

Characterizations of i-a-Si:H and p-a-SiC:H Film using ICP-CVD Method to the Fabrication of Large-area Heterojunction Silicon Solar Cells

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We investigated for comparison of large-area i-a-Si:H and p-a-SiC:H film quality like thickness uniformity, optical bandgap and surface roughness using both ICP-CVD and PECVD on the large-area substrate (diameter of 100 mm). As a whole, films using ICP-CVD could be achieved much uniform thickness and bandgap of that using PECVD. For i-a-Si:H films, its uniformity of thickness and optical bandgap were 2.8 % and 0.38 %, respectively. Also, thickness and optical bandgap of p-a-SiC:H films using ICP-CVD could be obtained at 1.8 % and 0.3 %, respectively. In case of surface roughness, average surface roughness (below 5 nm) of ICP-CVD film could be much better than that (below 30 nm) of PECVD film. HIT solar cell with 2 wt%-AZO/p-a-SiC:H/i-a-Si:H/c-Si/Ag structure was fabricated and characterized with diameter of 152.3 mm in this large-area ICP-CVD system. Conversion efficiency of 9.123 % was achieved with a practical area of 100 mm × 100 mm, which can show the potential to fabrication of the large-area solar cell using ICP-CVD method.

Keywords : Solar cell, Large-area, Heterojunction, Silicon, ICP-CVD

1. INTRODUCTION

A key prerequisite for a significant global utilization of solar electricity is the reduction of the high costs currently associated with photovoltaic power supply. One promising approach to achieve this common aim is to increase the conversion efficiency of the solar cells by the use of innovative processing sequences that are able to combine highest cell efficiencies with simple, cost-effective and large-area fabrication techniques. Over the past two decades, the efficiencies of laboratory-size c-Si solar cells have improved significantly. Values of up to 24.7 % are reported in literature for 4 cm² devices under 1-sun AM 1.5 G illuminations[1]. However, these cells have generally been fabricated by very complicated processing sequences, requiring several high-temperature steps at temperatures above 1000 °C as well as numerous photolithography steps. Due to complex technology, it is apparent that an economic mass production of these cells is not possible. Recently, efforts aiming at a simplification of the above-mentioned

fabrication process of being dependent on the application of costly photolithography. Recently, the innovative simpler and large-area processing has been developed continuously. Instead of the high-temperature process, Low-temperature process of plasma technology has been focused on a viewpoint of high efficiency, cost-effective and large area. Since the Sanyo Electric Co. reported the so called HITTM (Heterojunction with Intrinsic Thin film) concept, heterojunction solar cells based on a-Si:H/c-Si have been suggested to be one of the best alternatives to the bulk crystalline silicon solar cell[2]. There are many advantages in fabricating solar cells with a high conversion efficiency and simultaneous surface passivation. Recently, many studies focusing on the importance of intrinsic a-Si:H films in heterojunction solar cells has been reported[3,4]. The high efficiency HIT cell (> 21 %) over 100 cm² area and higher open circuit voltage was reported by *M. Taguchi et al* and *Wang et al*, respectively[5,6]. Inductively coupled plasma chemical vapor deposition (ICP-CVD), which is remote PECVD method, has some advantages in large-

area deposition at low temperatures because of its high plasma density and good uniformity.

In this paper, we investigated for comparison of film quality (i.e. surface roughness and optical bandgap) with large-area i-a-Si:H and p-a-SiC:H layers using both ICP-CVD and PECVD. Our group has reported the optimized conditions of each layer by ICP-CVD[7-10]. The heterojunction solar cell with 2 wt%-AZO/p-a-SiC:H/i-a-Si:H/c-Si/Ag structure was fabricated and characterized with the area of 100 × 100 mm in this large-area ICP-CVD system.

2. EXPERIMENTS

2.1 Preparations

First, the i-a-Si:H and p-a-SiC:H films were deposited on n-type (100) oriented CZ c-Si (5.5~6.5 Ω·cm, 650 μm, 100 mm diameter) wafers using both ICP-CVD and PECVD. Wafer cleaning was performed as follows. First, a wafer was boiled in the mixture of 4:1 sulfuric acid and hydrogen peroxide for 10 minutes. Next, after native oxide was removed by dipping in buffered oxide etchant (BOE 7:1, Baker) for 10 seconds, and then deionized (D.I.) water rinse was performed. Cleaned wafer were loaded on the chuck with 152.4 mm diameter and transferred to a process chamber for film deposition. The absorbed water vapor was removed by baking the substrate holder and process chamber wall for 2 h at 200 °C and 60 °C, respectively. The chamber consists of a stainless chamber coupled with a turbo-molecular pump, which yields a base pressure of 5×10^{-7} torr. Pure silane (SiH₄), Suzuki Shokan Co. Semiconductor Grade, was used as the source gas. The plasma was generated by an inductively coupled electrical field produced from the antenna coil. The distance between the dielectric plate and substrate chuck was approximately 23 cm. In brief, all samples were deposited under same conditions, except ICP power and RF power. From here, it is important to adjust power generated from ICP and RF, respectively. We confirmed that 300 W of ICP power is almost similar to 30 W of RF power through data-sheet offered by manufacturer. Deposition time over all samples was fixed at 300 seconds.

