

Research Article

Performance Improvement of Microcrystalline p-SiC/i-Si/n-Si Thin Film Solar Cells by Using Laser-Assisted Plasma Enhanced Chemical Vapor Deposition

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The microcrystalline p-SiC/i-Si/n-Si thin film solar cells treated with hydrogen plasma were fabricated at low temperature using a CO₂ laser-assisted plasma enhanced chemical vapor deposition (LAPECVD) system. According to the micro-Raman results, the i-Si films shifted from 482 cm⁻¹ to 512 cm⁻¹ as the assisting laser power increased from 0 W to 80 W, which indicated a gradual transformation from amorphous to crystalline Si. From X-ray diffraction (XRD) results, the microcrystalline i-Si films with (111), (220), and (311) diffraction were obtained. Compared with the Si-based thin film solar cells deposited without laser assistance, the short-circuit current density and the power conversion efficiency of the solar cells with assisting laser power of 80 W were improved from 14.38 mA/cm² to 18.16 mA/cm² and from 6.89% to 8.58%, respectively.

1. Introduction

Recently, the silicon- (Si-) based thin film solar cells with several advantages, such as high absorptivity, easy fabrication, and low cost, have been extensively studied [1, 2]. The hydrogenated amorphous-Si (a-Si:H) films and the microcrystalline-Si (μ c-Si) films have been popularly utilized to fabricate the Si-based thin film solar cells. However, the a-Si:H films deposited using a plasma enhanced chemical vapor deposition (PECVD) system suffer from the light illumination induced degradation (Staebler-Wronski effect) [3]. This degradation phenomenon could be attributed to that when the a-Si:H thin film solar cells were illuminated by sunlight for a period time, a part of Si-H bonds in the a-Si:H films were broken, and the resulting dangling bonds produced carrier quenching centers, which degraded the performances of the solar cells. In contrast, the μ c-Si films did not have this problem and were more suitable to be applied to construct the thin film solar cells. In this work, the laser-assisted plasma enhanced chemical vapor

deposition (LAPECVD) system invented by our research group was used to directly deposit μ c-Si films without further annealing treatment [4–8]. The silane (SiH₄) reacting gas could be easily and efficiently decomposed into Si atoms under the combined action of the plasma and CO₂ laser, due to the high absorption coefficient of SiH₄ reacting gas at a wavelength of CO₂ laser (10.6 μ m). Consequently, the high quality microcrystalline intrinsic Si (μ c-i-Si) films could be deposited by the LAPECVD system at low temperature for the Si-based thin film solar cells. However, compared with the a-Si thin film solar cells, the open circuit voltage (V_{oc}) and fill factor (FF) of the μ c-Si thin film solar cells were lower [9, 10]. To overcome the above problem, the p-SiC film was deposited as the window layer to enhance the V_{oc} and FF. In addition, since the SiC is a wide bandgap material, the carrier recombination in the SiC layer is slower, which is beneficial to the improvement in the efficiency of resulting solar cells.

Since the quality of Si thin films played an important role in the Si-based thin film solar cells, in addition to the film deposition technique, many treatment technologies were

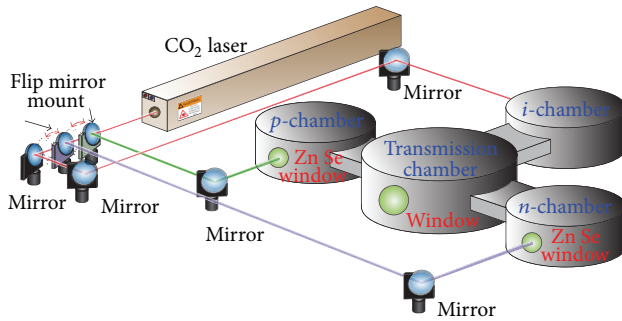


FIGURE 1: Schematic diagram of three-chamber LAPECVD system.

also utilized to passivate the dangling bonds in the Si thin films, such as hydrogen plasma treatment [11–13], HNO_3 treatment [14], chemical HF treatment [15], wet-chemical treatment [16], and Al_2O_3 passivation [17]. In this work, at the deposited processes, to avoid the contamination between the films by the external environment, all the fabricated processes of the microcrystalline p-SiC/i-Si/n-Si solar cells were kept in the vacuum environment. Consequently, among those treatment technologies, the hydrogen treatment technique was used to treat the p-SiC layer surface for decreasing the dangling bonds and improving the performance of the microcrystalline p-SiC/i-Si/n-Si thin film solar cells.

