

Effect of Intrinsic Layer Energy Gap and Thicknesses Optimization on the Efficiency of p-i-n Amorphous Silicon Solar Cell

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Abstract— Amorphous silicon solar cells with single p-i-n layer were grown on 10 cm² ITO coated glass substrates. Fabrication process done by using 13.56 MHz RF-Plasma Enhanced Chemical Vapor Deposition (PECVD). Hydrogen flow on the deposition process is widely known to enable the passivation of the dangling bond on Silicon bonds. The passivation of dangling bond affects the band gap of each layer and cell performance in the absorption of photon. In the deposition process of intrinsic layer, SiH₄ gas flow is set constant at 2.5 sccm, while variation is done in hydrogen gas flow at 0 sccm – 90 sccm. Energy gaps obtained for p-layer and n-layer are 2.0 eV and 2.2 eV at thickness 64 nm and 36 nm respectively. Optimizations have been done for intrinsic layer which band gaps are 1.4 eV, 1.6 eV and 1.9 eV at thickness 400 nm. The solar cell efficiency was increased from 4.8% to 5.64% based on the band gaps variety. In addition, i-layer thicknesses were also varied from 400 nm, 500 nm and 600 nm. Thicknesses variation shows an increase of 5.78% in the solar cell efficiency.

Keywords— Amorphous silicon solar cell, energy gap, efficiency, thicknesses.

I. INTRODUCTION

Research on renewable energy sources interests many scientists to prevent an increasing pollution due to the high consumption of fossil fuel nowadays. Lot of researches such as wind turbin, biofuel and nuclear reactor are being exposed in order to generate unlimited energy sources. A hydrogenated silicon solar cells is one of the topic that have been chosen on many researches because they are safe for environment, low cost production, able to be used as a power supply in area without electricity and promising a neverending energy resources in the future [1].

The frequent researches nowadays are about hydrogenated amorphous silicon solar cell (a-Si:H). They have been chosen because they can be fabricated on many types of substrate. The general fabrication process is using Plasma Enhanced Chemical Vapor Deposition (PECVD) which can easily run the hydrogenation and doping process on a thin film. By using PECVD, the deposition parameters are able to be tuned into very wide variations which may caused different optical and electronical characteristics on a-Si:H thin film. The fabrication method through PECVD device also widely used by large-scale industry because it can produce many solar cells to fullfill the industrial needs.

The deposition process by PECVD device has its own advantages [2]. These advantages include:

1. The ability to grow single layer with different parameters on a single deposition process.
2. There is no tendency of physical damage at the crystal during deposition time.

3. The process does not require special treatment after completed process such as removing excess dopant or lowering the temperature.
4. Deposition process is using lower temperature than other.

The crystalization growth parameter has many effects that can influence thicknesses and the quality of solar cell such as substrate temperature, pressure, gas flow rate, plasma power, and gas source. An optimization is required in order to achieve a single junction p-i-n amorphous silicon solar cell. One of the influencing factors is the layer thicknesses. It plays an important role by determining the energy band gap of a layer which will determine how much of the photon spectrum energy can be absorbed by the cell. Almost all radiations from sunlight spectrum has photon energy 1.4 eV ~ 2.0 eV that matches the energy gap of silicon as semiconductor material. Therefore, based on electron excitation theory, each layer of p-i-n solar cell should be optimized during the deposition process.

Characteristics of the deposited layers will affect the output performance of solar cell during the efficiency measurement, which is generally dependent on short circuit current density (J_{sc}), open circuit voltage (V_{oc}), and fill factor (FF). Beside of that, one layer that plays an important role in the absorption of photon energy in solar cell modules is the intrinsic layer (i-layer), where most of the photon energy will be absorbed and the process of electron-hole generation is starting.

In the previous research that has been done, fabrication of amorphous silicon solar cells with a single p-i-n junction has an average efficiency 2.7% by uncontrolled energy gap of each p-i-n layer [3]. In another optimization study, the optimum efficiency of microcrystalline silicon solar cells were increased from 9% to 12% by varying the energy gaps of p-i-n layers and its thicknesses [4]. In recent study, the

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different treatment of hydrogen gas ratios ($R=H_2/SiH_4$) yielded different efficiency performances, from 6.6% solar cell efficiency at ratio $R=30$ increasing slightly into 8.6% at ratio $R=20$ [5].

