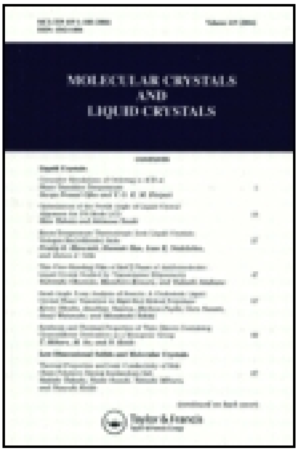

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Study of the p-i-n Layer to Enhance a-Si:H Solar Cell Efficiency Based on Single Junction

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We investigated the optimum thickness of the p-, i-, and n-layers to improve transmittance of the p-layer, the absorbance of the i-layer and the recombination rate of the n-layer. a-Si:H-based solar cells with different thicknesses for each layer were fabricated using plasma enhanced chemical vapor deposition (PECVD) and their performance parameters were compared. The optical properties of the intrinsic layer (i-layer) and the optimum hydrogen content in the i-layer were investigated and analyzed using UV/Vis/NIR and FT-IR, respectively. The optimum thicknesses of the p-, the i-, and the n-layer represented about 300, 2000, and 600 Å, respectively. The maximum absorbance and the minimum transmittance were measured at an i-layer thickness of 2000 Å in the wavelength range between 400 and 800 nm. The FT-IR measurements showed the optimum hydrogen content in the i-layer was about 10.1 at.%. We verified that the thickness of each layer and the hydrogen content had greatly influenced the electrical properties of the fabricated cells.

Keywords a-Si:H solar cell; PECVD; thickness; hydrogen content

Introduction

a-Si:H solar cells fabricated using PECVD have been variously studied to apply to industry, since the a-Si:H solar cell was first developed by Carlson of David Sarnoff Research Center in 1976 [1]. a-Si:H solar cells have many advantages compared to crystalline silicon solar cells; for example, they have high photoconductivity of about 10^{-3} S/cm under AM1 (Air Mass 1:100 mW/cm^2), 10 times higher absorption coefficient in the range from 370 to 780 nm, the feasibility of large area solar cell, and simple process for fabrications at low temperature. The fundamental operation of the a-Si:H solar cell is identical to that of p-n junction on which the crystalline silicon solar cells are based. The traditional solar cell is described as follows. Light rays irradiating the solar cell produce electron-hole pair (EHP). Then, the electric field in the depletion region drives out the EHPs produced to neutral regions. The EHPs generated in neutral regions hardly affect the conversion efficiency of the solar cells, except for being generated in diffusion length toward the depletion region [2]. Therefore, the i-layer is added between the p- and the n-layer to enlarge the depletion region affecting conversion efficiency of the a-Si:H solar cell [2,3,4]. The appropriate

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thickness for the i-layer has to be determined, because the efficiency is degraded by the decreased electric field in the i-layer, if the i-layer is too thick. The n- and the p-layers with the appropriate thicknesses have to be deposited since the p- and the n-layer are related to the window layer and recombination rate, respectively. The p-layer, window layer, has to transmit as much as possible incoming light into the i-layer without degeneration of the electric field in the i-layer. The n-layer has to minimize carrier recombination to collect as many generated carriers as possible. Moreover, the hydrogen content in the a-Si:H film affects electrical characteristics of the a-Si:H film, since it plays a role of filling the deep trap in the energy band gap of a-Si:H [5,6].

In this work, we fabricated a-Si:H solar cells with single junction. The optimum thickness of each layer was determined by evaluating the performance parameters of the fabricated solar cells. Then, to determine the optimum electrical properties of the i-layer, the absorbance, transmittance, and hydrogen content were investigated. The absorbance and the transmittance of the i-layer were measured using UV/Vis/NIR. The optimum hydrogen content in the i-layer was analyzed using FT-IR.