2. Experiments

Figure 1 shows the schematic configuration of the three-chamber LAPECVD system used in the work. The three chambers were designed to prevent the dopants cross contamination during the deposition of the n-type, intrinsic-type (i-type), and p-type Si-based films. To investigate the function of the laser assistance for the improvement in the properties of the deposited i-Si films, 150 nm-thick i-Si films were deposited on glass substrates using a LAPECVD system with various assisting laser powers of 0, 50, 60, 70, and 80 W. Meanwhile, the radio frequency (RF, 13.56 MHz) power, chamber pressure, flow rate of hydrogen-diluted SiH_4 (5%) reacting gas, and substrate temperature were set to be 20 W, 0.6 torr, 60 sccm, and 250°C, respectively. The bonding configuration and crystallization characteristics of the deposited i-Si films were analyzed using Fourier transform infrared (FTIR) spectrometry, micro-Raman scattering spectroscopy, and X-ray diffraction (XRD), respectively.

Figure 2 shows the schematic configuration of the p-SiC/i-Si/n-Si thin films solar cells. A 25 nm-thick p-SiC layer was deposited on the fluorine-doped tin oxide- (FTO-) coated glass substrate with texture structure using the LAPECVD system with assisting laser power of 80 W. The reacting gases, hydrogen-diluted SiH_4 (5%), methane (CH_4), and hydrogen-diluted diborane (B_2H_6) (1%), were utilized as the Si, C, and p-type dopant sources, respectively. The corresponding flow rate was 70 sccm, 25 sccm, and 4 sccm, respectively. The RF power, chamber pressure, and substrate temperature were kept at 20 W, 1.1 torr, and 250°C, respectively. The hole concentration and conductivity of the p-SiC

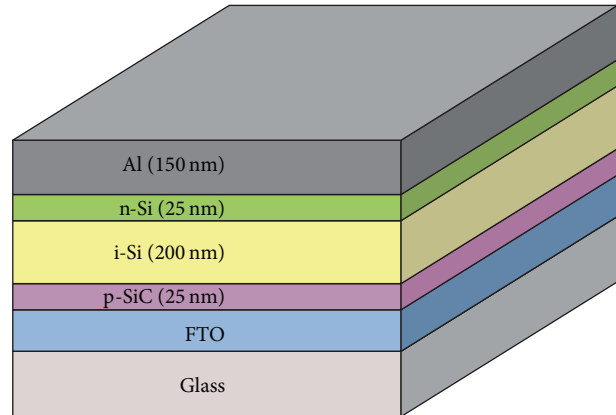


FIGURE 2: Schematic configuration of the p-SiC/i-Si/n-Si thin film solar cells.

layer deposited with assisting laser power of 80 W were $4.06 \times 10^{17} \text{ cm}^{-3}$ and $2.58 \times 10^{-2} \mu\text{S/cm}$, respectively. Prior to the deposition of the i-Si absorption layer, the p-SiC surface was passivated using hydrogen plasma treatment at RF power of 20 W for 25 min. A 200 nm-thick i-Si layer was immediately deposited on the p-SiC layer using the LAPECVD system with assisting laser power of 80 W. The RF power, chamber pressure, flow rate of hydrogen-diluted SiH_4 (5%) reacting gas, and substrate temperature were kept at 20 W, 0.6 torr, 60 sccm, and 250°C, respectively. Subsequently, a 20 nm-thick n-Si layer was deposited, using the same equipment with assisting laser power of 80 W, on the i-Si absorption layer. The hydrogen-diluted SiH_4 (5%) and hydrogen-diluted phosphine (PH_3) (1%) reacting gases were used as the Si and n-type dopant sources, respectively. The corresponding flow rate was 40 sccm and 10 sccm, respectively. The RF power, chamber pressure, and substrate temperature were kept at 60 W, 0.4 torr, and 250°C, respectively. The electron concentration and conductivity of the n-Si layer deposited with assisting laser power of 80 W were $5.74 \times 10^{19} \text{ cm}^{-3}$ and $8.75 \mu\text{S/cm}$, respectively. Finally, a 150 nm-thick Al electrode was deposited on the n-Si layer using the electron beam evaporator. The active area of the solar cell was 0.025 cm^2 . The p-SiC/i-Si/n-Si thin film solar cells deposited without laser assistance were also fabricated for comparison. The hole concentration and conductivity of the p-SiC layer deposited without laser assistance were $2.73 \times 10^{16} \text{ cm}^{-3}$ and $3.45 \times 10^{-3} \mu\text{S/cm}$, respectively. The electron concentration and conductivity of the n-Si layer deposited without laser assistance were $2.61 \times 10^{18} \text{ cm}^{-3}$ and $5.26 \times 10^{-1} \mu\text{S/cm}$, respectively.

