar cell to the multiplication of V_{oc} and I_{sc}[18]. The FF is given in equation (3).

$$FF = \frac{P_{max}}{V_{oc} I_{sc}} \tag{3}$$

Nowadays, typical FF value for market solar cells are ranged between 0.70 to 0.85 depending on the material and structure of the cell[16].

In this paper, the bifacial solar cell structure of n^+pp^+ was developed by SILAVACO with a modification on the Si wafer, which is partial transparent Si wafer that made from drill process. Electrical simulation on bifacial solar cell designed by Athena and data provided presented by Atlas. The simulated graphical results and performance output data was investigated as comparative study between different thickness of Si thin film after drilling process. The influence of the thickness will effect doping concentration. Besides of performance and energy yield, this paper performs shunts study in order to examine the ability of laser in improving the performance in shunted region[19]. Shunt resistance[20] able to be determined from dark *I-V* curve with an average bifaciality of used cell (η_{rear}/η_{front}) was 80%[21]. The saturation current density, J_0 is determined through metallization diffusion on cell as it is directly contact with phosphorus emitter[22]. The J_0 can be calculated using this equation;

$$ln\frac{J_{sc}}{J_0} = \frac{qV_{oc}}{kT} - 1 \tag{4}$$

where k is the Boltzmann's contant, q is the electronic charge and T is the absolute temperature in Kelvin[23]

II. MODELING METHOD

A. Device Structure and Input Parameter in Athena

In Athena, bifacial solar cell was simulated with configuration of 200 µm × 200 µm in *x* and *y*. The p-type Si wafer with the crystallographic orientation wafer of <100> was used and the impurity boron was set at 2×10^{16} cm^{-3}[13]. The vertical thickness resolution (y_{max}) was set at 95µm. The size of the pyramid was developed by 10µm width with 5µm height for front and rear surface. In order to create active zone, n+ and p+ solar cell emitter, ion implantation with phosphorus and boron concentration of 1.0×10^{17} and an energy of 30 keV were used. It was then followed by diffusion that was set at 20 minutes for 900ºC. In accordance with this study, hole drilling (Fig 3) was simulated by creating a trench with hollow deep that began with 85 µm, 90 µm and 93 µm. The wall of the trench was creating uneven pyramid structure due to uneven topography after drilling process. Subtraction between y_{max} and trench deep produce thickness of Si thin film on hole drilling which were 10 µm, 5 µm and 2 µm. The different value of thin Si film thickness shows the rate of wafer transparency. The maximum thickness will simulate at 100 µm with minimum thickness is 0 µm which means through-hole structure. The pyramid structure on trench slope is formed on 54.74^{o} plane.

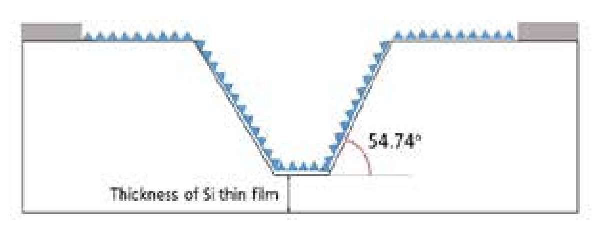


Fig 3: The pyramid structure is formed on wafer surface and trench slope at 54.74^{o} with a variation of Si thin film thickness after drilling.

The anode and cathode simulation contact was executed by deposition of 5µm thick aluminum layer on the backside of Si wafer and etching operation was necessary to remove excess aluminum in order to reduce the thickness to 2 µm.

B. Model and Input Parameters in Atlas

In Atlas, the simulation program was specified to develop the device structure of bifacial solar cell on partial transparent Si wafer. All the materials that been used in the model development such as silicon, phosphorus, boron and aluminum were defined by default in Atlas database. Both anode and cathode modeled as Schottky contacts that was depend of the mobility of charge carriers on the doping concentration and on the electric field)[24]. Shockley-Read-Hall recombination model (SRH)[25] lifetime of the electrons, taunΘ and taupΘ were set at 10^{-3}. The interface recombination model velocities assumed for electrons (s.n) and holes (s.p) were set respectively at 10 cm/s. The illumination of bifacial solar cell by the solar spectrum at AM 1.5 with beam number was set 1. Next, the X-origin and Y-origin were defined the initial point at 1500 and -201 with beam angle at 90^{o}. In solving the parameter, the voltage anode, final voltage and voltage step were set at 0V, 0.8V and 0.1V. Electrical simulation was started with zero bias on all electrodes (thermal equilibrium state). When the thermal equilibrium stated examined in this simulation, it initialized the light and polarized state by graphical interface in TONYPLOT and by extraction of numerical values EXTRACT in Atlas.

In this paper, five different model of bifacial solar cell of partial transparent Si wafer were developed with different thicknesses of thin Si film that indicated different rate of wafer transparency. The thin Si film can be referred at Fig 1A. The cells were A (100 µm), B (10 µm), C (5 µm), D (2 µm) and E with 0 µm that indicated through holes Si wafer. The device performance was investigated photon absorption on the different wafer transparency.

III. RESULTS AND DISCUSSION

The results in Fig 3 show the simulated current-voltage (*I-V*) t of different thickness for Si thin film of 100 µm (A), 10 µm (B), 5 µm (C), 2 µm (D) and through-holes or 0 µm (E). The different value of Si thin film thickness shows the rate of wafer transparency. Output of bifacial solar cell model on partial transparent Si wafer shows that front and rear surface demonstrated the identical outcomes. The V_{oc} values for A was 0.737V, Voc values for B and C was 0.738V while D and E have been 0.719V. The short-current densities (J_{sc}) were 33.11 mA/cm^2, 31.31 mA/cm^2 and 31.16 mA/cm^2 for A, B and C. Meanwhile for D and E, J_{sc} was dropped to 13.87 mA/cm^2 and 13.58 mA/cm^2. These values were shown in Table 1.