Experiment & Measurements

2.1. a-Si:H film preparation

All the p-, i-, and n-layers were deposited using PECVD. The substrate temperature and the working pressure (W.P.) were kept at 250 °C; and 750 mTorr, respectively. The RF powers for the p-, the n-, the i-layer were set to 100, 100, and 150 W, respectively. The i-layers, whose thickness varied from 500 to 3000 Å, were deposited using a SiH_4/H_2 gas mixture with a volume ratio of 1:1. An UV/Vis/NIR spectrometer was employed to analyze the variation of light absorbance and transmittance for the different i-layer thicknesses. The optimum hydrogen content in the i-layer deposited with different H_2 gas flow rates was investigated, since it was well-known that the hydrogen content in a-Si:H film alters electrical characteristics of film. The hydrogen content in each i-layer was analyzed using FT-IR. The p-layers were deposited using SiH_4 (10%, diluted by He)/B_2H_6 (3%, diluted by H_2) gas mixture with a volume ratio of 3.3/1. The thickness of the p-layers was prepared from 150 to 350 Å. The n-layers were prepared under SiH_4/PH_3 (1%, diluted by H_2) gas mixture with a volume ratio of 5:1. The thicknesses of n-layers were altered from 200 to 800 Å. The performance parameters of solar cells varying the thickness of each layer were compared to determine the optimum thickness of each layer.

2.2. Fabrication of the a-Si:H solar cells

The 0.3 × 0.3 mm^2 a-Si:H solar cells which consisted of glass/indium tin oxide (ITO)/p-layer/i-layer/n-layer/Al electrode were fabricated. All the solar cells were fabricated on top of corning glass coated with indium tin oxide (ITO). Each layer was deposited after a pattern process by a shadow mask. When the solar cells with different thickness of i-layers were fabricated, the thicknesses of the p- and the n-layer were fixed at about 250 and 500 Å, respectively. In the case of solar cells for the p-layer, the thickness of the i-layer and the n-layer were fixed at 2000 Å and 500 Å, respectively. A p-layer thickness of 300 Å and i-layer thickness of 2000 Å were employed to determine the optimum thickness of the n-layer. An Al electrode of 2000 Å, deposited using a thermal evaporator, was used as the back electrode. The thickness of each film and performance parameters of the fabricated cells were analyzed using an α-Step analysis and a standard solar simulator equipped with a xenon flash and an AM 1.5G filter, respectively.

Results and Discussion

In this work, we tried to determine the optimum a-Si:H solar cell by comparing the performance parameters of solar cells with different thicknesses for each layer. The four performance parameters, V_{oc}, J_{sc}, FF, and efficiency, were compared. The four performance parameters were sufficient to determine the optimum thickness of each layer. The solar cell performance was characterized by J-V measurement under standard AM 1.5G illumination. The conversion efficiency was calculated by V_{oc}, J_{sc}, FF, and input power. This is represented by the following equation,

$$\eta = \frac{FF \cdot V_{OC} \cdot I_{SC}}{P_{input}}$$

That is, the energy conversion efficiency of a solar cell is defined as the ratio of maximum output power and input power [7].

Figure 1 shows the variation of performance parameters for solar cells with different thicknesses of the i-layer. The high V_{oc} was measured as the thickness of the i-layer was increased from 500 to 1500 Å, whereas the low V_{oc} was measured at solar cells from 2000 to 2500 Å thick. J_{sc} was the highest at a thickness of 2000 Å. V_{oc} and J_{sc} both decreased at 2500 Å. The optimum solar cell performance parameters were when V_{oc}, J_{sc}, FF, and efficiency were 0.43 V, 6.32 mA/cm^2, 0.49, and 1.36%, respectively, for a 2000 Å thick solar cell. As the i-layer was too thin, the electric field in the i-layer, which was related to V_{oc}, was increased, whereas J_{sc} was decreased due to low absorbance of incoming light. Although the

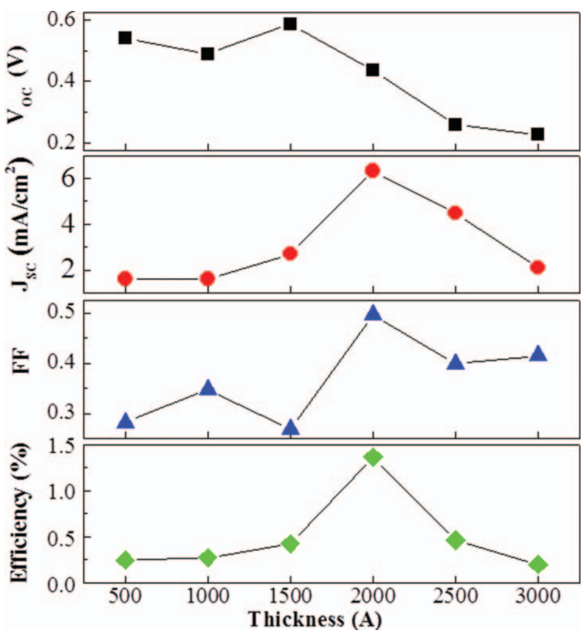

Figure 1. Performance parameters of solar cells with different i-layer thicknesses.

