

Research Article

The Compromise Condition for High Performance of the Single Silicon Heterojunction Solar Cells

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For optimum performance of the hydrogenated amorphous silicon/crystalline silicon (a-Si : H/c-Si) heterojunction solar cells, featuring a doping concentration, localized states, as well as thickness of emitter layer are crucial, since Fermi level, surface passivated quality, and light absorption have to be compromised themselves. For this purpose, the effect of both doping concentration and thickness of emitter layer was investigated. It was found that with gas phase doping concentration and emitter layer thickness of 3% and 7 nm, solar cell efficiency in excess of 14.6% can be achieved. For high gas phase doping concentration, the degradation of open-circuit voltage as well as cell efficiency was obtained due to the higher disorder in the emitter layer. The heavily doped along with thicker in thickness of emitter layer results in light absorption on short wavelength, then diminishing short-circuit current density.

1. Introduction

Heterojunction solar cells consisting of crystalline silicon (c-Si) and hydrogenated amorphous silicon (a-Si:H) offer a low cost and high efficiency energy conversion alternative to conventional crystalline silicon solar cells. Compared to conventional silicon solar cells with diffused n/p junction and back surface field layers (BSF), noteworthy cost reduction can be obtained due to a completely low temperature ($\sim 200^\circ\text{C}$) formation process for both the n/p junction and BSF layer using hydrogenated amorphous silicon technology. Presently, Sanyo's heterojunction with intrinsic thin layer (HIT) solar cells showed the world record efficiency of 23% for double-junction structure [1]. However, for the single-junction HIT solar cell fabricated on polished wafers has reported approximately 13 ~ 14% efficiency [2–6], in which the open-circuit voltage (V_{oc}) did not exceed 580 mV, and the fill factor 74% could be obtained. Beside Sanyo, most research groups have been working on single-junction HIT solar cell using p-type c-Si as a base substrate.

When using a-Si:H and c-Si for junction formation, there are different aspects to be taken into account. Firstly

to obtain high open circuit voltage (V_{oc}) and thus efficiency, the Fermi level in the emitter layer should be as close as to the nearest band as possible, which means that doping concentration is as high as it could be. The high doping concentration, nevertheless, also results in the high defect density in the films and leads to enhanced surface recombination [4]. The preferred doping concentration of emitter for HIT solar cell performance is still a matter of discussion. Sanyo's group has held world record efficiency of 23%, despite of, the limitation outside of Sanyo because of improper deposition condition such as doping concentration and so on. E. Conrad et al. suggested an optimal doping concentration ($\text{B}_2\text{H}_6/\text{SiH}_4$) of around 2000–3000 ppm [7]. Using simulation, N. Hernández-Como et al. proposed that the efficiency increases with increasing emitter doping concentration. Above a concentration of $3 \times 10^{19} \text{ cm}^{-3}$, the solar cell efficiency reaches its saturation value [8].

Also the emitter thickness variation could determine the short-circuit current as well as built-in potential in case of very thin layer of a-Si:H(p). On raising the emitter thickness, a-Si:H(p) layer incorporated into solar cells acts as a "dead

layer” and no electrons generated within the emitter layer are extracted due to intense carrier recombination within the defect emitter layer [9]. Reports on the optimum conditions varied in the literature and they can be classified roughly into two groups. Most research groups argue that 4 ~ 5 nm is thick enough for good device performances [1, 9]. While, emitter thickness of around 15 nm is mentioned to be thin enough by another [10]. In this paper, the compromise conditions for doping concentration, as well as the thickness of emitter layer, were investigated to set up a baseline for single p/n heterojunction solar cells.

2. Experiment

The commercial Czochralski-grown (CZ) c-Si(n) substrate with <100> orientation, resistivity of 1–10 $\Omega \cdot \text{cm}$, and 525 μm thickness has been used to fabricate the HIT solar cells. The crystalline Si substrates were treated by a sequence consisting of (1) acetone/methanol/DIW cleaning, (2) RCA cleaning. Native oxide was removed by a 1 min. dip in 1% hydrofluoric acid right before a-Si:H deposition. To change the doping concentration of the a-Si:H emitter, the gas phase doping concentration, $\text{B}_2\text{H}_6/\text{SiH}_4$, was varied in range of 2 to 10%, while the thickness of the a-Si:H emitter was fixed at 7 ± 0.05 nm. For the emitter thickness variation set, the gas phase doping concentration was 3%, the optimization condition in previous set, while emitter thickness varied in range of 3–15 nm. For the transparent conductive oxide (TCO), Indium Tin Oxide (ITO) thin film was deposited by rf magnetron sputtering at a substrate temperature of 200°C with thickness of about 80 ± 5 nm, followed by the deposition of silver/aluminum finger as the emitter contacts. Aluminum was evaporated on backside to create a good ohmic contact prior to area defining with mesa etching.