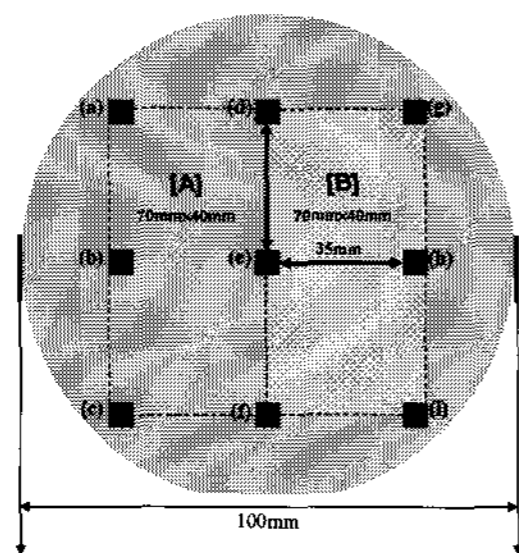


Fig. 1. The measuring points used in this experiment. The distance between each point is 35 mm, apart from wafer center.

2.2 Characterization

In order to determine the quality of the films and solar cell devices on c-Si wafer with 100 mm diameter, which divides this area into nine sections, labeled alphabetically, beginning in the top left section. As shown Fig. 1, thickness, bandgap and surface roughness was measured after fixing 9-points on the samples. The distance between the centers of each point is 35 mm, apart from wafer center. Thickness of all samples were measured by stylus profiler (Nanofocus, μsurf) and then, surface morphology was investigated using scanning probe microscope(PSIA, XE-100). Optical bandgap on each point of samples was measured by spectroscopic ellipsometer (Jobin yvon, UVISEL).

2.3 Fabrication

We fabricated the simple and large-area HIT solar cells with 2 wt%-AZO/p-a-SiC:H/i-a-Si:H/c-Si/Ag structure. As shown in Fig.1, Solar cells with a cell area of 28 cm² were used for the investigation of cell's efficiency distribution. These with practical area of 100×100 mm were also fabricated. Silver was evaporated onto the rear side of c-Si wafer and then, annealed at 850 °C for 20 minutes. An i-layer (3 nm) and p-layer(12 nm) was sequentially deposited using ICP-CVD system on front side of cleaned Si wafer with 100 mm diameter. For formation of TCO layer, the RF sputtered 2 wt% Al₂O₃-doped ZnO film with 120 nm put on it. Finally, Ag as front electrode was evaporated with grid.

The photo IV measurements were performed under AM1.5, 100 mW/cm² irradiation in a solar simulator (Wacom co. Ltd, WXS-105H) using I-V tracing system(EKO co, MP-160).

3. RESULTS AND DISCUSSION

3.1 Intrinsic a-Si:H films

With the optimum set of parameters, which are depicted in our previous works[7,8], the uniformity of the film thickness and on the material quality over the whole area of 78.5 cm² was examined. As shown in Fig. 2, ICP-CVD i-a-Si:H films with a thickness uniformity of ± 2.803 % on the whole area could be achieved and grown at a deposition rate of 2.1 Å/s. whereas, PECVD i-a-Si:H films showed the poor uniformity of ±15 % on the same area.

Optical bandgap(E_g) of a-Si:H film could be obtained from the wavelength dependence of its absorption coefficient(α). The E_g is determined by extrapolating $[\alpha(E)n(E)E]^{1/1+p+q}$ versus the photon energy E to $\alpha(E)$, for $\alpha \geq 10^3$ cm⁻¹:

$$[\alpha(E)n(E)E]^{1/1+p+q} = B(E-E_g) \quad (1)$$

where $\alpha(E)$ is the absorption coefficient, $n(E)$ is the refractive index of a-Si:H. The p and q are constants

