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Performance of heterojunction solar cells with different intrinsic a-Si:H thin layers deposited by RF- and VHF-PECVD

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ABSTRACT

The effect of plasma excitation frequency on the performance of intrinsic hydrogenated amorphous silicon (a-Si:H) films and heterojunction solar cells by radio-frequency (RF, 13.56 MH_Z) and very-high-frequency (VHF, 40 MH_Z) plasma-enhanced chemical vapor deposition (PECVD) have been investigated. The thickness and microstructure of intrinsic a-Si:H films were measured by spectroscopic ellipsometry and Fourier transform infrared spectroscopy (FTIR). The a-Si:H/c-Si interface passivation quality were determined by minority carrier lifetime and transmission electron microscopy (TEM). The current–voltage (I–V) performance of the HJT solar cells were also evaluated. The results reveal that a-Si:H films developed by RF-PECVD with a large area of parallel-plate reactors (> 1 m^2) exhibit better thickness uniformity, lower microstructure factor, and higher minority carrier lifetimes. Hence HJT solar cells have achieved efficiency of 24.9%, compared with cell efficiency of 24.6% with intrinsic a-Si:H films developed by VHF-PECVD.

1 Introduction

Silicon heterojunction solar cell (HJT) technology is entering large-scale industrialization because of its high conversion efficiency and high power performance [1–5]. The high open-circuit voltage (V_{oc}) of the HJT solar cells is derived from the hydrogenated amorphous silicon (a-Si:H) film passivation on the dangling bond on the crystalline silicon (c-Si) surface [6, 7]. Therefore, the quality of the a-Si:H film during deposition is crucial for HJT performance.

Radio-frequency (RF, 13.56 MH_Z) PECVD is a suitable strategy for the large area deposition of a-Si:H films at low temperature with good film uniformity, but its higher ion bombardment energy could lead to damage to the crystalline silicon surface

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[8]. This is exacerbated when the RF power is increased, resulting in a higher growth rate. Very-high-frequency (VHF, 40 MHz) PECVD is another industrial process for a-Si:H film manufacture. The electric field intensity decreases with increasing excitation frequency, which reduces the bombardment of the c-Si surface [9]. In addition, the high electron density in the plasma increases the probability of electron collision with silane gas molecules, so a high amount of SiH_2 and SiH_3 in the reaction can be produced, resulting in a faster growth rate of the a-Si:H film [10–12]. Epitaxial layers are probably formed near the a-Si:H/c-Si interface [13, 14], which are defective and decrease the interface passivation [7]. However, there are only a few reports on the performance of a-Si:H single-layer films and HJT solar cells with intrinsic layers deposited by RF (13.56 MH_Z)- and VHF (40 MH_Z)-PECVD.

In this paper, the film thickness uniformity and microstructure of a-Si:H films fabricated by RF-and VHF-PECVD were measured and analyzed. The a-Si:H/c-Si interface passivation quality were investigated, and finally the current–voltage (I–V) performance of HJT solar cells were evaluated.

2 Experimental

N-type Czochralski (CZ) c-Si wafers with a thickness of 150 μm were used for the manufacture of HJT solar cells. As-cut M2 (156.75 × 156.75 mm^2) wafers underwent a saw-induced damage removal, texturing for pyramid morphology, chemical polishing, and standard RCA cleaning process. Intrinsic a-Si:H layers of the same thickness were deposited in conventional parallel-plate PECVD systems operating at RF (13.56 MHz) and VHF (40 MHz) excitation. Table 1 lists the main PECVD process parameters. The doped layers (p- and n-a-Si:H) were all deposited in the VHF-PECVD system under identical conditions. Transparent conductive oxide (TCO) films were sputtered by a direct current (DC) power supply at room temperature. Silver electrodes with 9-busbar were screen-printed on the ITO films. Figure 1 shows schematic drawings of HJT solar cell: (a) structure and (b) band diagram. Detailed experimental information about the HJT solar cells prepared has been published previously [15, 16].

The thickness and microstructure of a-Si:H films were measured by Syscos spectroscopic ellipsometry and Fourier transform infrared spectroscopy (FTIR). The a-Si:H/c-Si interface passivation quality were determined by a Sinton WCT-120 tester for minority carrier lifetime measurement and high-resolution transmission electron microscopy (HR-TEM) using an FEI Titan ETEM G2. The current–voltage (I–V) performance of HJT solar cells were measured using a triple-A class solar simulator.