thicker i-layer was able to enhance J_{sc}, since the incoming light was absorbed effectively, the electric field was decreased. The J_{sc} decreased from the thickness of 2500 to 3000 Å would be due to the increase of the recombination rate in the i-layer. V_{oc} and J_{sc} both could not be improved by adjusting the thickness of the i-layer. This indicated the need to trade-off between improvement of V_{oc} and J_{sc}. The results of absorbance and transmittance spectra for the i-layers with different thicknesses, represented in Fig. 2 (a) and (b) , support the foregoing discussion. The spectral responses were measured in a wavelength range between 400 and 800 nm. In the range from 600 to 800 nm, the absorbance and transmittance of the 1000 Å thick i-layer were the lowest value compared to that of 2000 and 3000 Å. The maximum absorbance and the minimum transmittance were represented at an i-layer thickness of 2000 Å. The trends of variation in absorbance and transmittance for different

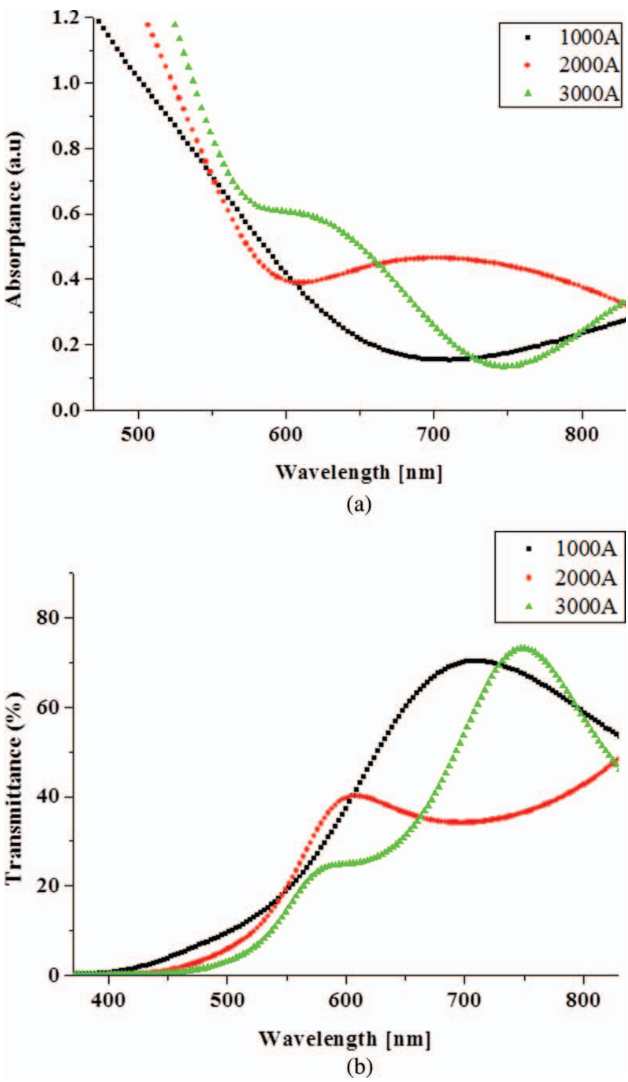

Figure 2. (a) Absorbance spectra of i-layers with different thickness. (b). Transmittance spectra of i-layers with different thickness.

thicknesses of i-layer were similar to that of the variation of performance parameters of solar cells with different i-layer thicknesses.

Figure 3 (a) shows J-V characteristics curve of solar cells according to variation of thickness for the p-layer and (b) represents the trend of variation of each parameter. As the thicknesses of the p-layer were increased from 150 to 250 Å, V_{oc} was characterized as a low value. V_{oc} was increased sharply from the p-layer 300 Å thick and J_{sc} was decreased at that