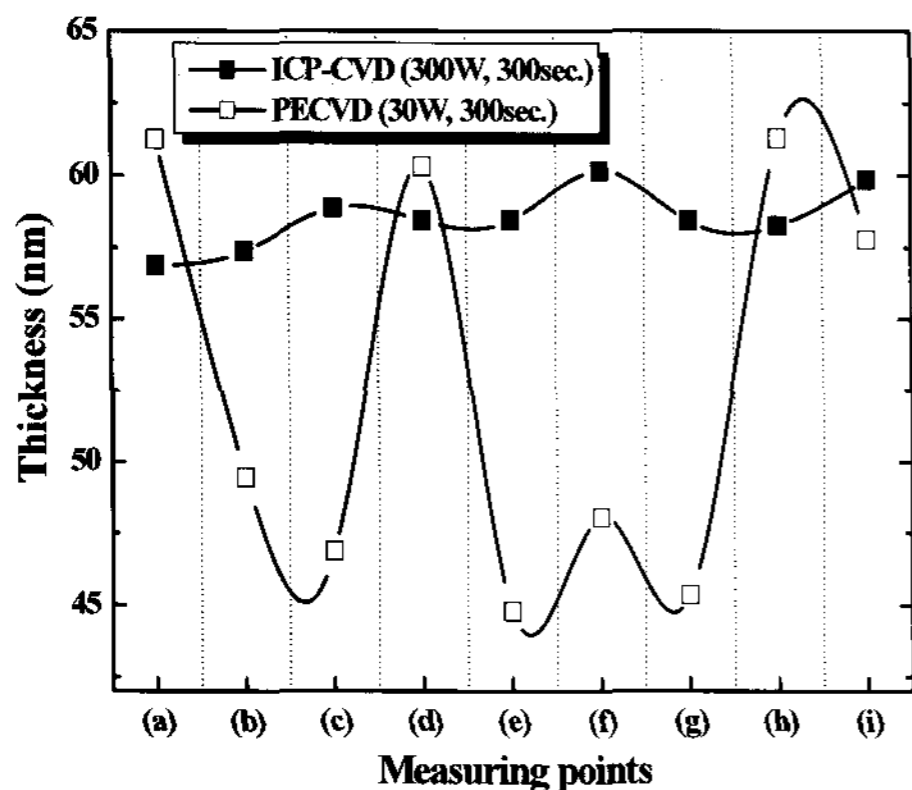


Fig. 2. Thickness distribution of i-a-Si:H films deposited by ICP-CVD and PECVD, respectively.

related to the shape of the band edges and B is a constant. If the density of states has a square-root energy dependence near the band edges, as is commonly the case in crystalline semiconductors ($p=q=1/2$), equation 1 describes the so called *Tauc Plot* and the corresponding the *Tauc gap*. The pseudo refractive index $\langle n(E) \rangle$ and extinction coefficient $\langle k(E) \rangle$ of sample could be obtained by SE and then, experimental data could be modeled by a Tauc-Lorenz dispersion law to extract material characteristics[11]. In this work, SE measurements were performed from 1.5 eV to 5.0 eV with a 0.01 eV step.

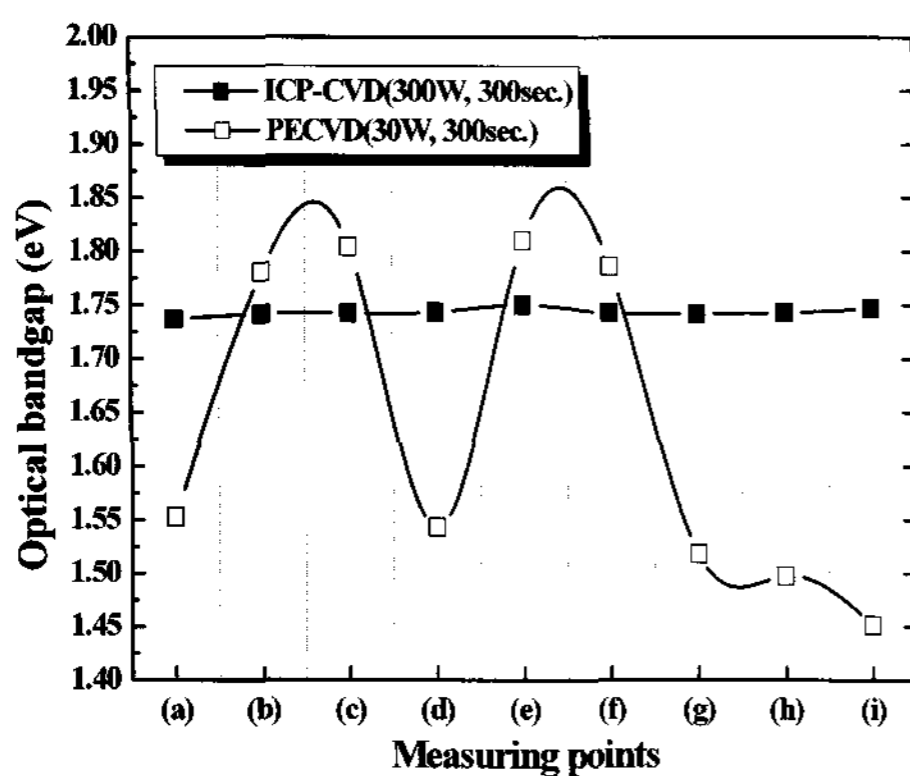


Fig. 3. Variations of optical bandgap versus measuring points.