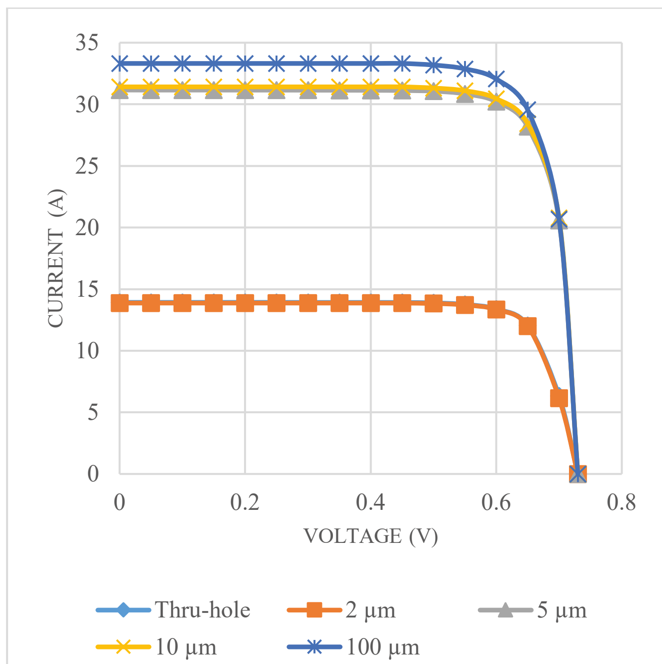


Fig 3: Simulated I-V curves for bifacial solar cell on partially transparent with different thickness of Si thin film for the transparency (100 µm, 10 µm, 5 µm, 2 µm and through-hole, 0 µm).

TABLE 1: Simulated outcome of partially transparent bifacial solar cell with different thickness of Si thin film for the

transparency (100 µm, 10 µm, 5 µm, 2 µm and through-hole, 0 µm).

Bifacial Solar Cell	Thickness (µm)	V_{oc} (V)	J_{sc} (mA/cm^2)	FF	Eff (%)
A	100	0.737	33.11	0.797	19.48
B	10	0.738	31.31	0.803	18.61
C	5	0.738	31.16	0.803	18.46
D	2	0.719	13.87	0.809	8.07
E	0	0.719	13.58	0.807	8.09

Saturation current density, J_o was calculated using (4). From the calculation, J_0 obtained was 10^{-10} A/cm^2 to 10^{-13} A/cm^2 which higher than optimum value of 10^{-14} A/cm^2. P_{max} was calculated based on (2), where rectangle under the curve corresponding between I_{max} and V_{max} in Fig 3. It is commonly able to determine the largest area rectangle under the knee curve, the higher the P_{max} value produce for a cell. Cell A with Si thin film of 100 µm for transparency produced higher power with 19.214V, while D and E produces 7.8033V, respectively. The calculated values of J_0 and P_{max} were shown in Table 2.

TABLE 2: Saturation current density, J_o and power maximum, P_{max} for different thickness of Si thin film.

Bifacial Solar Cell	P_{max} (W)	J_o (A/cm^2)
A	19.214	3.74E-11
B	18.479	3.41E-11
C	18.324	3.39E-11
D	7.803	3.15E-11
E	7.803	3.08E-11

The simulated results of bifacial solar cell on partial transparent Si wafer gave an early prediction of the cell performance when the fabrication process performed. The partial transparent Si wafer will have demonstrated by laser-pulsed processing for drill hole array. The performance of cell output was attributed to many factors. The main factor was the ability of the cell to absorb more photons through hole array and distributed the photon to the rear surface. The efficiency in A which is 100 µm thin was the highest which is 19.48%. This is due to the absorption beam that distributes on constant pyramid structure. For B and C, which is thin Si film of 10 µm and 5 µm, the simulated efficiency obtained were 18.61% and 18.46%, which was slightly lower than A (100 µm). It is important to note that the B (10 µm) and C (5 µm) were more transparent from A (100 µm). But, fill factor (FF) for both B and C were higher than A. It shows that the quality of the cell with hole array was higher due to larger absorption area. The efficiency of D (2 µm) and E (0 µm) were 8.07% and 8.09% with FF higher than A, B and C. E was through-holes while D was the most transparent compared to A, B and C. The efficiency of D and E were low due to higher photon transmission; thus the photons escape to surrounding. However, but the FF of D and E shows the cell were able to absorb from rear surface.

The simulated V_{oc} shows good quality of Si silicon solar cell where the value obtained was0.7 V. These simulation results also indicate that the superior passivation and back surface field were needed in this fabricated bifacial solar cell on partial transparent Si wafer in order to have excellent output performance. This was proven by J_{sc} value that was attribute the good passivation quality of ARC layer for bifacial solar cell A, B and C. Poor passivation in D and E were most probably from the hole array that no does not well passivated.

CONCLUSION

The performance of bifacial solar cell on partial transparent Si wafer model simulation was investigated by using SILVACO Software. The bifacial solar cell with a thin Si film in range between of 5 to 10 µm shows an excellent result with an efficiency of 18.6%. The efficiency produced by 100 µm was 19.48%, however the efficiency simulated form 2 µm to through-holes Si wafer or 0µm thin was 8%. The cell A with 100 µm thin Si was less transparent compared to cell D and E. Therefore, this study performed a prediction on the cell performance during the fabrication of bifacial solar cell on partial transparent wafer. The investigation of try and error on the rate of wafer transparency can be eliminated by demonstrated this simulation study. Further investigation on the optimization wafer transmittance, fabricated device performance and the effect of reflector concentration towards rear surface to increase the backside efficiency will be performed.

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