3 Results and discussion

3.1 Intrinsic a-Si:H films

The intrinsic a-Si:H films were deposited by RF- and VHF-PECVD separately on glass substrates placed in the slot of a tray, and their thickness were tested by a Syscos spectroscopic ellipsometer. Figure 2 shows the thickness distribution of the intrinsic a-Si:H film over the tray with 7 × 8 square slots. The dimension of each slot was 15.7 × 15.7 cm, which was just for one M2 c-Si wafer. Intrinsic a-Si:H single -layer films by VHF-PECVD presented larger thickness deviations. Statistical analysis shows that the a-Si:H single-layer films fabricated by RF-PECVD have a thickness uniformity of 7.44%, while those fabricated by VHF-PECVD have a thickness deviation of 13.72%. The deposition rate, reactor size was similar for both RF- and VHF-PECVD, while the frequency was different. The large area of the parallel-plate reactor (> 1 m^2) equipped with a very-high frequency (40 MHz) power supply may cause a non-uniform voltage distribution across the electrode, resulting in a non-

Table 1 Main PECVD process parameter

Intrinsic a-Si:H	PECVD (MHz)	Temperature (°C)	Pressure (mbar)	Power density (mW/cm^2)
Film A	RF (13.56)	210	0.6	65
Film B	VHF (40)	180	0.6	33

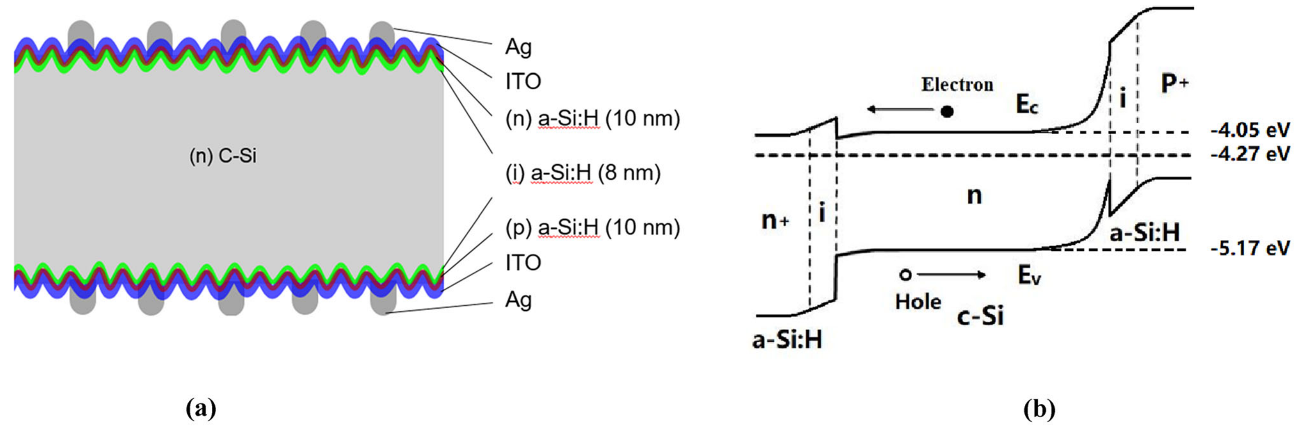


Fig. 1 Schematic drawings of HJT solar cell: **a** structure and **b** band diagram. E_c denotes the conduction band edge, E_v the valence band edge, E_f the Fermi level