Based on the description above, the optimization of energy gap and thicknesses on single p-i-n junction layer were studied. In this paper, we report our studies of H_2 dilution effect on solar cell performance. The research optimization variant focused on the effect of hydrogen dilution on band gap of each layer, layer thicknesses and output efficiency. It is expected that this study will also help the next research in determining the best match parameters in solar cell fabrication process to enhance the solar cell performance.

A. Hydrogenated Amorphous Silicon

Hydrogenated amorphous silicon as a thin film in solar cell modules can be fabricated at low deposition temperature which is less than 300°C . Hydrogenated amorphous silicon is denoted as a-Si:H where "H" indicates term hydrogenation.

An important point that distinguish amorphous silicon structures from crystal structures is the atomic disorder structure. Figure 1 shows structure atom of silicon where each silicon atom binds covalently to the other four silicon with the uniform angle and length. In atomic structure, the coordination number for silicon atom is 4 on a single silicon crystal. Therefore, in an amorphous silicon structure does not show the regularity of long range order and its structure is seen as continuous random network. It also can be seen that some silicon atom is binds covalently to other four silicon atom which means a-Si:H has regularity like single crystalline silicon in short range order [6].

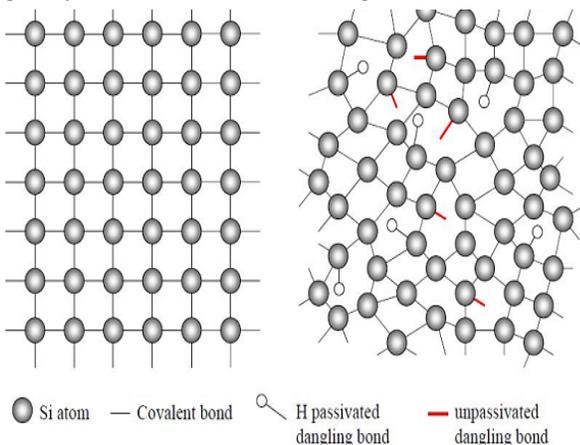


Figure 1. Atomic model structure of crystalline silicon and hydrogenated amorphous silicon.

The irregularity variations on bonding angle and bonding length between a-Si:H atom will cause a weak bond structure. Energy from weak bonds is lower than the optimal energy of single crystal silicon thus defect may be caused if atom receive a certain amount of energy. The defect may be in form of dangling bonds, such as the existence of reactive free electron, which create a distract gap between valence band and conduction band. In order to prevent dangling bonds, free electrons can be passivated by hydrogen atoms so that the structure is called hydrogenated amorphous silicon solar cell.

B. Single p-i-n Junction Silicon Solar Cell

Single p-i-n junction silicon solar cell structure is shown in figure 2. It has an intrinsic layer which differs it from standard p-n junction solar cell. The existing layer is undoped and located between p-layer and n-layer. Addition of i-layer is needed because amorphous silicon solar cell has narrower depletion region area than crystalline. The three layers present in the p-i-n junction solar cell are very thin extrinsic layer and thicker intrinsic layer which their thicknesses are around 20 nm and 500 nm respectively.

Sunlight in the form of photons will firstly enter a transparent oxide conductor. Photons then fall on a very thin and transparent p-layer that can be called "window layer". After going through window layer, photon will enter intrinsic layer and being absorbed. Almost all the photon will be absorbed on thick intrinsic layer while the excess photon will enter n-layer and reabsorbed. The absorbed photon will give excitation energy for electrons and leaving holes on valence band. Such process is named electron-hole generation which caused solar modules generate electricity.

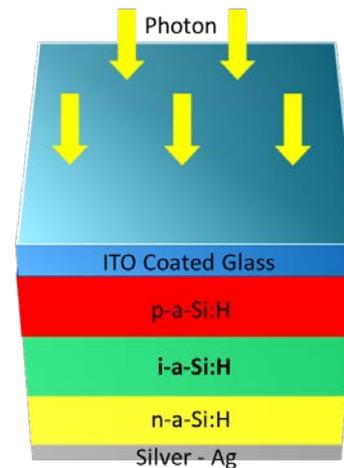


Figure 2. Schematic structure of p-i-n junction silicon solar cell under direct sunlight.