Figure 3 shows material properties, optical bandgap (E_g) of nine points, from 'a'-'i', of the substrate as a function of position. Generally, the optical bandgap of intrinsic layer should be laid from 1.6 to 1.8 eV. E_g values of ICP-CVD film were satisfied with the region of intrinsic layer on the whole area. For the 9 positions on the 100 mm diameter in the PECVD film, other points except 'b', 'c', 'e' and 'f' showed the unsatisfied values.

Average surface roughness (R_a) in i-a-Si:H film using

both ICP-CVD and PECVD method was shown in Fig. 4(a). As a whole, ICP-CVD film with R_a of below 5 nm could be obtained. At the same time we can see that ICP-CVD film show the best R_a ($=0.195$ nm) at the center. In case of PECVD film, surface roughness has the high values on the whole area. Left side of center in the deposited film showed the best R_a ($=14.38$ nm) among these. The morphology of film could be supported from AFM image (Fig. 4(b), (c)). It was measured with 10 μ m scan length.

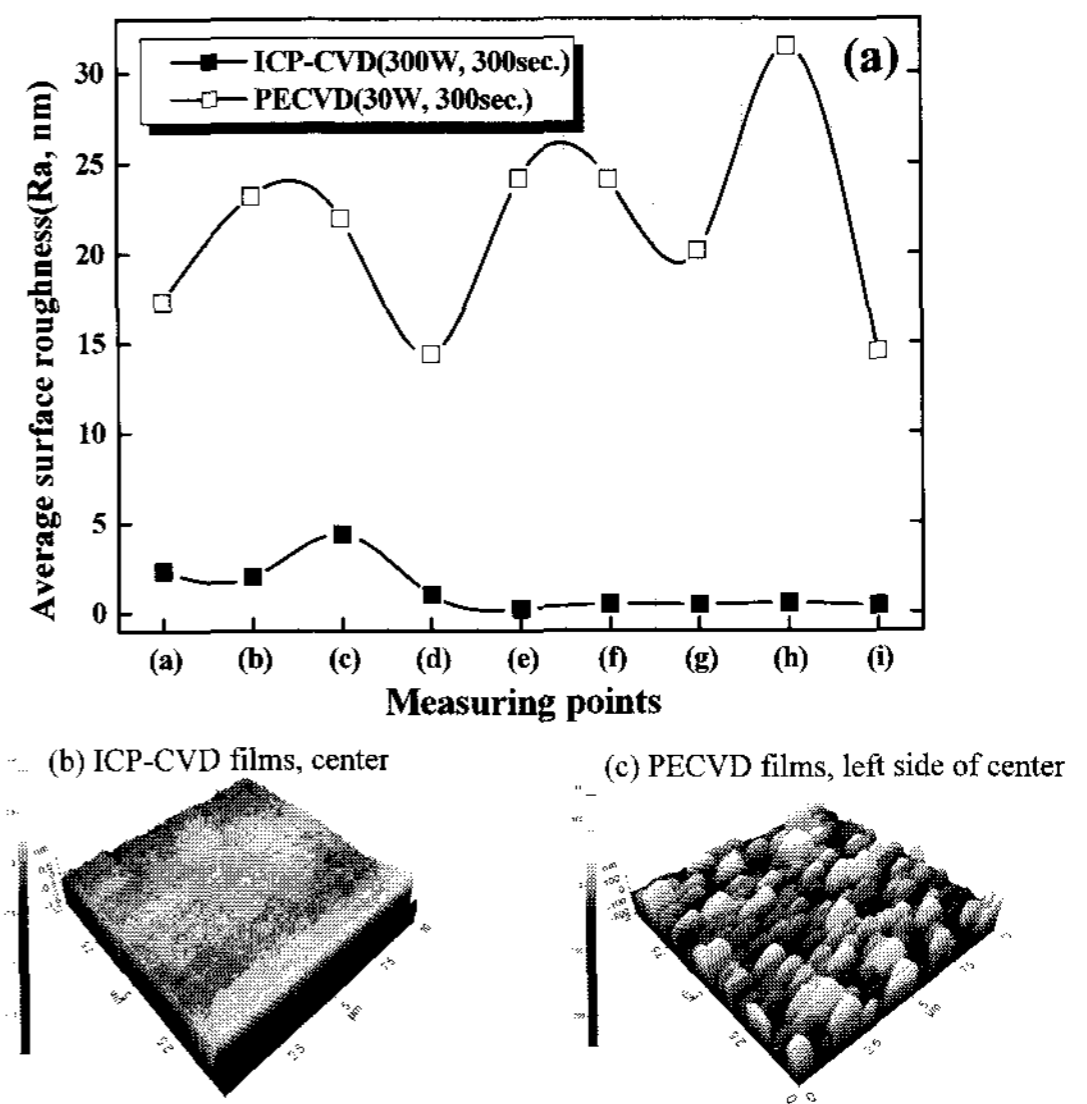


Fig. 4. Values (a) of average surface roughness (R_a) and AFM images of center (b) and left side of center (c) of film using ICP-CVD and PECVD method, respectively.

