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Optimization of the absorber layer for a-Si:H and a-$Si_{1-x}Ge_x$:H single-junction solar cells

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This paper focuses on the optimization of the absorber layers in single-junction a-Si:H and a-$Si_{1-x}Ge_x$:H solar cells. For a-Si:H thin-film solar cells, we have found the electrode-to-substrate (E/S) spacing is an important parameter. By optimizing the E/S spacing, the cell efficiency was improved from 7.62% to 8.70% due to an improvement in material quality and J_{SC}. For a-$Si_{1-x}Ge_x$:H solar cells, by optimizing the Ge-content, the microstructure parameter and the graded bandgap, we were able to improve the cell efficiency to 8.15%.

1 Introduction The use of hydrogenated amorphous silicon in the thin-film solar cell has become one of the low cost solar cell technologies since the first device was fabricated by Carlson [1]. The efficiency of the a-Si:H based thin-film solar cell has been improved to a record of 13% [2]. However, relatively little further improvement has since been made, mostly due to the defective nature of the amorphous material which seems to limit the performance of the solar cells. Although there have been many previous studies, it is still a challenge to obtain high quality absorber materials. Despite the shortcoming of the a-Si:H which suffers light-induced degradation [3], the large bandgap and high absorption coefficient still make it indispensible in either single or multi-junction solar cells. The optimization and innovation are still needed for further improvement of the amorphous material and the solar cells.

Similar to a-Si:H, the hydrogenated amorphous silicon germanium (a-$Si_{1-x}Ge_x$:H) had also attracted much attention [4]. The incorporation of germanium (Ge) in the a-Si:H film has the capability of lowering the optical bandgap while keeping the high absorption coefficient compared to the crystalline material. Nevertheless, it requires more effort to improve the material quality since alloying with Ge tends to introduce additional defects.

In this paper, some of our recent work on the optimization of the absorber layer in a-Si:H and a-$Si_{1-x}Ge_x$:H single-junction solar cells will be presented. Properties of the materials were improved by optimizing process parameters, and the corresponding improvements of the solar cell devices are shown.

2 Experimental A PECVD system with a frequency of 27.12 MHz was utilized to deposit amorphous film on commercial transparent conducting oxide (TCO) glass with substrate temperature kept at 200 °C. A superstrate configuration and a back reflector structure were used. In order to minimize the Staebler-Wronski effect (SWE) [5], an appropriate thickness of the updoped a-Si:H or a-$Si_{1-x}Ge_x$:H film was chosen for the active layers.

The single-junction a-Si:H thin-film solar cell consists of amorphous silicon-carbide p-layer as the window layer. The carbon content was adjusted by introducing different methane (CH_4) to silane (SiH_4) flow rates to obtain the optimized film considering both the optical bandgap and conductivity. On the other hand, doped amorphous silicon films were used for the amorphous silicon germanium cells. Germanium was added into the amorphous silicon germanium films by introducing germane into the silane and hydrogen gas mixture. Different bandgaps were obtained by adjusting the flow rate ratio of germane (GeH_4), R_{GeH4}, defined as (GeH_4) / (SiH_4+GeH_4) and the flow rate ratio of hydrogen, R_{H2}, defined as (H_2)/(SiH_4+GeH_4).

The microstructure parameter or the H-bonding configuration parameter, R, defined as the ratio of the integrated intensity of SiH_2 mode at 2100 cm^{-1} to that of the SiH_2 and SiH modes at 2100 cm^{-1} and 2000 cm^{-1}, or $SiH_2/(SiH+SiH_2)$, as obtained from Fourier transform infrared spectroscopy (FTIR) , was used as a measure of the film quality. The Ge contents in the a-$Si_{1-x}Ge_x$:H alloy were measured by X-ray photoelectron spectroscopy (XPS). The solar cells were characterized with an AM1.5G illuminated I–V measurement system and a quantum efficiency (QE) instrument.