C. Silicon Thin Film Energy Gap

Energy gap is an important factor in solar cell that need to be optimized. It controls the solar cell layer in the photon absorption characteristics. The decrease in energy gap will be followed by the increase of absorption rate. A thin layer can only absorb photons with same energy or higher than its energy gap while photons with lower energy are transmitted directly without absorption. Therefore, the energy gap of solar cell is an important parameter in the aspect of absorption and transmittance that can affect the efficiency performance under direct sunlight.

The energy gap of amorphous silicon layer can be determined using Tauc Plot method [7]. Energy gap calculation is calculated using the equation 1 and equation 2.

$$(ahv)^n = A (hv - E_g) \quad (1)$$

$$\alpha = - \ln(T) / d \quad (2)$$

Where α is the absorption coefficient calculated using transmittance data at UV-Vis measurement, d is the thicknesses of the thin layer, $h\nu$ is the photon energy, A is

the constant, n is $\frac{1}{2}$ for material with indirect band, and E_g is the energy gap.

Figure 3 shows how Tauc Plot method is used to determine the energy gap. By finding the linear line of $(\alpha h\nu)^{1/2}$ curve and pull it until intersects the x-axis, the intersection point can be regarded as the energy gap of thin film.

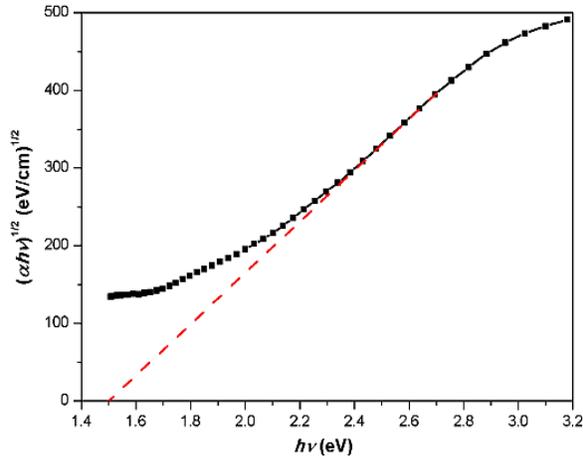


Figure 3. Schematic Tauc Plot diagram to determine the energy gap of silicon thin film.

D. I-V Characteristics

The equivalent circuit scheme is shown in figure 4 where the current source is parallel to variable resistance. The short circuit current (I_{sc}) is generated from the excitation process of excessive charge carriers due solar radiation whereas I_s is diode saturation current and R_v is variable resistance [8].

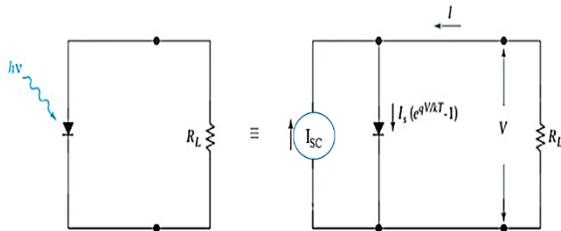


Figure 4. Ideal circuit current on solar cell modules under solar radiation.

In the performance measurement, efficiency not only influenced by output current and voltage, but also by its incident power and Fill Factor (FF). The fill factor here is the ratio of the maximum circuit power to short circuit current and open circuit voltage. Note that point, so to obtain maximum efficiency then the factors mentioned above need to be considered. These factors are expressed by Equation 3 and Equation 4.

$$\eta = FF \cdot I_{sc} \cdot V_{oc} / P_{in} \quad (3)$$

$$FF = I_m \cdot V_m / I_{sc} \cdot V_{oc} \quad (4)$$

Where η is the conversion of solar cell efficiency, P_{in} is the power of the incoming rays, I_m and V_m are maximum output current and voltage under load.