3.2 P-a-SiC:H films

Generally, the optical bandgap increases linearly with increase of C_2H_4 flow rate. It is clear that the optical bandgap of deposited a-SiC:H films could be controlled by C_2H_4 percentages to (H_2+SiH_4) in wide range. Moreover, the optical bandgap of decreased with increase of B_2H_6 flow rate. Such bandgap narrowing with increases in B_2H_6 flow rate is well-known phenomena. Based on our results, B_2H_6 and C_2H_4 flow rate was fixed at 6 sccm and 0.8 sccm, respectively.

Thickness distribution of p-a-SiC:H films using ICP-CVD and PECVD was shown in Fig. 5. Thickness of ICP-CVD film was thicker than that of PECVD film under the same deposition time. Low deposition rate of PECVD film may be ascribed to increase of etch rate by carbon and hydrogen, which was reacted with coupling-charge plasma. Thickness uniformity ($\pm 1.82\%$) of ICP-CVD film is much better than that ($\pm 5.01\%$) of PECVD film.

As shown in Fig. 6, optical bandgap values of ICP-CVD film is more distributed on the whole area. Similarly, Fig. 7(a) shows that ICP-CVD film with R_a of

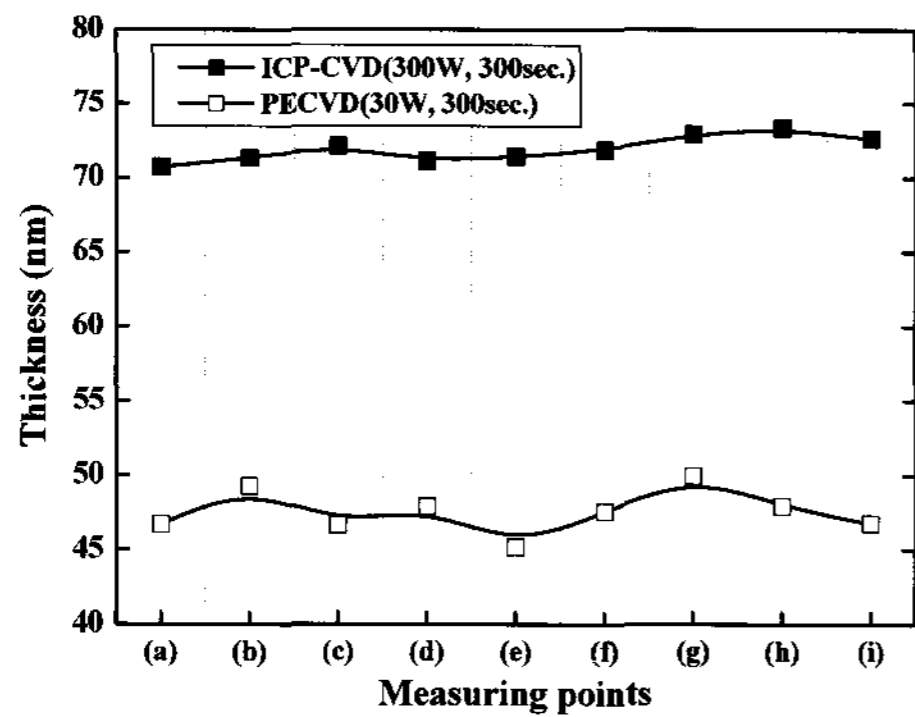


Fig. 5. Thickness distribution of p-a-SiC:H films by ICP-CVD and PECVD, respectively.