3. Experimental Results and Discussion

The bonding configurations of the i-Si films deposited with various assisting laser powers were carried out using a Fourier transformation infrared (FTIR) spectrometry. Figure 3 shows the absorption spectra $\alpha(\omega)$ of the deposited i-Si films, where $\alpha(\omega)$ was the absorption coefficient as a function of wavenumber ω of the light. In particular, the absorption

spectrum $\alpha(\omega)/\omega$ of the i-Si films deposited with assisting laser power of 80 W was shown in the inset of Figure 3. All the measured spectra, after decomposition, exhibited two bands with peak positions of 2000 cm^{-1} and 2100 cm^{-1} , which correspond to the stretching vibrations of SiH and SiH₂, respectively. The microstructure factor R was defined as $R = I_{2100}/(I_{2100} + I_{2000})$, where I_{2000} and I_{2100} were the corresponding intensity of the two decomposed bands. The R of the i-Si films deposited with assisting laser power of 0, 50, 60, 70, and 80 W was 0.382, 0.318, 0.282, 0.237, and 0.221, respectively. The R value decreased with the assisting laser power. In other words, the intensity of the band corresponding to SiH₂ in the deposited i-Si films decreased with the assisting laser power, which implied that the high quality i-Si films could be obtained using the LAPECVD system. The hydrogen concentration (N_{H}) of the i-Si films deposited with assisting laser power of 80 W was estimated by the equation shown below [18]:

$$N_{\text{H}} = A_{2000} \int \frac{\alpha_{2000}(\omega)}{\omega} d\omega + A_{2100} \int \frac{\alpha_{2100}(\omega)}{\omega} d\omega, \quad (1)$$

where A_{2000} and A_{2100} are proportionality constants at wavenumber of 2000 cm^{-1} and 2100 cm^{-1} and equal $9.0 \times 10^{19}\text{ cm}^{-2}$ and $2.2 \times 10^{20}\text{ cm}^{-2}$, respectively, $\alpha_{2000}(\omega)$ and $\alpha_{2100}(\omega)$ are the absorption coefficients of the bands centered at wavenumber of 2000 cm^{-1} and 2100 cm^{-1} , respectively, and ω is the frequency in cm^{-1} . The hydrogen content (C_{H}) of the i-Si films deposited with and without laser assistance could be also estimated by the equation $N_{\text{H}}/N_{\text{Si}} \times 100\%$, where N_{Si} of $5 \times 10^{22}\text{ cm}^{-3}$ is the number density of crystal Si [19]. Figure 4 shows the hydrogen concentration and hydrogen content of the deposited i-Si films as a function of the assisting laser power used in the film deposition. As shown in Figure 4, the N_{H} of $1.10 \times 10^{21}\text{ cm}^{-3}$ and the C_{H} of 2.20% for the i-Si films deposited with assisting laser power of 80 W were smaller than the N_{H} of $5.98 \times 10^{21}\text{ cm}^{-3}$ and the C_{H} of 11.96% for the i-Si films deposited without laser assistance. The N_{H} and C_{H} of the deposited i-Si films decreased with the laser power. It could be attributed to the fact that the SiH₄ reacting gas could be efficiently decomposed into Si atoms by the combined action of plasma and CO₂ laser and less hydrogen atom was left in the obtained microcrystalline i-Si films.