II. METHOD

A. Substrates Preparation

Substrate used in the deposition process is Indium Tin Oxide (ITO) layer coated on a glass. ITO glass has a good

conductivity for electricity and provides convenience in making electrical circuits. ITO glasses were cut into size $10 \times 10 \text{ cm}^2$ and being cleaned with 97% alcohol using ultrasonic cleaner. After being cleaned, the glasses are stored in a dry box with silica gel inside to prevent the surface contamination.

B. Layer Deposition

The substrate deposition condition on PECVD was performed on standard radio frequency (13.5 MHz) with each layer parameters are shown in the table 1. The p-layer was deposited under 480 mTorr chamber pressure on vacuum state. Deposition time was done in 15 minutes at 210°C temperature and the input power is set to 5 Watt. Silane gas (SiH_4) was used as the gas source in the deposition process with B_2H_6 as dopant gas. SiH_4 and B_2H_6 gas flow rate were set into 20 sccm and 2 sccm respectively.

The n-layer was deposited under 530 mTorr chamber pressure on vacuum state while deposition time and input power were set the same as p-layer deposition process. Silane gas (SiH_4) was used as the gas source in the deposition process with PH_3 as dopant gas. SiH_4 and PH_3 gas flow rate were set into 20 sccm and 5 sccm respectively. The hydrogen dilution process was done for both p-layer and n-layer with constant flow 40 sccm and 20 sccm respectively.

TABLE 1.
SOLAR CELL DEPOSITION PARAMETER FOR EACH LAYER.

Layer	SiH_4 (sccm)	H_2 (sccm)	B_2H_6 (sccm)	PH_3 (sccm)	Power (Watt)	Temp. ($^\circ\text{C}$)
p-layer	20	40	2	-	5	210
i_1 -layer	2,5	0	-	-	5	270
i_2 -layer	2,5	40	-	-	10	270
i_3 -layer	2,5	90	-	-	5	270
n-layer	20	20	-	5	5	210

Deposition process for intrinsic layer has differed into three variations. PECVD chamber pressure was set into vacuum at the limit of 2000 mTorr and silane gas used for intrinsic layer growth was set into a constant variable at 2.5 sccm. The first intrinsic layer has no hydrogen dilution ratio ($R=0$) and growth under 10 Watt of input power. The second intrinsic layer was grown under 40 sccm hydrogen gas flow ($R=16$) and input power was set into 10 Watt. The third intrinsic layer was grown under extreme 90 sccm hydrogen gas flow ($R=36$) and input power was set into 5 Watt.

C. Single p-i-n Junction Fabrication

Figure 5 shows the deposition process diagram occurring within the PECVD. The p-layer was deposited on the first chamber during its deposition time. The substrate was then transferred into another chamber for the i-layer deposition process. The deposition process of i-layer was done separately from the extrinsic in order to prevent the contamination of dopant gases which will affect the impurity of silicon.

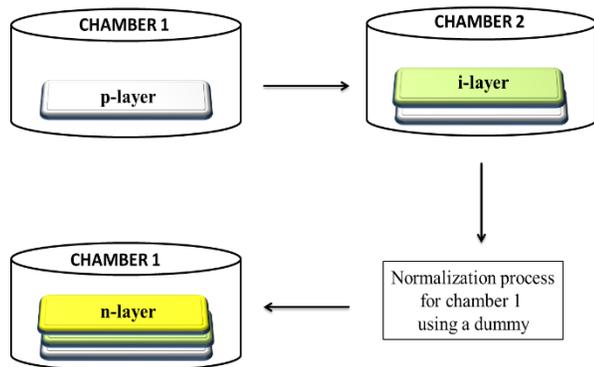


Figure 5. Schematic diagram for fabrication method of p-i-n structure solar cell inside PECVD chamber.

After i-layer deposition process was finished, the substrate was not transferred back directly into the first chamber. The substrate was kept in the constant condition inside chamber 2 without gas flow while the dummy sample was used to normalize the first chamber by flashing nitrogen gas into it. The normalization process for chamber 1 is needed in order to make sure that the n-layer deposition process is free from p-layer dopant gas contamination.