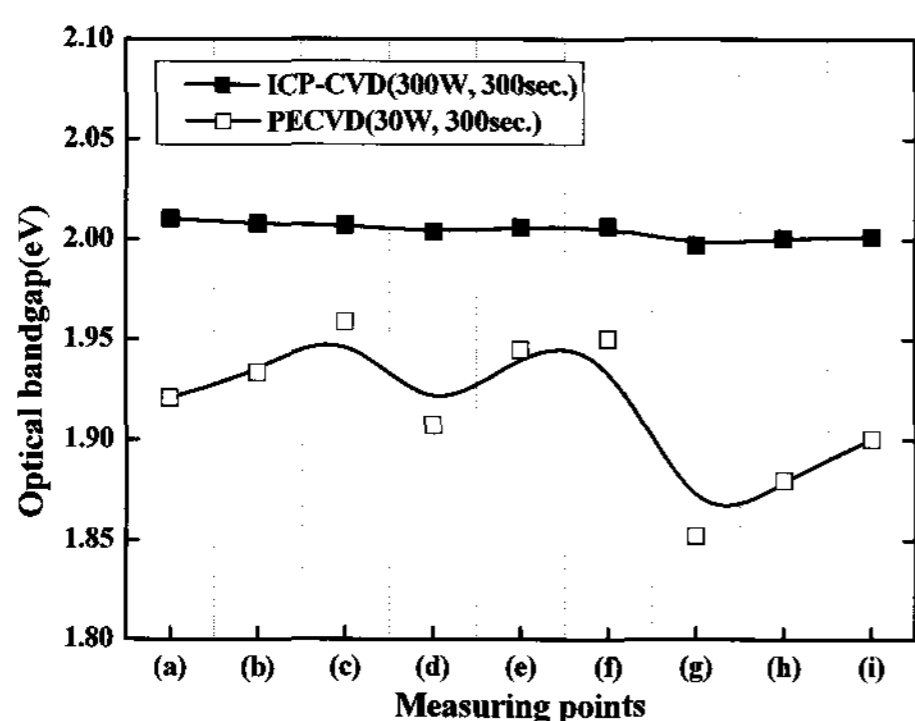


Fig. 6. Variations of optical bandgap versus measuring points.

below 5 nm could be totally obtained. For AFM image of ICP-CVD film, The best R_a of 0.245 nm showed at center of film with 10 μm scan length.

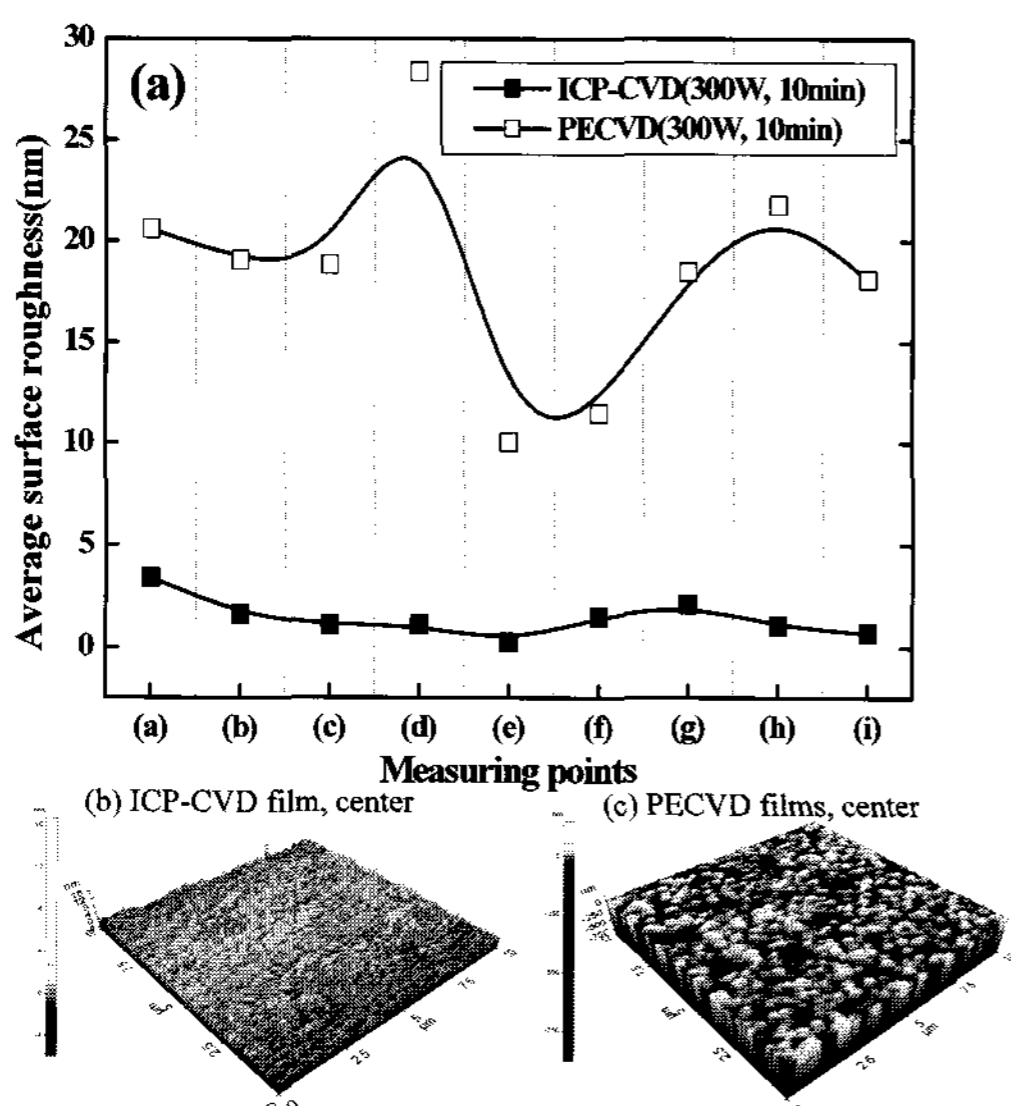


Fig. 7. Values (a) of average surface roughness (R_a) and AFM images of center of ICP-CVD film(b) and PECVD film(c), respectively.