To further clarify the microstructure and the chemical bonding characteristics of the i-Si films deposited with various assisting laser powers, the micro-Raman scattering spectra were measured and the results are shown in Figure 5. As shown in Figure 5, the Raman peak of the i-Si films shifted from 482 cm^{-1} to 512 cm^{-1} as the assisting laser power increased from 0 W to 80 W, indicating a gradual transformation from amorphous to crystalline Si. Therefore, these micro-Raman results verified that the CO₂ laser-assisted deposition led to an enhancement in the crystallinity of the i-Si films and the microcrystalline i-Si films were obtained when deposited with laser assistance of higher power.

The crystallinity of the i-Si films deposited with various assisting laser powers was also examined using X-ray diffraction (XRD) and the results are shown in Figure 6. In the XRD results, no diffraction peak could be found for

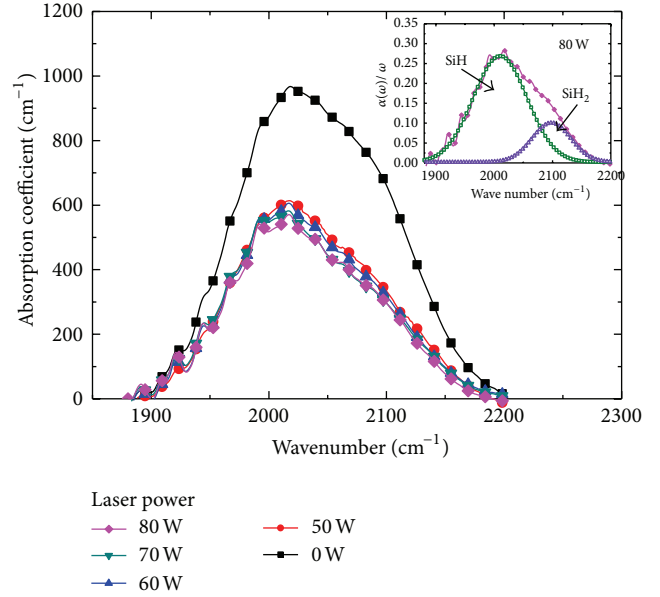


FIGURE 3: Absorption spectra $\alpha(\omega)$ of the i-Si films deposited with various assisting laser powers. The inset shows the absorption spectrum $\alpha(\omega)/\omega$ of the i-Si films with assisting laser power of 80 W.

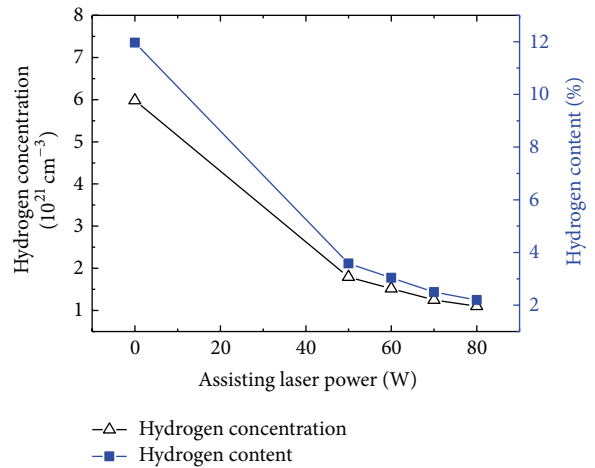


FIGURE 4: Hydrogen concentration N_{H} and hydrogen content C_{H} of the i-Si films deposited with various assisting laser powers.

the i-Si film deposited without laser assistance. On the contrary, for all of the i-Si films deposited with laser assistance, three main diffraction peaks at 2θ positions of 28.47° , 47.34° , and 56.17° were observed clearly, which correspond to the (111), (220), and (311) diffraction of the diamond-cubic Si, respectively. The above XRD results further confirmed that the microcrystalline i-Si films could be directly deposited using LAPECVD system at substrate temperature of 250°C .