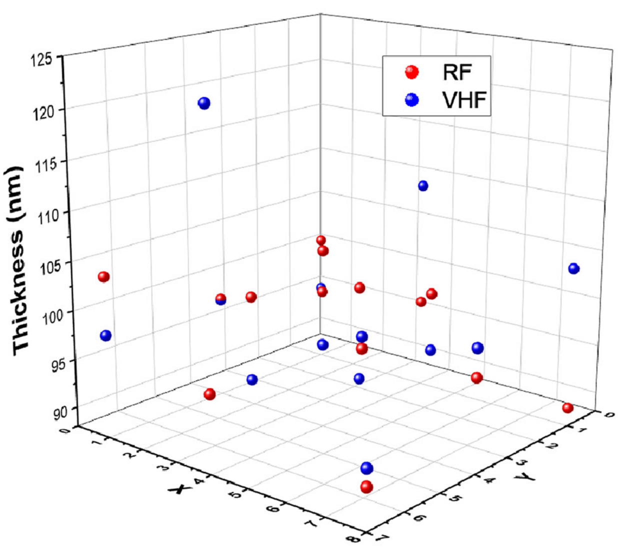


Fig. 2 Thickness distribution of intrinsic a-Si:H films in a tray

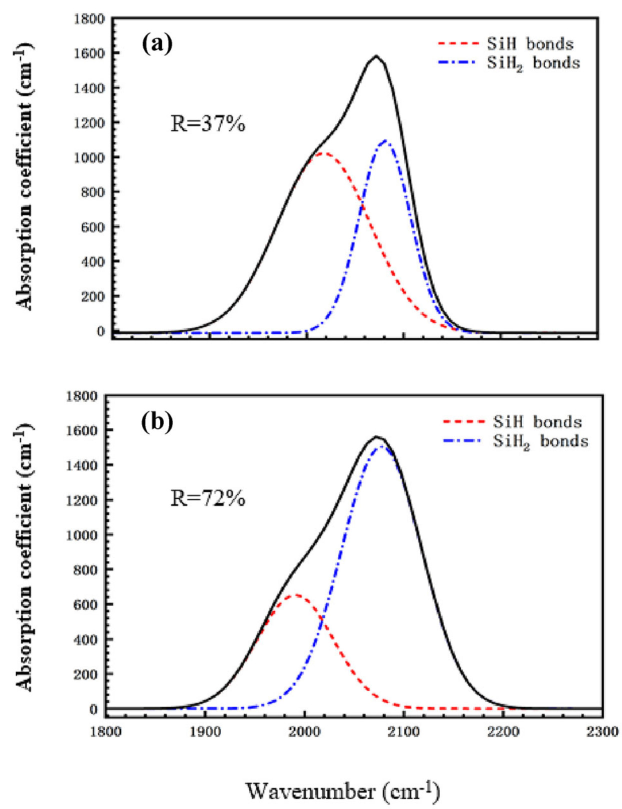


Fig. 3 FTIR absorbance spectra of intrinsic a-Si:H films prepared by **a** RF-PECVD and **b** VHF-PECVD

uniform film thickness originating from the standing wave effects [17, 18]. Therefore, film thickness uniformity is a challenge when using the VHF-PECVD method.

In addition, double-sided polished c-Si wafers (100 orientation) were used for structural measurements using a Nicolet IS-10 spectrometer. Figure 3a and b represent the FTIR spectra of a-Si:H layers deposited by the RF-PECVD and VHF-PECVD methods, respectively. IR absorption measurements reveal an amorphous network structure, discriminating between the compact and porous amorphous material. Peaks from mono-hydride (SiH) bonds (2000 cm^{-1}) and higher hydride (SiH_2) bonds (2090 cm^{-1}) were observed in the FTIR spectra. The microstructure factor R consists of the $I_{SiH2}/(I_{SiH2} + I_{SiH})$ ratio, which represents the quality of the films [19, 20]. As shown in Fig. 3a and b, intrinsic a-Si:H films B prepared by the VHF-PECVD system have a higher peak intensity at 2090 cm^{-1}, and a lower peak intensity at 2000 cm^{-1}.

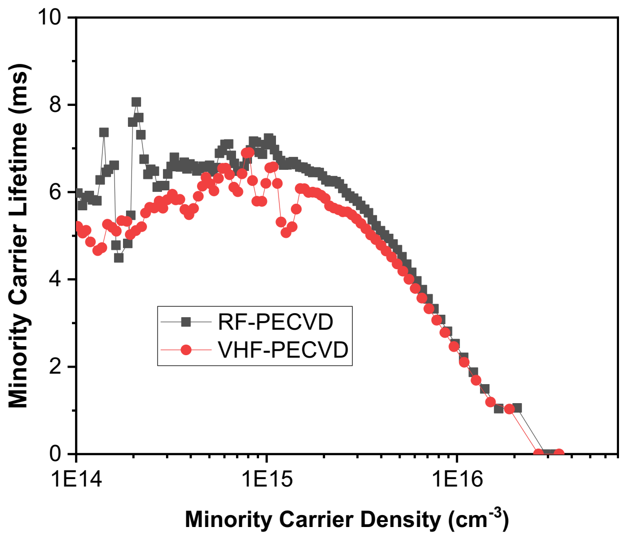


Fig. 4 Minority carrier lifetime as a function of minority carrier density for samples with intrinsic layers deposited in different PECVD systems

The calculated microstructure factor R for film B is 0.72 larger than that of film A (0.37), which means that the quality of the deposited a-Si:H film by VHF-PECVD is porous, containing voids and defect states [21, 22]. The low microstructure factor R for the intrinsic a-Si:H films A prepared by RF-PECVD could be attributed to the moderate ion bombardment that will affect the etching of the weak bonds and therefore result in improved material quality [23].