3 Results and discussion The use of the undoped a-Si:H in the thin-film solar cell as the absorber layer requires a high quality material with low defect density in order to reduce the electron-hole recombination and the light-induced degradation. The process parameters can significantly influence the gas-phase and the surface reactions during film growth, reflected by the different bonding structure of the deposited film. Figure 1 shows the FTIR spectra acquired from the films with different electrode-to-substrate (E/S) spacing. The large E/S spacing during deposition brings about more gas phase reactions leading to a less dense and defective structure. As the E/S spacing increased from 14 mm to 25 mm, the deposition rate increased from 0.21 nm to 0.33 nm. Accompanied with the increasing deposition rate, the peak located at 2100 cm^{-1} increased, leading to an increase in the microstructure parameter, R, from 0.04 to 0.29. The SiH_2 bonding configuration often indicates a weakly bonding structure associated with the light-induced degradation [6]. It is believed that the dangling bonds created may become recombination centers that suppress the transport of the photo-generated carriers. The calculated H-content from IR spectrum increased from 10.7% to 15.6% as the E/S spacing increased. Although the H-content increased, the bandgap stayed unchanged.

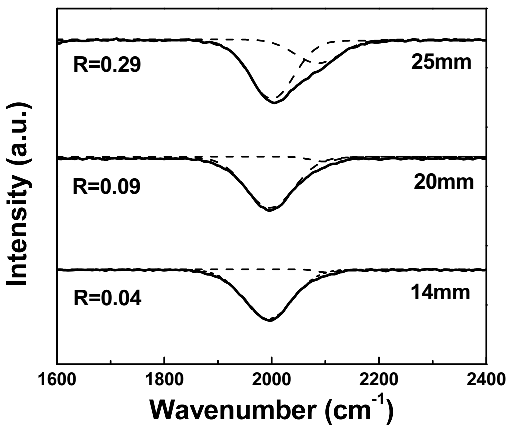

Figure 1 The FTIR spectrum obtained from a-Si:H films with different E/S spacing (mm) showing variations of microstructure parameter, R.

The I–V measurement corresponding to the solar cells with different E/S spacing is shown in Fig. 2. The a-Si:H single-junction solar cells have an absorber layer thickness of 300 nm. With increasing the E/S spacing, the cell efficiency dropped from 8.42% to 7.62%. This is mainly due to the decreasing current density (J_{SC}) from 12.59 mA/cm^2 to 11.41 mA/cm^2, while the open-circuit voltage (V_{OC}) remains the same (0.91 V). According to the previous FTIR results, the higher R corresponds to a higher SiH_2 content, and a more defective film. It is likely that the cell performance could be further improved with even smaller E/S spacing, had it not been limited by the equipment.

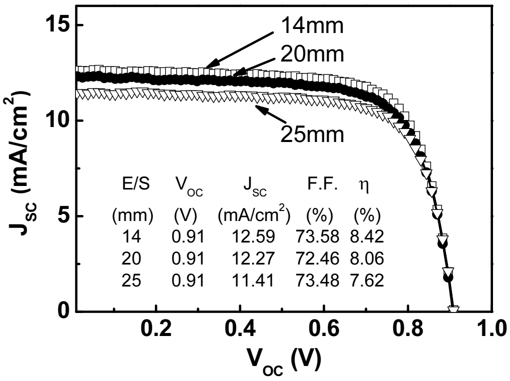

Figure 2 J–V characteristics of the absorber layers prepared with E/S spacing of 14 mm, 20 mm and 25 mm, respectively.

We have also studied the a-$Si_{1-x}Ge_x$:H single-junction solar cells which is used in multi-junction solar cells to boost the absorption of long-wavelength photons. Germanium was alloyed into the amorphous silicon film through the addition of GeH_4 gas during deposition. However, the incorporation of Ge inevitably introduces defects in the film which is unfavorable for the extraction of the photo-generated carriers. Therefore, hydrogen was also introduced not only to improve the film quality [7] by reducing dangling bonds and SiH_2 content, but also to increase the incorporation of Ge in the film.

