



Effect of Hydrogen Dilution on the Intrinsic a-Si:H Film of the Heterojunction Silicon-Based Solar Cell

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In this work, effects of a hydrogen dilution ratio on the intrinsic amorphous hydrogenated silicon (i-a-Si:H) film of heterojunction silicon-based (HJS) solar cells were systematically studied. Long lifetime samples were obtained for $R \leq 5$, indicating a good a-Si:H/c-Si interface. The dark conductivity was drastically decreased for $R \geq 2$, indicating a good film quality. Consequently, an optimized power conversion efficiency of the HJS solar cells was obtained at a moderate R between 2 and 5. In contrast to the previous emphasis on long lifetime, the results indicate that both the interface and film qualities are correlated to the hydrogen dilution, which are important to achieve high-efficiency HJS solar cells. We show that the most optimized HJS solar cell exhibits a marked efficiency of 17.27%.

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The heterojunction silicon-based (HJS) solar cell has recently attracted more attention because of its very high efficiency and simple structure which is composed of hydrogenated amorphous silicon (a-Si:H) layers and a crystalline silicon (c-Si) substrate.¹⁻³ All of the processes required to produce of the heterojunction solar cells can be implemented below 250°C using plasma enhanced chemical vapor deposition (PECVD) system and HJS solar cells with a high energy conversion efficiency (>23%) and record high open circuit voltage (V_{oc}) of >740 mV can thus be obtained.² The success of heterojunction solar cells is due to the insertion of an intrinsic a-Si:H (i-a-Si:H) layer between an emitter layer and a c-Si substrate. This i-a-Si:H layer effectively passivates the silicon surface, reducing the surface recombination velocity.

Numerous deposition parameters control the quality of an i-a-Si:H layer.⁴⁻⁸ The key considerations in setting the deposition parameters are the need to passivate the surface of a c-Si substrate; to prevent the initiation of the localized epitaxial growth at the a-Si:H/c-Si interface and to reduce the defects in a-Si:H films.^{4,9,10} Hydrogen dilution of the silane gas mixture is extensively used in the deposition of a-Si:H films in thin film solar cells to improve performance and stability.¹¹⁻¹⁴ Furthermore, some studies have discussed the effects of the H_2 dilution ratio ($R = SiH_4/H_2$) in HJS solar cells. Kim et al. pointed out that an R of 2-4 can effectively improve the efficiencies of p-type HJS solar cells compared to those without H_2 dilution.⁶ More recently, Jeon et al. and Dao et al. used radio frequency PECVD and inductive coupled plasma CVD, respectively, to deposit a-Si:H films on c-Si substrates with various R.^{7,8} The optimum R values to obtain the highest effective lifetime were very different ($R = 15$ for Jeon et al. and $R = 1$ for Dao et al.), perhaps because different deposition systems were used. Note that both groups studied the quality of the a-Si:H layer without the fabrication of HJS solar cells. Das et al. fully produced HJS solar cells with R values from 0 to 10.⁵ They found a high effective lifetime does not ensure a high HJS solar cell efficiency because of the low fill factor (FF).

In this work, the a-Si:H films were deposited using very high frequency (80 MHz) PECVD system at a low temperature of ~200°C with R values from 0 to 8. Surface passivation quality of i-a-Si:H films on c-Si substrates, microstructure at the a-Si:H/c-Si interface and the dark conductivity of i-a-Si:H films were investigated. We found that the quality at the a-Si:H/c-Si interface and the quality inside the a-Si:H film are both important to obtain high efficiency HJS solar cells.

The n-type CZ Si(100) substrates were cut into 2×2 cm. The resistivity and thickness were 1-5 Ω cm and 170 μ m, respectively. Samples were dipped in 5% HF to remove the native oxide layer

and were rinsed in de-ionized water. The a-Si:H thin films were deposited using a 80 MHz PECVD system. An i-a-Si:H layer with the a thickness of ~5 nm was deposited on a c-Si substrate, and then a B-doped a-Si:H film was deposited as a p-type emitter layer with a thickness of ~20 nm using B_2H_6 as the precursor. A Ga-doped ZnO (GZO) film with a thickness of 80 nm was sputtered on a p-type a-Si:H layer as an anti-reflection coating and conductive layer, and then an Ag grid layer using a shadow metal mask to define the grid pattern with a thickness of ~200 nm. To simplify and elucidate the effect of the H_2 dilution ratio ($R = H_2/SiH_4$), Ag/GZO layers were directly sputtered on the back of a c-Si substrate as metal contact layers without a back surface field (BSF) layer. The performance of each HJS solar cell was characterized under standard test conditions (25°C, 1000 W/m^2 , AM 1.5 G). The dark current-voltage (I-V) measurements were done to extract the conductivities of the i-a-Si:H films. The i-a-Si:H films were symmetrically deposited on the c-Si substrate to evaluate the quality of surface passivation, which was determined by the micro photo conductance decay (u-PCD, SemiLab WT-2000) to extract the effective lifetime. The microstructure at the a-Si:H/c-Si interface was investigated by high-resolution transmission electron microscopy (HR-TEM, JEOL- 2100F).