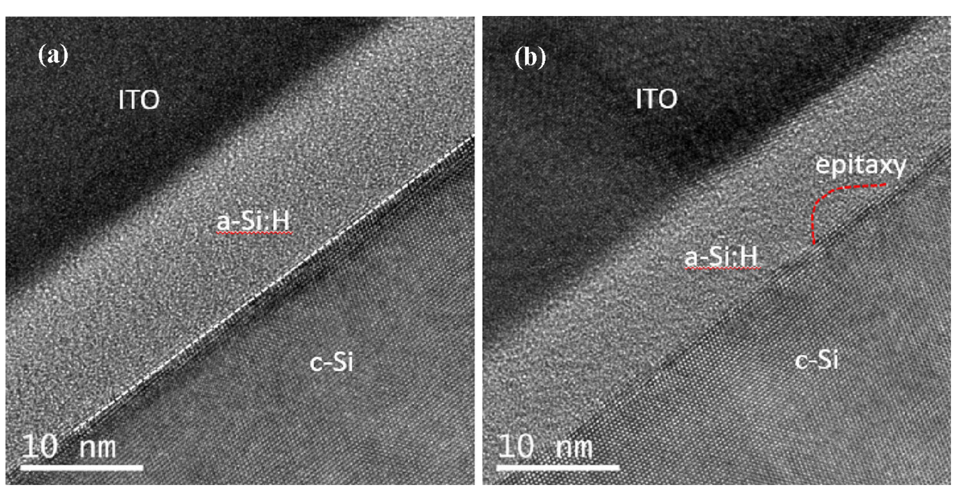
3.2 HJT solar cells

Figure 4 shows the minority carrier lifetime response as a function of time for the c-Si wafers passivation on both surfaces, with intrinsic a-Si:H films without annealing. In both cases, minority carrier lifetimes as high as 4 mms (at an excessive carrier density of 5×10^{15} cm^{-3}) were obtained, suggesting good passivation of the c-Si substrates. More importantly, the minority carrier lifetime for wafers with intrinsic layers deposited by RF-PECVD was higher than that of cells with the intrinsic layer deposited by VHF-PECVD, confirming the effectiveness of the passivation as suggested by the FTIR results in Fig. 3.

The a-Si/c-Si interface on the HJT solar cell was observed by cross-sectional TEM to further investigate the intrinsic layer passivation, as shown in Fig. 5. A local epitaxial component with a thickness of 2 nm appeared at the a-Si:H/c-Si interface for the cell with intrinsic layers deposited by VHF-PECVD, as shown in Fig. 5b, which could be attributed to the non-uniform a-Si:H thin film deposition and the non-optimized process. In comparison, a sharp interface and no epitaxial component exist in the a-Si:H/c-Si interface, as shown in Fig. 5a. It is possible that moderate ion bombardment at the surface of the c-Si acts as a barrier to prevent the epitaxial layer from forming.

Figure 6 shows the I–V curve of two cells prepared with RF- and VHF-plasma-deposited intrinsic a-Si:H films. Compared to VHF-PECVD, the efficiency of the RF-PECVD cell was higher by 0.3%, which can be attributed to the better a-Si:H film quality, thickness uniformity, and passivation quality resulting in higher V_{OC}, FF, and I_{SC}. The existence of a thin epitaxial layer at the a-Si:H/c-Si interface in Fig. 5b could explain the lower V_{OC} and FF for the HJT solar cell with VHF-PEVD-deposited intrinsic layers, due to the higher defect density at the interface [7].

Fig. 5 HR-TEM images of HJT solar cells with the intrinsic layers deposited by **a** RF-PECVD and **b** VHF-PECVD



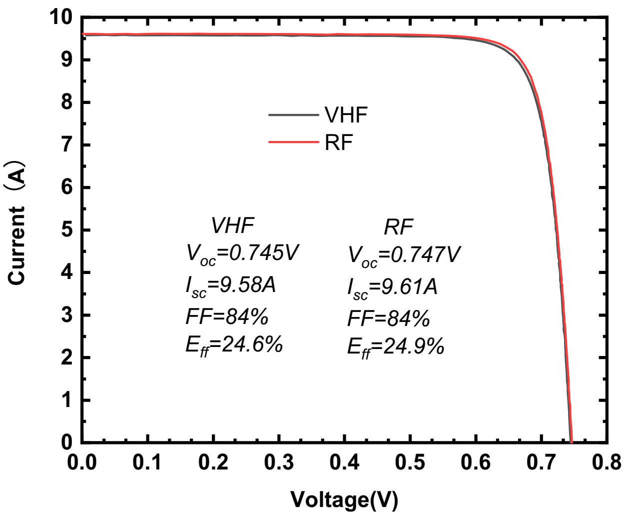


Fig. 6 IV characteristics of cells with different intrinsic layers deposited by RF- and VHF-PECVD

4 Conclusion

The performance of a-Si:H single-layer films and HJT solar cells prepared using RF- and VHF-plasma-deposited intrinsic a-Si:H films were compared. The a-Si:H film fabricated by RF-PECVD (large area of parallel-plate reactors, > 1 m^2) presented better thickness uniformity, material quality and a-Si:H/c-Si interface passivation performance, and thus higher overall efficiency. To improve VHF-PECVD-deposited a-Si:H films quality and prevent epitaxial silicon growth at the c-Si surface, further process optimization is necessary. Eliminating standing wave effect and improving film thickness uniformity put higher requirements for large area VHF-PECVD hardware design.

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