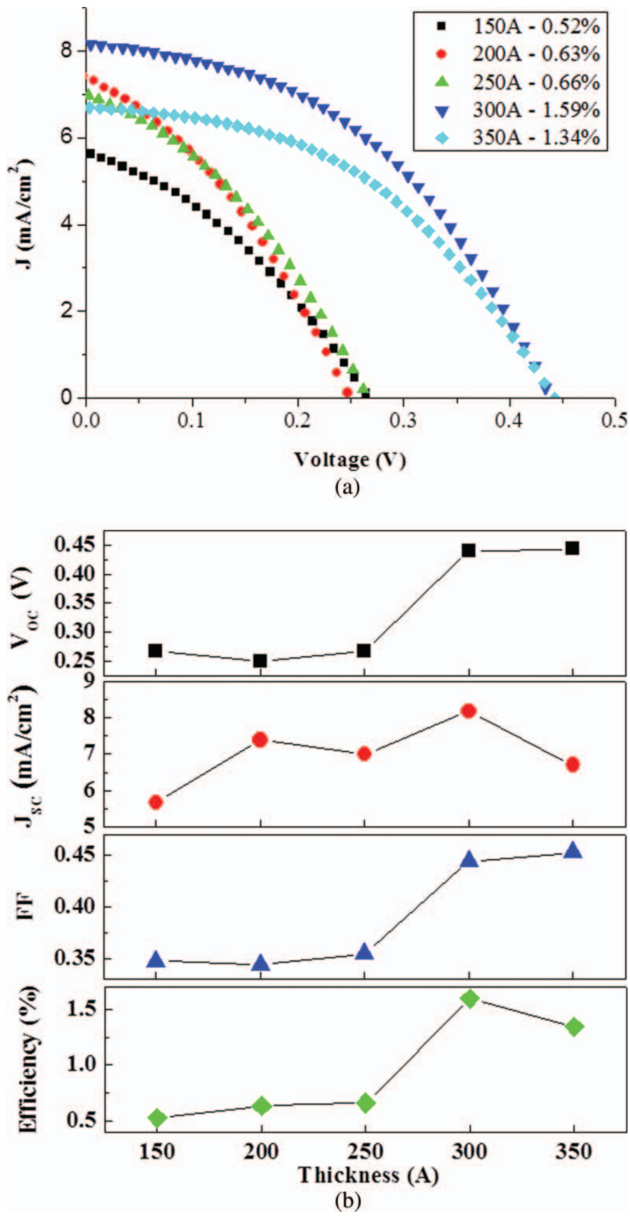

Figure 3. (a) J-V characteristics curve of solar cells varying p-layer thickness. (b). Performance parameters of solar cells varying p-layer thickness.

of 350 Å. The maximum conversion efficiency was observed for the solar cell with a 300 Å thick p-layer. In this case, V_{oc}, J_{sc}, FF, and efficiency were 0.43 V, 8.17 mA/cm^2, 0.44, and 1.59%, respectively. Incoming light has to efficiently penetrate the p-layer to reach as much of the i-layer as possible to attain high conversion efficiency. Therefore, the p-layer has to play a role of a window layer and simultaneously generate the electric field in the i-layer efficiently. When the p-layer was too thin, V_{oc} represented low values, since a thin p-layer could not generate sufficient diffusion potential in the i-layer. If the p-layer was too thick, surface absorbance in the p-layer increased. So, lower efficiency was represented since the thicker p-layer could just increase the electric field in the i-layer but incoming light could not reach enough the i-layer.

The variation of J-V characteristics curve and each parameter for a-Si:H solar cells according to variation of thickness for the n-layer were represented in Fig. 4 (a) (b) and. V_{oc} and J_{sc} both yielded low values from the n-layer 200 to 400 Å thick and V_{oc} sharply increased at a thickness above 500 Å. This might be related to the increased electric field in the i-layer. The maximum J_{sc} was observed at 600 Å and, from 700 Å, it diminished again. It was expected that the recombination rate of carriers in the too thick layer was increased more than that in the thin layer. The conversion efficiency reached the maximum value when a 600 Å thickness was employed. In this case, V_{oc}, J_{sc}, FF, and efficiency were 0.5 V, 9.35mA/cm^2, 0.44, and 2.1%.