Figure 1 shows the PV characteristic parameters, including open circuit voltage (V_{oc}), short current density (J_{sc}), fill factor (FF), series resistance (R_s), and solar cell efficiency of HJS solar cells as functions of R in the intrinsic a-Si:H layers. There are some interesting findings can be extracted from Fig. 1. First, both V_{oc} and J_{sc} are almost unchanged when R is smaller than 5. They decrease drastically to 0.55 V and 22 mA/cm^2 , respectively, when R is larger than 5. Second, the series resistance decreases rapidly from 5 to 2 Ω as R is 2 and further decreases to 1 as R rises to 8. Third, the FFs increase with R. Fourth, the efficiencies of the HJS solar cells increase to 8.4% at R = 2, and remain almost the same as R increases from 2 to 8. Notably, the typical "S" curves are observed in the I-V measurement at $R < 2$.

The relationship between lifetime and V_{oc} is given by the following equation:

$$V_{oc} = \frac{kT}{q} \ln \left(\frac{J_{sc}}{J_0} + 1 \right) \quad [1]$$

and

$$J_0 = \frac{qn_i^2 W}{N_D \tau} \quad [2]$$

Here, K is Boltzmann's constant, T is the absolute temperature, q is the electric charge, W is the thickness of the silicon substrate and τ is the effective lifetime. N_D and n_i denote the donor concentration

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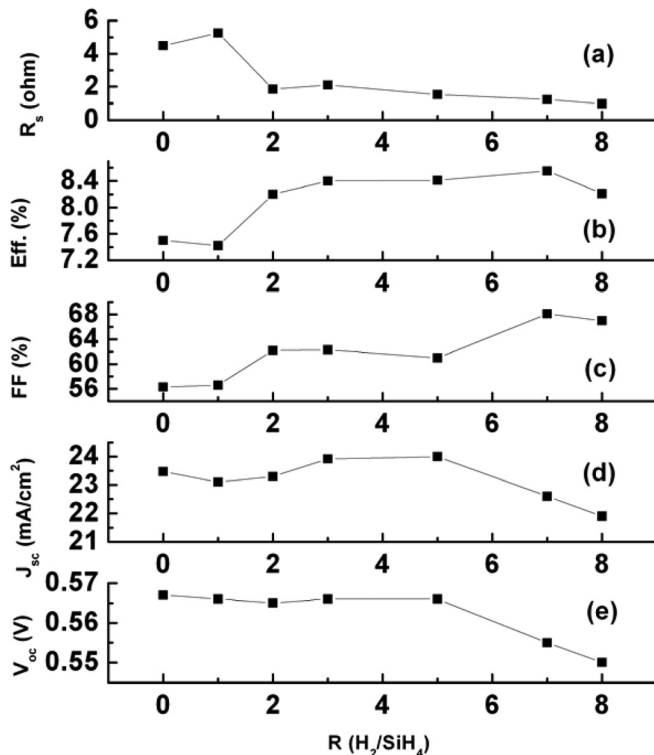


Figure 1. Photovoltaic characteristics of (a) series resistance, R_s (b) conversion efficiency, Eff. (c) fill factor, FF (d) short circuit current density, J_{sc} and (e) open circuit voltage, V_{oc} for HJS solar cells as a function of the hydrogen dilution ratio, R.

and intrinsic concentration of the silicon substrate, respectively. Figure 2 shows the effective lifetimes of i-a-Si:H films symmetrically deposited on n-Si substrates as a function of R. Two regions are clearly distinguished. All of the lifetimes are almost the same ($\sim 100 \mu\text{s}$) when R is smaller than 5, whereas decreases rapidly to $70 \mu\text{s}$ as R rises to 8. These results suggest that H₂ dilution in the a-Si:H films plays a critical role in the passivation of the c-Si substrates. This tendency is wholly consistent with the relation between V_{oc} and R in Fig. 1, which is consistent with Eq. 1. As mentioned earlier, localized epitaxy on a c-Si substrate seriously affects the passivation effect of a-Si:H films on a c-Si substrate. HRTEM was