D. I-V Measurement

Generally, efficiency testing and solar cell current-voltage characteristics are performed under direct sunlight. This is done to obtain the real results of solar cell performance. Figure 6 shows the scheme of a tested solar cell which is connected to the electrical circuit or avometer. The radiation of sunlight will generate electricity through silver conductive paste as an ohmic contact on solar cell. The ohmic contact is connected to a circuit by a wire that has been equipped with amperemeter, voltmeter and a rheostat. The measurement of current-voltage data is taken by changing the scale of variable resistor.

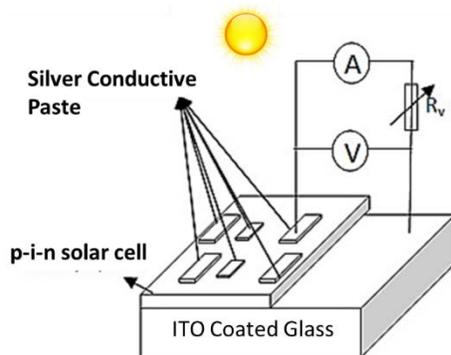


Figure 6. Schematic electrical circuit for solar cell i-v measurement.

III. RESULT AND ANALYSIS

A. Layer Characteristics

Each fabricated layer has been characterized to determine its physical properties. Layer thicknesses was measured using Atomic Force Microscopy (AFM). The obtained result of thicknesses is used to determine the deposition rate of each layer. UV-Vis Spectrometry was used in this research to obtain the transmittance data and determining the energy gap through Tauc Plot method. The characteristics of each layer are listed in table 2.

TABLE 2.
SOLAR CELL DEPOSITION PARAMETER FOR EACH LAYER.

Layer	R H ₂ /SiH ₄	Deposition Rate (nm/s)	Time (min)	Thicknesses (nm)	Energy Gap (eV)
p-layer	2	0.072	15	43	2.0
i ₁ -layer	0	0.028	236	400	1.9
i ₂ -layer	16	0.012	570	400	1.6
i ₃ -layer	36	0.042	160	400	1.4
n-layer	1	0.120	15	36	2.2

In a-Si:H solar cell, the p-layer has an energy gap of 2.0 eV. The intrinsic layer was differed into three samples and obtain energy gaps of 1.9 eV, 1.6 eV and 1.4 eV for hydrogen ratio 0, 16 and 36 respectively. The decrease in energy gap is caused by a hydrogen atom which gives dissociation effect through increasing ion/electron collisions and affects energy from the growing surface by filling vacancies in the gap. Another factor that posses the decreasing energy gap is the possibility of increasing crystallization degree which present at a high hydrogen dilution ratio [9].

One important factor in fabricating layer is its thickness. The thickness of p-layer and n-layer was made thin so that the incoming photons are not much absorbed in it. Extrinsic layer is more intended as a window layer or photon filler which absorb photons according to the needs. The intrinsic layer in this study was made thicker than extrinsic layer in order to optimize the photon absorbance.

B. Solar Cell Performance

Table 3 shows the efficiency performance of solar cell depends on intrinsic layer energy gap. The J_{sc} and cell efficiency are increase by approximately 0.0147 A/m² and 0.75% when i-layer energy gap changed from 1.4 eV to 1.6 eV. The graph also shows the decrease of 0.24 % in cell efficiency, as indicated by decreasing J_{sc} and fill factor when i-layer band gap increased to 1.9 eV.

TABLE 3.
SAMPLE STRUCTURE AND CELL PEFORMANCE.

Sample	Structure	Jsc (A/m ²) x 10 ⁻²	Voc (V)	FF (%)	Efficiency (%)
A	p-i ₃ -n	2.65	0.214	40.4	4.86
B	p-i ₂ -n	4.12	0.163	41.1	5.61
C	p-i ₁ -n	4.04	0.159	39.7	5.37

In accordance with the solar flux distribution, the maximum flux of sunlight lies in range 1.4 eV - 2.0 eV energy band for red to green spectrum. The more flux the sunlight spectrum received by the solar cells, the more photon energy absorbed according to the energy gap of the window layer. It appears that the efficiency of the solar cell with an intrinsic layer energy gap 1.6 eV and 1.9 eV has better performance than solar cells which the intrinsic layer energy gap lies on 1.4 eV because the effect of photon distribution.