Figure 7 shows the current density-voltage (J - V) characteristics of the p-SiC/i-Si/n-Si thin film solar cells deposited without and with 80 W laser assistance. The corresponding short-circuit current density (J_{sc}), open-circuit voltage (V_{oc}), fill factor (FF), and power conversion efficiency (η) were estimated and listed in the inset of Figure 7. The J_{sc} of

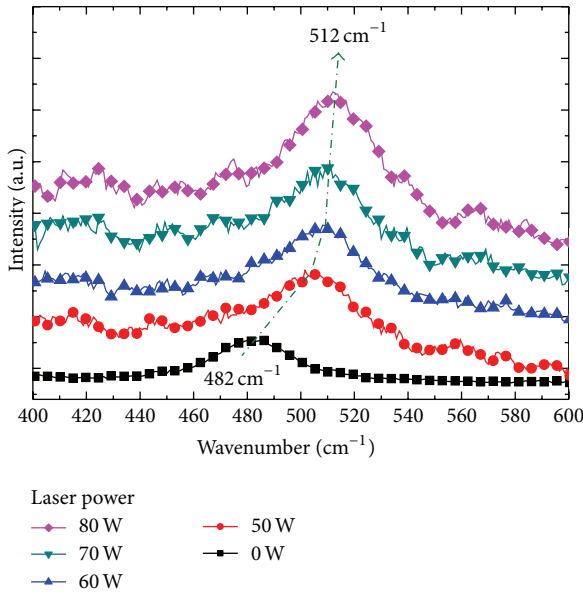


FIGURE 5: Micro-Raman scattering spectra of the i-Si films deposited with various assisting laser powers.

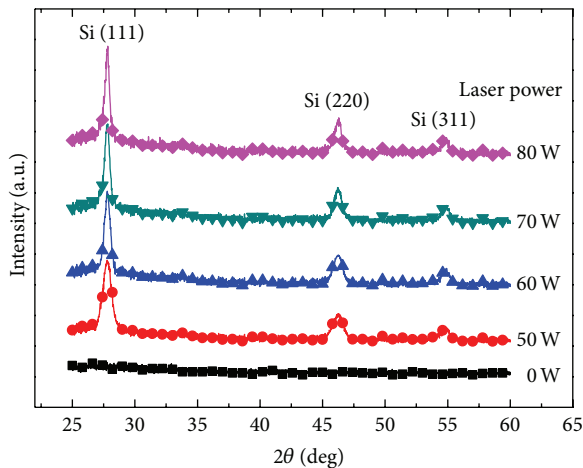


FIGURE 6: XRD spectra of the i-Si films deposited with various assisting laser powers.

the p-SiC/i-Si/n-Si thin film solar cells with 80 W laser assistance was 18.16 mA/cm^2 , much larger than the value of 14.38 mA/cm^2 for the cell without laser assistance. The increase in J_{sc} could be attributed to the enhancement of the crystallinity of the active layer i-Si film deposited with laser assistance. Besides, the electron and hole concentrations in the laser-assisted Si-based solar cells were higher than that in the non-laser-assisted Si-based solar cells. The high built-in electric field could be increased with the high carrier concentration, which increased the separation velocity of the photo-generated electron-hole pairs in the active layer. Therefore, it could reduce the carrier recombination and increase the J_{sc} of the resulted solar cells with laser assistance. On the contrary, the V_{oc} of the p-SiC/i-Si/n-Si thin film solar cells decreased from 0.80 V to 0.75 V as the assisting laser