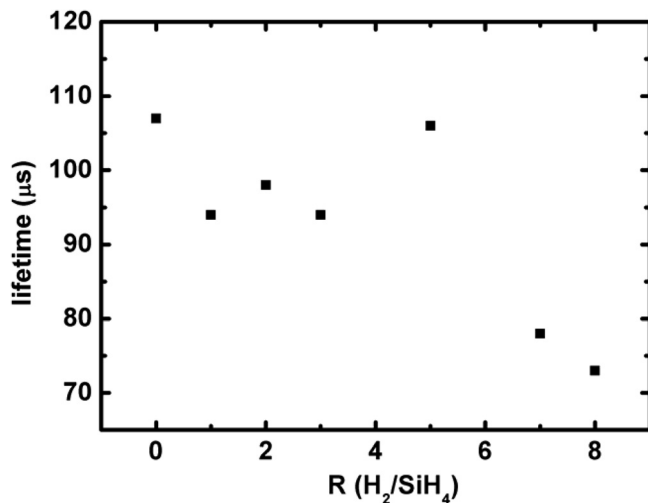


Figure 2. Effective lifetimes of i-a-Si:H films symmetrically deposited on n-Si substrates as a function of the hydrogen dilution ratio, R.

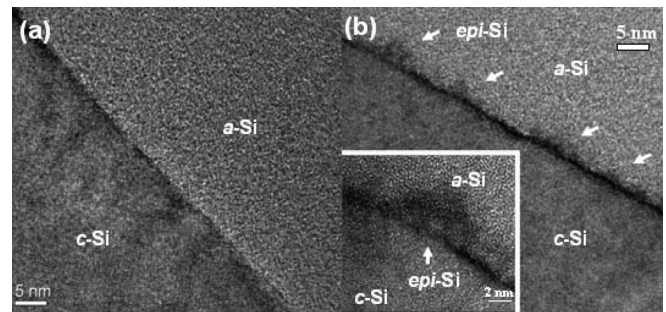


Figure 3. HRTEM images of the a-Si:H/c-Si interface at (a) $R=0$, (b) $R=8$.

utilized to investigate the micro-structure of an interface of an a-Si:H/c-Si, as shown in Fig. 3. The a-Si:H/c-Si interface with $R=0$ is abrupt while that $R=8$ exhibits localized partial epitaxial growth and is rough. In this study, the lifetime is reduced if the a-Si:H/c-Si interface is roughened. The localized epitaxial growth with an averaged size of $\sim 2.5 \text{ nm}$ scattered on the c-Si substrate suggests more dangling bonds which act as recombination centers in the midgap states at an interface of an a-Si:H/c-Si, leading to a poorer passivation.^{4,15}

Reducing the defect density of an intrinsic a-Si:H film is very important if the film is to be applied in an HJS solar cell. The dark conductivity of an a-Si:H film, which implies the quantities of defects, is widely used to evaluate the quality of an a-Si:H film.^{16–19} Carriers can transport in an a-Si film through the localized defect states by a defect-assisted hopping mechanism.²⁰ Figure 4 shows the dark conductivity of intrinsic a-Si:H thin films as a function of R. For $8 \geq R \geq 2$, the dark conductivity remains constant at about $1.6 \times 10^{-11} \text{ S/cm}$. However, the dark conductivity increases rapidly to about $6 \times 10^{-10} \text{ S/cm}$ at $R=0$, suggesting that hydrogen is critical to the conductivity of i-a-Si:H films. Very probably, these defects are passivated by hydrogen, which further hamper the transportation of carriers, reducing the dark conductivity. Notably, these defects act as recombination centers when the HJS cell is under illumination. Very recently, Rahmouni et al.¹⁰ showed by simulation that FFs decreased from 0.769 to 0.721 as the defect density in the i-a-Si:H film increased from 9×10^{14} to $9 \times 10^{17} \text{ cm}^{-3}$, indicating how defects inside the i-a-Si:H film affect the HJS cell performance. This can explain the low FF at $R=0$ in our study.