Sample A has the largest open circuit voltage (V_{oc}) compared to the other two samples. As the hydrogen dilution ratio decreases, the open circuit voltage also shows a decrease as shown in table 3. The presence of a hydrogen atom at the time of deposition can increase the diffusion

coefficient on a grown surface, thus forming a crystalline phase seed on the layer. With the increase in hydrogen ratio, it can form a more stable thin film and has a high carrying mobility.

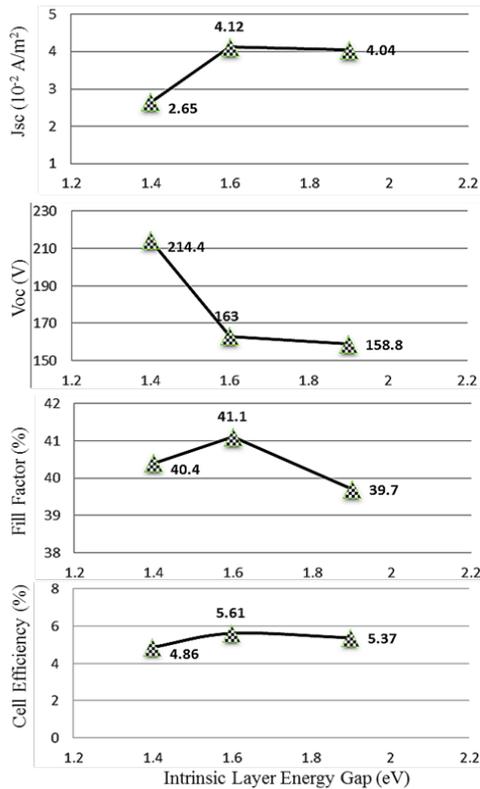


Figure 7. Solar cell efficiency based on intrinsic layer energy gap

Figure 7 shows the performance graph of p-i-n solar cell efficiency against the i-layer energy gap. In the 1.4 eV to 1.6 eV energy gap ($R = 36$ to $R = 16$) there was an increase in efficiency and fill factor of 0.75% and 0.7%. Performance decrease occurred in the 1.9 eV energy gap where efficiency and fill factor are decreased by 0.24% and 1.3%. The reason for the significant increase lies in the how large the gap between p-layer energy gap and i-layer energy gap. The p-type layer has an energy band gap of 2.0 eV which means sample A has a 0.6 eV difference in the energy gap. This causes the inefficient conversion of absorbed photon energy.

Light which energy gap is less than 2.0 eV enters the p-type layer and is received by an i-layer with energy gap 1.4 eV. Photons with a 1.4 eV energy gap will be absorbed optimally by the intrinsic layer and generate electron-hole pairs, while photons with energy less than 1.4 eV will be transmitted to the n-type layer. One of the causes of low efficiency lies in photons which has energy gap more than 1.4 eV. Photons with a higher energy gap than i-layer will be absorbed and move the electrons toward the conduction band and leave the vacancies (hole) on the valence band. The electron-hole pair releases heat energy and rapidly relaxes back on the edge of the band.

The energy released by the electron-hole pairs is wasted, make the layer temperature increase and causing low solar cell performance when exposed to the sun. A similar case was found in samples B and C with a 1.6 eV and 1.9 eV i-layer energy gap. However, the narrow 0.4 eV and 0.1 eV

differences reduce the absorption losses so that their performance is higher than sample A.

One of the factors that affects the performance of solar cells is the hydrogen dilution ratio during the deposition process. Sample C without hydrogen gas solubility ($R = 0$) obtained an efficiency of 5.37% with a fill factor of 39.7%. Dilution of 40 sccm hydrogen gas in the intrinsic layer of sample B can improve the efficiency of solar cell. This is due to the hydrogen atom binding on the reactive free electron of Si atom. With the binding of a hydrogen atom to an empty Si bond, the defect in the bandgap energy will decrease. With reduced defects in the energy gap, the electrons in the valence band will be more easily excited to the conduction band and lead to a better carrier stability, greater electrical conductivity and higher efficiency.