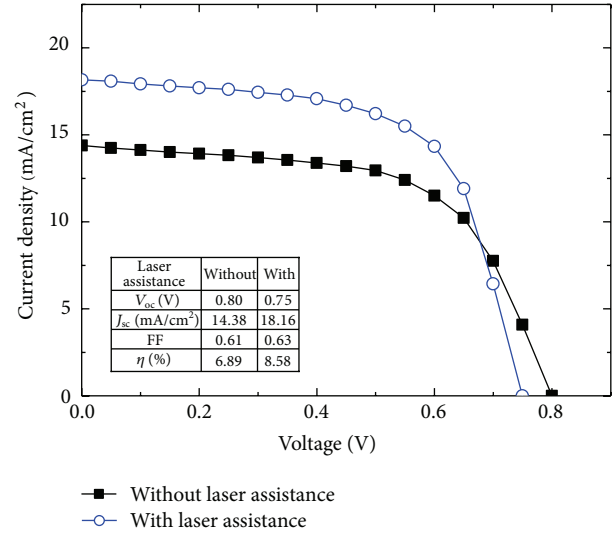


FIGURE 7: Current density-voltage characteristics of the p-SiC/i-Si/n-Si thin film solar cells deposited without and with assisting laser power of 80 W. The inset table shows the V_{oc} , J_{sc} , FF, and η of the p-SiC/i-Si/n-Si thin film solar cells deposited without and with assisting laser power of 80 W.

power used in the film deposition increased from 0 W to 80 W. The reduction of the V_{oc} for the laser-assisted Si-based solar cells was attributed to the crystallization variation of the i-Si absorption layer. The i-Si film deposited without laser assistance was amorphous, while the i-Si film deposited with laser assistance was microcrystalline. It is well known that the energy bandgap of the amorphous Si is larger than that of the microcrystalline Si, which interprets the obtained variation of V_{oc} . Furthermore, the FF of the p-SiC/i-Si/n-Si thin film solar cells decreased when the i-Si layer was deposited under higher assisting laser power. This phenomenon was attributed mainly to the reduction of the V_{oc} . As shown in Figure 7, the power conversion efficiency of the p-SiC/i-Si/n-Si thin film solar cells deposited with and without laser assistance was estimated to be 8.58% and 6.89%, respectively. The significant improvement of the power conversion efficiency for the laser-assisted Si-based solar cells was attributed to the fact that the laser-assisted i-Si absorption layer had lower hydrogen concentration and better crystallinity compared with the non-laser-assisted i-Si absorption layer.

4. Conclusion

In this work, the LAPECVD system was used to prepare the i-Si films as the active layers of solar cells. According to the FTIR measurement, the estimated hydrogen concentration of the deposited i-Si films decreased from $5.98 \times 10^{21} \text{ cm}^{-3}$ to $1.10 \times 10^{21} \text{ cm}^{-3}$ as the assisting laser power used during the film deposition increased from 0 W to 80 W. The micro-Raman and XRD measurements demonstrated that the i-Si films deposited without and with laser assistance were amorphous and microcrystalline, respectively. In particular, deposited with 80 W laser assistance, the high quality i-Si

films with low hydrogen content and microcrystalline structure were obtained.

The p-SiC/i-Si/n-Si thin film solar cells with the active layer i-Si deposited without and with 80 W laser assistance were fabricated and investigated. The short-current density of the laser-assisted Si-based solar cells was larger than that of the cells without laser assistance. The improvement in conversion efficiency of the laser-assisted Si-based thin film solar cells was more than 22.5% compared with the solar cells without laser assistance.

Conflict of Interests

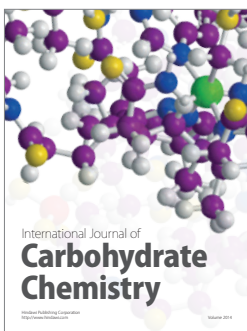
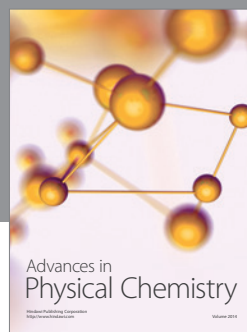
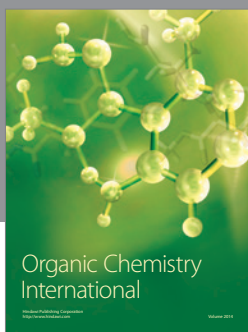
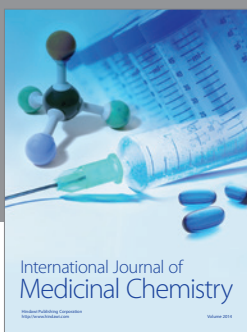
The authors declare that there is no conflict of interests regarding the publication of this paper.

Acknowledgments

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