As mentioned earlier, the typical “S” curves are observed in the I-V measurement at $R < 2$. In an HJS cell, an i-a-Si:H film is sandwiched between an emitter layer and a base substrate. An i-a-Si:H

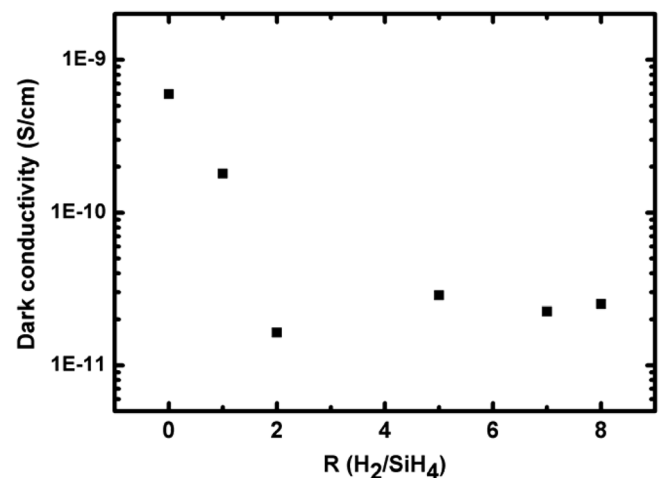


Figure 4. The measured dark conductivity values as a function of the hydrogen dilution ratio, R for the i-a-Si:H thin films.

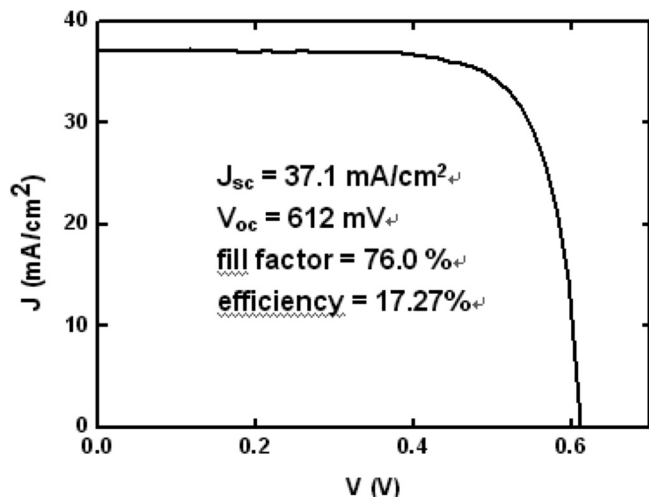


Figure 5. Illuminated current density-voltage (J-V) curve of the optimized HJS solar cell.

film in an HJS cell must be a good passivation layer to reduce the density of states on the surface of the silicon substrate. It also acts as a conducting layer through which minority carriers can pass under illumination. For example, an i-a-Si:H film with a high lifetime can be obtained at $R=0$, suggesting a good surface passivation. However, the dark conductivity results in Fig. 4 reveal too many defects inside an i-a-Si:H film, which make it too resistive to conduct minority carriers and further are responsible for a high series resistance, as shown in Fig. 1. Meanwhile, an i-a-Si film with a low dark conductivity can be obtained at $R=8$, suggesting high film quality. It had a low lifetime, indicating a worse interface property between the a-Si:H and the c-Si substrate, as supported by the microstructural observation in Fig. 3. The optimization of the i-a-Si:H films for the HJS solar cells is the trade-off between the series resistance and lifetime. Consequently, optimal i-a-Si:H films will be obtained at an R of 2–5. They have both a favorable film quality and a favorable interface property, which explain the HJS solar cell efficiencies at $R=2-5$.

An abrupt a-Si:H/c-Si interface (or a high effective lifetime) does not guarantee a high HJS cell efficiency, because the defects inside the i-a-Si:H film can seriously affect the HJS solar cell performance. Only when the defects inside an a-Si:H film are passivated (or reduced) and the a-Si:H/c-Si interface is abrupt, can a high HJS cell efficiency be expected. In this work, the spatial distribution of the defects of the a-Si:H film from the surface to the bulk is controlled by introducing the hydrogen during deposition. At $R=0$, a well-passivated surface with an abrupt a-Si:H/c-Si interface is obtained, but because of the insufficiency of the hydrogen, the defects in the i-a-Si:H film cannot be effectively passivated. As the amount of the

hydrogen is increased, the defects inside an a-Si:H film are passivated at $R=2-5$. As the amount of the hydrogen is increased further to $R=8$, localized epitaxy occurs at the a-Si:H/c-Si interface, detrimentally affecting the transportation of the minority carriers. The HJS solar cell with an optimized i-a-Si:H film and a back surface field layer showed an efficiency of 17.27% (aperture area) in Fig. 5.

Heterojunction silicon-based solar cells were fabricated by varying R from 0 to 8. The i-a-Si:H films with excellent passivation were obtained at $R \leq 5$. The i-a-Si:H films that were deposited at $R \geq 2$ contained fewer defects. Optimum HJS cell efficiencies were achieved at $2 \leq R \leq 5$. This result indicates not only an abrupt a-Si:H/c-Si interface but also a high a-Si:H film quality are required to optimize HJS cell efficiency.

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