3.3 Solar cell characterization

To probe the suitability of the material for large-area cells, the simple HIT solar cells with 2 wt%-AZO/p-a-SiC:H/i-a-Si:H/c-Si/Ag structure were fabricated. Figure 8 show the solar cell characteristics, represented by the I-V curve, over the sections 'A' and 'B' of the substrate with 100 mm diameter. For each section the result of the area (28 cm^2) solar cell is given.

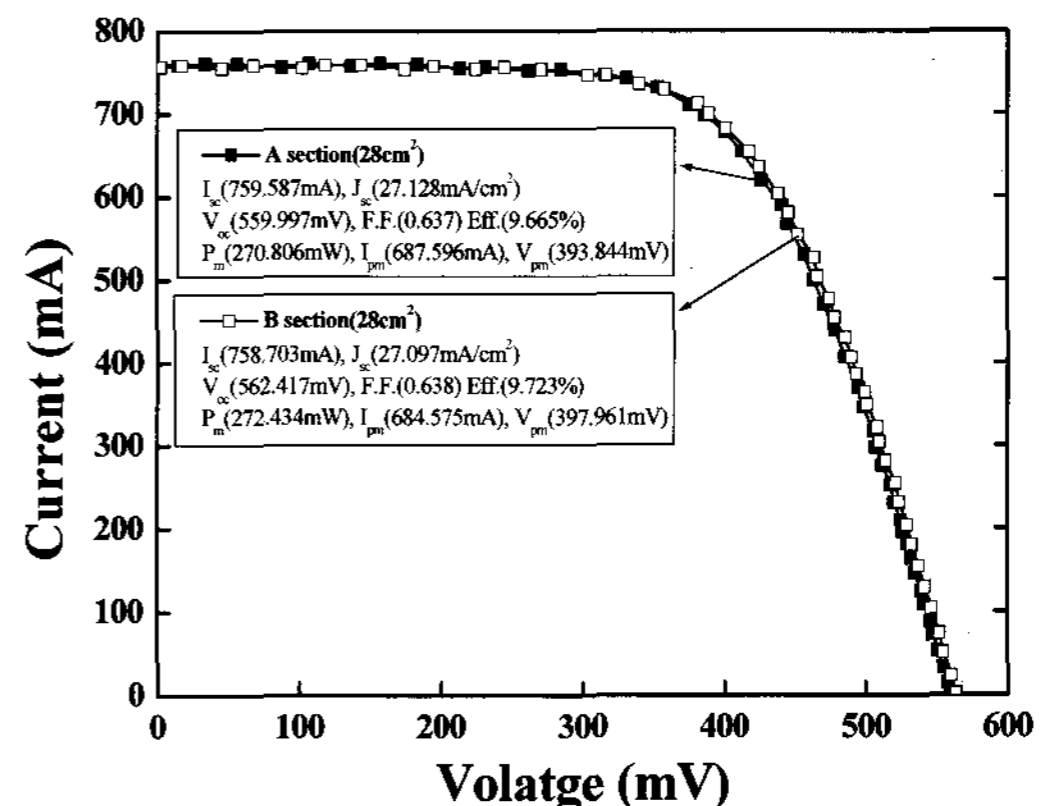


Fig. 8. I-V characteristics of left(section 'A') and right(section 'B') part in HIT solar cells with cell area of 28 cm^2 under simulated AM 1.5 G 100 mW/cm^2 .

The conversion efficiency (η) of 'A' section was 9.665 %, the short-circuit current density (J_{sc}) was 27.128 mA/cm^2 , the fill factors(FF) was 0.637 and the open circuit voltage (V_{oc}) was 559.997 mV. The higher value for efficiency of the cells with $\eta=9.723\%$ was shown at 'B' section. This result is mainly caused by increase (562.417 mV) of V_{oc} . FF and J_{sc} value of 'B' section cell was similar to those of 'A' section.