This is shown in Fig. 3, where the increase in GeH_4 flow, or the film Ge content, is accompanied by a higher R. As the R_{GeH4} increased from 8.3% to 16.7% under hydrogen dilution ratio of 3, the Ge content increased from 26 at% to 37 at%, which was accompanied by an increase in R from 0.04 to 0.11. We found that Ge is preferentially incorporated into the film as compared to the GeH_4 content in the gas phase. Such an enhancement of the Ge incorporation corresponds to a factor of 2.3–3.3 compared to Si.

By introducing more hydrogen during deposition, the microstructure parameter can be effectively reduced from 0.4 to 0.1. However, too much hydrogen can be detrimental due to powder formation in the reactor, resulted in an increase in R.

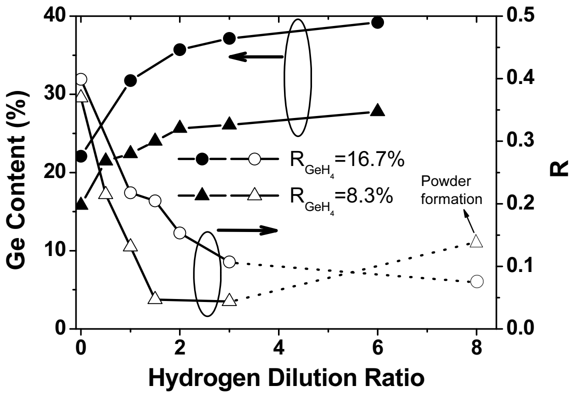

Figure 3 Ge content and microstructure parameter (R) as a function of hydrogen dilution ratio with R_{GeH4} of 8.3% and 16.7%.

The shift of the optical absorption of the a-$Si_{1-x}Ge_x$:H solar cells can be verified by the external quantum efficiency (EQE) measurement. Figure 4 shows the comparison of the solar cells with different Ge content. By increasing the Ge content in the film, the bandgap decreases, allowing more absorption of low energy photons. The position of the absorption peak shifted from 520 nm to 590 nm, as the film Ge content changed from 0 to 37.2% and the bandgap moved from 1.75 eV to 1.51 eV. The photo-generated current also extends to a wavelength near 900 nm. The maximum value of EQE obtained from a-Si:H was 81.7% which is much higher than the cell with the a-$Si_{1-x}Ge_x$:H. Such a reduction in carrier collection is consistent with a more defective nature of the a-$Si_{1-x}Ge_x$:H films. Although the long wavelength response was increased, there is still much room for further improvement of the a-$Si_{1-x}Ge_x$:H film quality.

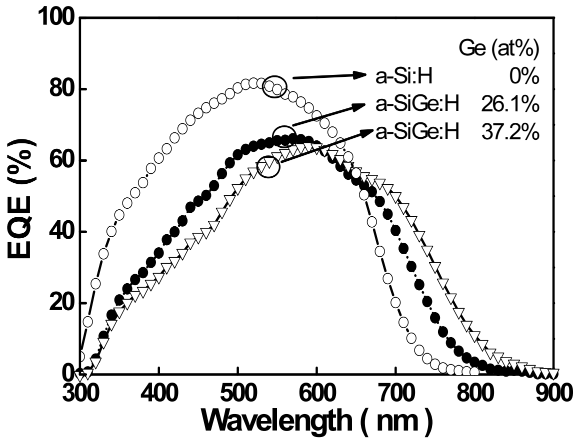

Figure 4 External quantum efficiency (EQE) of solar cells with Ge content ranged from 0% (a-Si:H) to 37.2% showing peaks shifting toward long wavelength.