Figure 5 represents electrical parameters of solar cells fabricated with different H_2 flow rate in the i-layer, when the p-layer of 300 Å, i-layer of 2000 Å, and n-layer of 600 Å were prepared. V_{oc} and J_{sc} both yielded a low value at the H_2 flow rate of 50 sccm. V_{oc} and J_{sc} both sharply increased at a H_2 flow rate of 100 sccm. V_{oc} increased from a H_2 flow rate of 150 to 250 sccm but J_{sc} gradually decreased. The solar cell fabricated with a H_2 flow rate of 100 sccm in the i-layer represented the maximum efficiency. V_{oc}, J_{sc}, FF, and efficiency were 0.48 V, 6.99 mA/cm^2, 0.41, and 1.38%, respectively. The hydrogen in a-Si:H film plays a role of filling localized states, so defects in a-Si:H film can decrease. The more the H_2 flow rate increased, the more V_{oc} increased; whereas, J_{sc} decreased from a H_2 flow rate of 150 sccm. The excess hydrogen that remained after filling the localized states in the i-layer would play a role of an impurity, conversely [8]. Therefore, J_{sc} would be decreased by the defects generated by hydrogen impurity; whereas, V_{oc} did not decrease. V_{oc}, which has the maximum voltage when performed at zero current, can be defined from the diode equation. This is represented by the following equation;

$$J = J_{Dark} - J_{Light} = J_0\left[\exp\left(\frac{qv}{nkT}\right) - 1\right] - J_{Light} \quad (1)$$

Put, $J = 0, J_{Light} = J_{sc}$

$$V_{oc} = \frac{nkT}{q}\text{In}\left[\left(\frac{J_{sc}}{J_0}\right) + 1\right] \quad (2)$$

This equation shows that V_{oc} is dependent on J_0. If the energy band gap increased, J_0 decreased, so V_{oc} would increase. However, the more the energy band gap increased, the less J_{sc} decreased, because the absorption spectrum decreased. The increase of V_{oc} would be caused by the decrease of J_0 or the increase of the energy band gap [7]. The excess hydrogen remaining around Si atoms could recombine with the bond-broken Si atom when the Si-H bond was broken, so excess hydrogen would form a more stable energy band gap

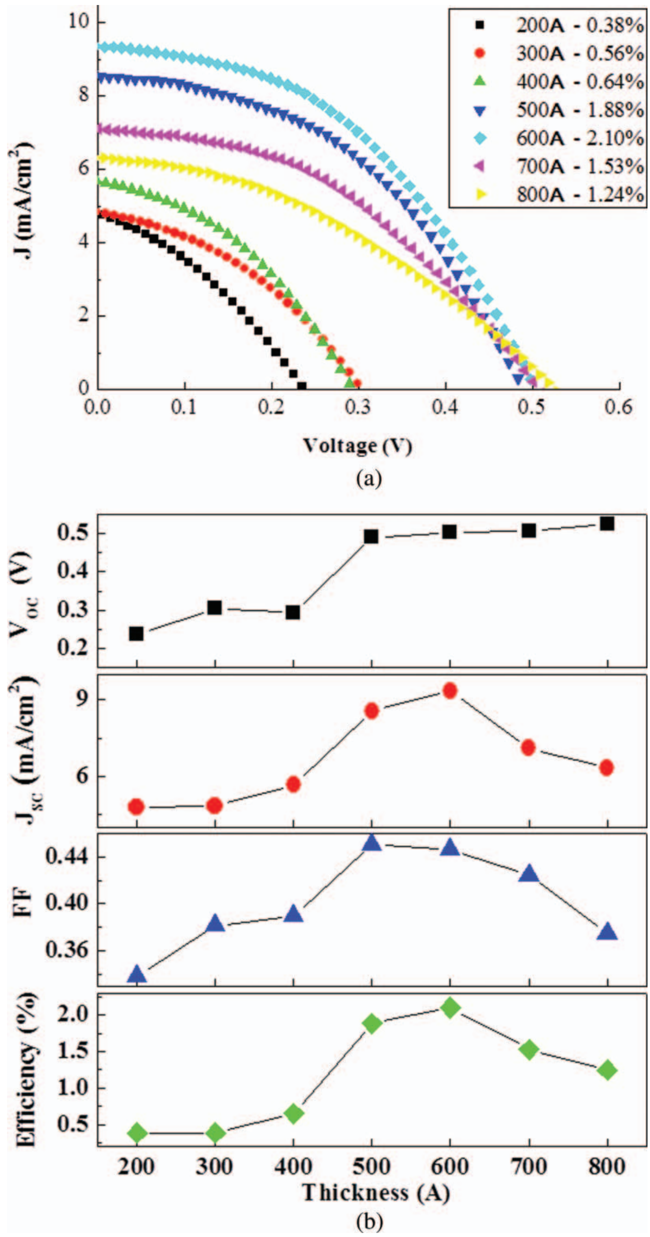

Figure 4. (a) J-V characteristics curve of solar cells varying n-layer thickness. (b). Performance parameters of solar cells varying n-layer thickness.

with a low trap level. Therefore, the a-Si:H with excess hydrogen would be characterized as if the optical band gap increased.