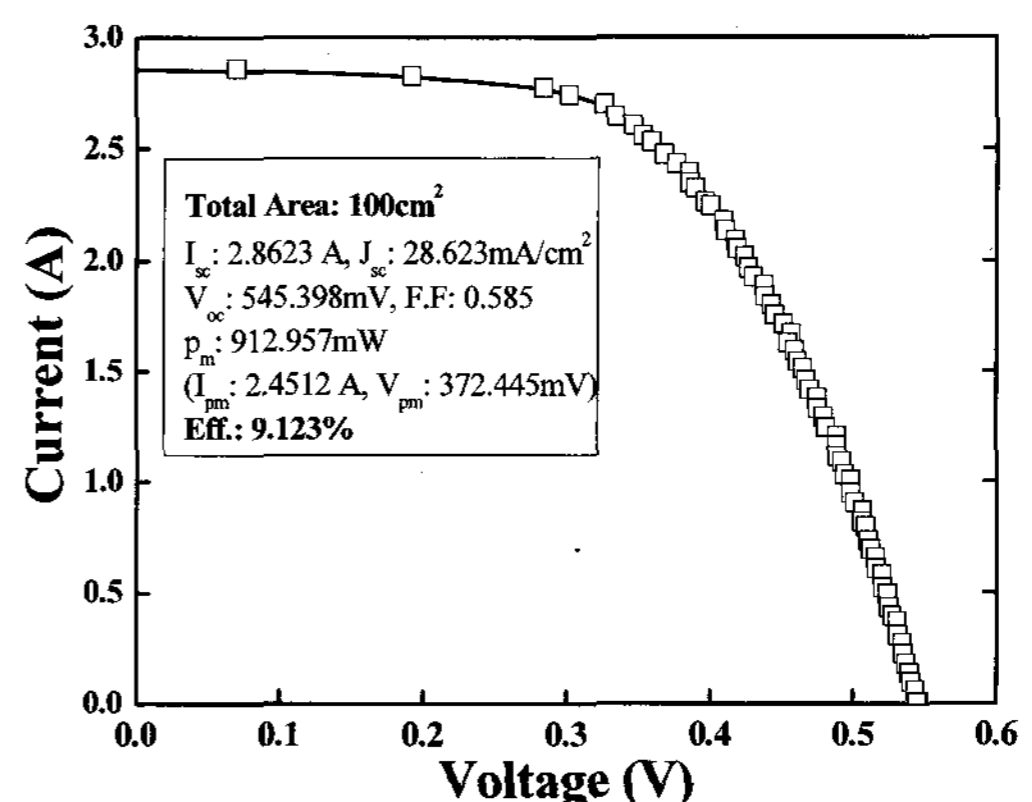


Fig. 9. I-V characteristics of HIT solar cells with cell area of 100 cm^2 under simulated AM 1.5 G 100 mW/cm^2 .

Furthermore, solar cell with the same structure was fabricated for application of large-area. As shown in Fig. 9, conversion efficiency of 9.123 % was achieved with a cell area of 100 mm × 100 mm. Compared to the results of small-area cell, V_{oc} and FF was decreased to 545.398 mV and 0.585, respectively. It may be caused by low shunt resistance (R_{sh}) and big series resistance (R_s). In order to achieve a high FF and V_{oc} , R_{sh} should be as high and R_s as small as possible[12]. The highest efficiency of HIT cell with same structure was 14 % by Sanyo Electric Co. and they could be achieved without any texture of surface. Compared to their results, these results were little worse because all process kept under one-chamber equipment and vacuum breaking. However, if our process kept under multi-chamber with isolation between p- and i- layer, we are expected to get the higher efficiency of HIT structure solar cell. Generally, the conventional solar cell based on pn junction has lower V_{oc} (~0.5 V) and high J_{sc} (28 mA/cm²). In our experiment, higher V_{oc} (0.545 V) and J_{sc} (28.6 mA/cm²) in the cell may be achieved due to good passivation on large-area. Also, we think that these results show the good potential to fabrication of the large-area solar cell using ICP-CVD method.

4. CONCLUSION

With the optimized conditions of i-a-Si:H and p-a-SiC:H layer thickness uniformity, optical bandgap and surface roughness of each layer on the large-area substrate (100 mm diameter) were investigated. As a whole, films using ICP-CVD could be achieved much uniform thickness and bandgap of that using PECVD. For i-a-Si:H films, its uniformity of thickness and optical bandgap were 2.8 % and 0.38 %, respectively. Also, thickness and optical bandgap of p-a-SiC:H films using ICP-CVD could be obtained at 1.8 % and 0.3 %, respectively. In case of surface roughness, average surface roughness (below 5 nm) of ICP-CVD film could be much better than that (below 30 nm) of PECVD film.

HIT solar cell with simple structure and its fabrication process were developed for large-area scale. Compared to left (section 'A') and right (section 'B') part in fabricated solar cell, conversion efficiency between 'A' and 'B' was 9.665 % and 9.723 %, respectively. It has little difference except V_{oc} values. As a result conversion efficiency of 9.123 % was achieved with a cell area of 100 mm × 100 mm, which can show the potential to fabrication of the large-area solar cell using ICP-CVD

method.

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