In the fabrication of the a-$Si_{1-x}Ge_x$:H solar cells, the doped a-Si:H is used as the p- and the n- layers. As a result, the bandgap mismatch between a-Si:H and a-$Si_{1-x}Ge_x$:H creates a barrier for carrier transport. Previous reports [8] have proposed a graded bandgap structure in the absorber layer not only effectively increases the short wavelength absorption near the p/i interface, but also enhances the hole transport near the i-n interface. Here, we modulated the GeH_4 flow rate to control the bandgap to be graded from 1.75 eV (a-Si:H) to 1.52 eV (a-$Si_{1-x}Ge_x$:H). The band structure in the absorber layer thus became like a U-shape in which the lowest bandgap was located in the middle of the i-layer.

Compared to the cell with constant bandgap, the J-V measurement result, showed in Fig. 5, reveals an improvement of the a-$Si_{1-x}Ge_x$:H device with absorber layer thickness of 240 nm. The collectively increase in V_{OC}, J_{SC} and F.F. contribute to a significant increase in cell efficiency from 7.53% to 8.15%.

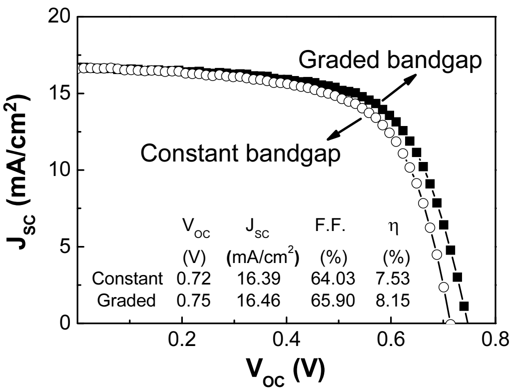

Figure 5 J-V characteristics of the a-$Si_{1-x}Ge_x$:H solar cells with constant and graded bandgap of the absorber layers.

The fabrication of the thin-film solar cell is a sophisticated process that requires careful optimization of each layer and treatment of interfaces. By integrating the techniques including thin-film optimization and the consideration of both electrical and optical properties, the efficiency of the a-Si:H and the a-$Si_{1-x}Ge_x$:H solar cells were improved to 8.70% and 8.15%, respectively. The lower bandgap of a-$Si_{1-x}Ge_x$:H leads to a smaller V_{OC} of 0.75 V, as compared to a V_{OC} of 0.89 V for a-Si:H cell. On the other hand, the a-$Si_{1-x}Ge_x$:H cell has a higher J_{SC}, indicating a better absorption near the infrared region. The different characteristics of the two types of the solar cells are demonstrated in Fig. 6.

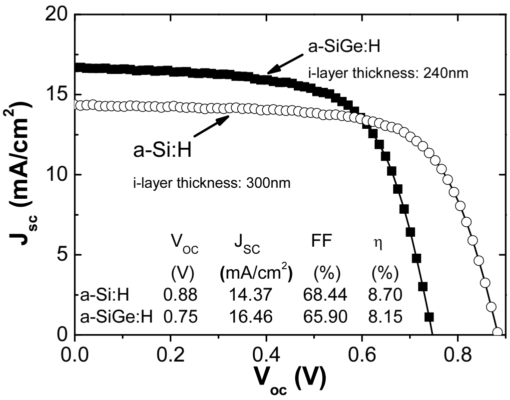

Figure 6 J–V characteristics of the a-Si:H and a-$Si_{1-x}Ge_x$:H single-junction solar cells

4 Conclusions We have found that the quality of the absorber layer can strongly influence the solar cell performance. In this paper we have studied both the a-Si:H and a-$Si_{1-x}Ge_x$:H single-junction solar cells. For the a-Si:H thin-film solar cells, we have found the E/S spacing is an important parameter. By optimizing the E/S spacing, the cell efficiency was improved from 7.62% to 8.70% due to an improvement in the material quality and short-circuit current. For the a-$Si_{1-x}Ge_x$:H solar cells, by optimizing the Ge-content, the microstructure parameter and graded bandgap, we were able to improve the cell efficiency to 8.15%.

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