Figure 6 shows the conversion efficiency shift of the a-Si:H solar cells where the i-layers were deposited with different H_2 flow rates. When the i-layer was deposited with an H_2 flow rate of 150 sccm, the hydrogen content in the i-layer was above 13 at.%.

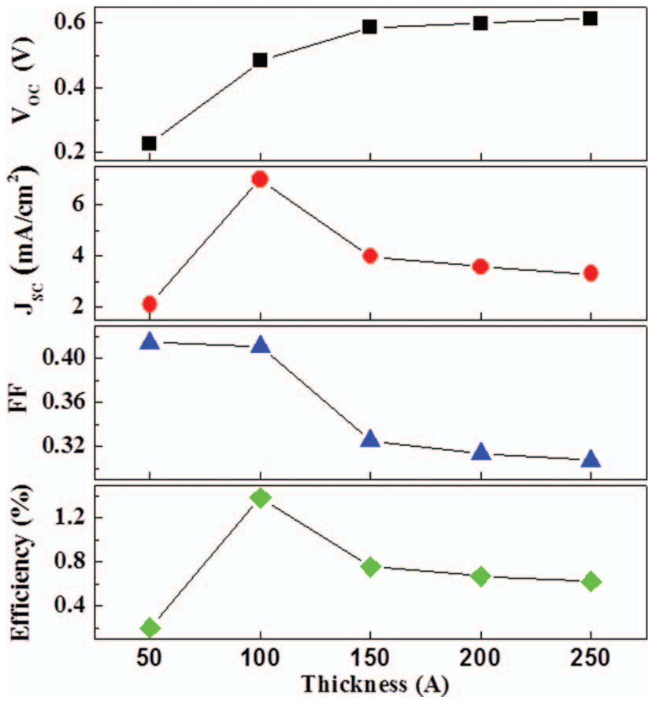

Figure 5. Performance parameters of solar cells according varying H_2 gas flow rate when the i-layer was deposited.

The efficiency of cells began to degenerate from a hydrogen content of 13 at.%. The best performance parameters among these cells would be observed at a hydrogen content of 10 at.%. It was expected that the excess hydrogen in the i-layer would be generated from the hydrogen content of 13 at.%.

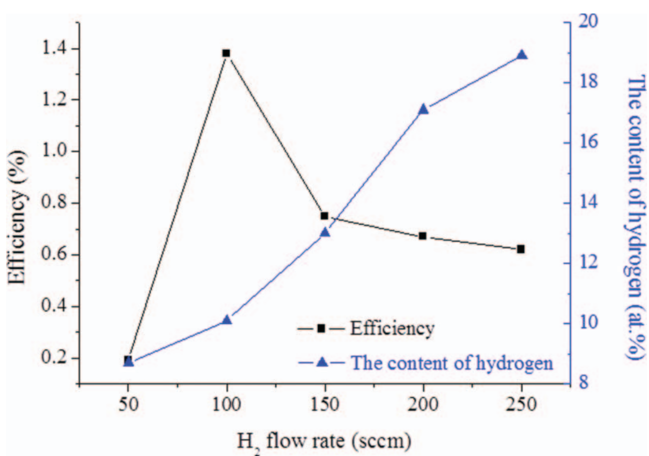

Figure 6. Shift of energy conversion efficiency of a-Si:H solar cells according to hydrogen content in the i-layers.

Conclusion

We fabricated a-Si:H solar cells with the p-i-n single junction of which each layer thickness was altered. The performance parameters of the fabricated cells were characterized and compared to determine the optimum thickness of each layer. The results showed the optimum thicknesses of the i-, the p-, and the n-layer were 2000, 300, and 600 Å, respectively. It was indicated that optimum thicknesses of each layer were important factors to increase light absorption in the i-layer and collect better the generated carriers. The absorbance, transmittance, and hydrogen content for the i-layer were investigated, since the i-layer had a direct impact on the electrical characteristics of the cells. At the i-layer thickness of 2000 Å, the highest absorbance and the lowest transmittance were attained. The performances of cells degenerated when the hydrogen content in the i-layer exceeded 13 at.%. It was expected that the impurity defects by excess hydrogen in the i-layer was generated from the hydrogen content above 13 at.%.

Acknowledgment

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