C. Optimization of Layer Thickness

The thickness of the intrinsic layer is a factor that can affect the performance of the solar cell considering the intrinsic layer is the main absorber layer. With an increase in i-layer thickness, the more photon energy will be absorb and multiply the electron-hole pairs generation. Sample B which has been optimized as discussed above is varied by its i-layer thickness as shown in Table 4. Sample B₂ with a 500 nm i-layer thickness has resulted 5.69% efficiency and 41.6% fill factor. Sample B₃ with 600 nm i-layer thickness yielded 5.78% efficiency and 42.6% fill factor.

TABLE 4.
SAMPLE STRUCTURE AND CELL PERFORMANCE.

Sample	i-Layer Thickness (nm)	J_{sc} (A/m 2) $\times 10^{-2}$	V_{oc} (V)	FF (%)	Efficiency (%)
B	400	4.12	0.163	41.1	5.61
B ₂	500	6.05	0.251	41.6	5.69
B ₃	600	5.13	0.277	42.6	5.78

Figure 8 shows a 400 nm – 600 nm increase in i-layer thickness that is followed by an increase cell performance. The open circuit voltage (V_{oc}) increased by 88.4 mV at a thickness of 500 nm and 114.1 mV at 600 nm thickness. Performance improvements through V_{oc} and I_{sc} output are indicated by 0.08% and 0.17% increasing efficiency at 500 nm and 600 nm thickness respectively.

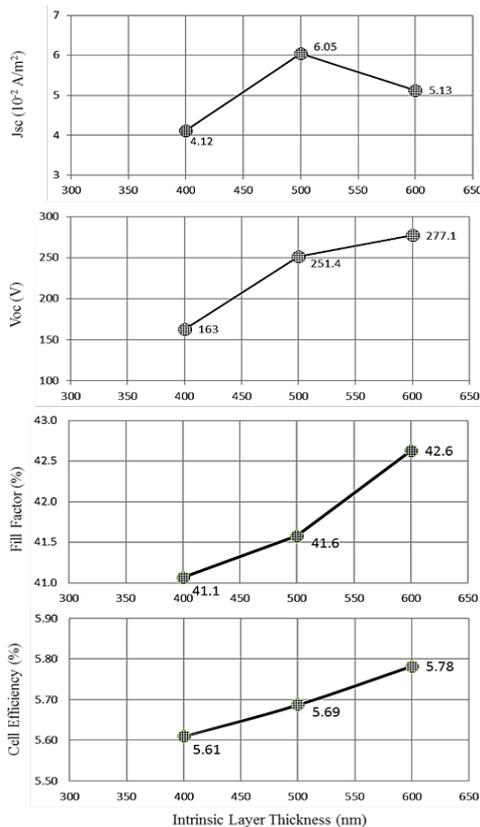


Figure 8. Increase of Efficiency Through i-Layer Thickness Optimization

The increase in solar cell performances followed by an increase in i-layer thickness are caused by broadening of the depletion region. The thicker i-layer will cause the depletion region to become wider so that the electrons and holes as donor and acceptor ions will multiply. Furthermore, the dilation of the depletion region causes an elongation in ion diffusion length which longer the lifetime and increase the drift currents [10]

IV. CONCLUSION

In this research, single p-i-n junction of a-Si:H solar cells were successfully made through deposition process using PECVD. The use of a varying hydrogen gas ratio ($R=0$ to $R=36$) lower the i-layer energy gap from 1.9 eV to 1.4 eV. The energy gap of i-layer is a dominant factor in determining the efficiency of solar cells. This study obtained 4.86%, 5.61% and 5.37% of solar cell efficiency

by varying i-layer energy gap from 1.4 eV to 1.9 eV. Increased i-layer thickness may widen the depletion region in the p-n junction region of solar cells. Gained 5.61%, 5.69% and 5.78% increases in efficiency for 400 nm, 500 nm, and 600 nm thickness respectively. The fabricated a-Si:H solar cell has an optimum efficiency peak of 5.78% with a 1.6 eV intrinsic layer energy gap at 600 nm thickness.

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