As confirmed previously [11], the a-Si:H(p) layer thickness controlled by spectroscopy ellipsometry (SE) shows excellent agreement with one evaluated from transmission electron microscopy (TEM). Hence, ellipsometry spectra (ψ , Δ) were collected using a rotating-compensator instrument (J. A. Woollam, HR-190) in this study. For the analysis, we used an optical model consisting of ambient/surface roughness layer (a-Si:H(p))/bulk layer (a-Si:H(p))/SiO₂/substrate (*n*-type c-Si), as shown in Figure 1. The dielectric function of the surface roughness layer was modeled as a 50/50 vol.% mix bulk layer material and voids [12]. The dielectric function of the a-Si:H(p) layer was modeled by the Tauc-Lorentz (TL) model [12], which is expressed by

$$\epsilon_{\text{imTL}}(E) \frac{A \cdot E_0 \cdot C \cdot (E - E_g)^2}{(E^2 - E_g)^2 + C^2 \cdot E^2} \cdot \frac{1}{E} \quad E > E_g, \quad (1)$$

$$\epsilon_{\text{imTL}}(E) = 0 \quad E \leq E_g,$$

where E_0 is the peak transition energy, E_g is the energy gap, and C is a broadening parameter, which can be related to the degree of disorder in the material. A is proportional to the height of imaginary part of the dielectric function. The

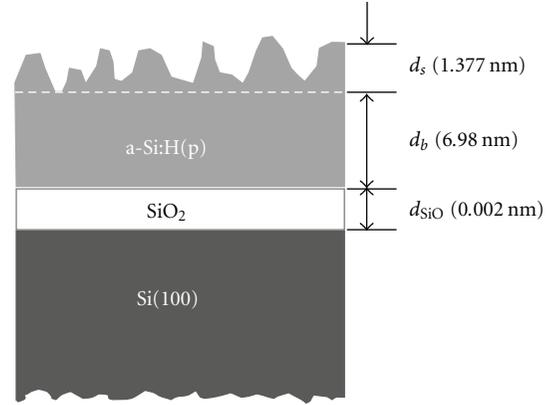


FIGURE 1: Optical model used for a-Si:H(p) layer formed on Si(100) substrates. The thickness for surface roughness layer, a-Si:H(p) layer, and SiO₂ layer is denoted as d_s , d_b , and d_{SiO_2} , respectively. The back-surface of the Si(100) substrate was roughened to eliminate back-side light reflection.

parameters of the dielectric function, the thickness of the films, and their roughness are obtained by analysis of the spectra using TL model. The values of the various parameters are reported in Table 1. To determine hetero-interface quality, the minority carrier lifetime (τ_{eff}) was measured by the quasi-steady-state photoconductance (QSSPC) method, using a commercial WCT-120 photoconductance setup from Sinton Consulting. The electrical characteristics and activation energy were studied using the coplanar method with a programmable Keithley 617 electrometer using the samples grown on the glasses. The optical transmittance was measured in the wavelength range of 300–1200 nm using UV-Vis spectrophotometer. The external quantum efficiency (EQE) measurements of heterojunction solar cells were performed by using xenon lamp, a monochromator, and optical filters to filter out the high orders with a light probe beam impinging normal on the sample. The solar cells were characterized by current-voltage measurement under AM1.5 conditions at 25°C.

3. Results and Discussion

From Figure 2, it is observed that the E_a decreases rapidly when X_g ($X_g = [\text{B}_2\text{H}_6]/[\text{SiH}_4]$) is increased from 2% to 3% and then it seems to saturate with further increase. As evidence from Figure 2(a), the minimum E_a is obtained for $X_g = 10\%$ and thus the best device performance should be obtained using this gas phase doping concentration. However, contrary to our expectations, the highest performance of device is observed for $X_g = 3\%$. The efficiency decreases for both higher and lower gas phase doping concentration. A similar variation is also observed for short-circuit current density (J_{sc}). The V_{oc} increases to a value of around 590 mV with the increasing in X_g of 3% and then seems to linearly shrink for further increase of X_g increases.

Figure 3 summarizes the degree of disorder (C) in a-Si:H(p) and minority carrier lifetime (τ_{eff}) of a-Si:H(p)

TABLE 1: Best-fit parameters extracted from the dielectric function modeling using the Tauc-Lorentz model. The results were obtained from the a-Si:H(p) thin films deposited at different gas phase doping concentrations.

X_g	d_s (nm)	d_b (nm)	d_{SiO} (nm)	A	E_0 (eV)	C	E_g (eV)
2%	1.978	7.082	0.052	80.88	3.97	1.69	1.62
3%	1.377	6.980	0.002	83.67	3.91	1.75	1.62
5%	0.909	7.071	0.154	93.96	3.84	1.82	1.59
10%	1.880	6.992	0.032	95.75	3.83	1.97	1.60

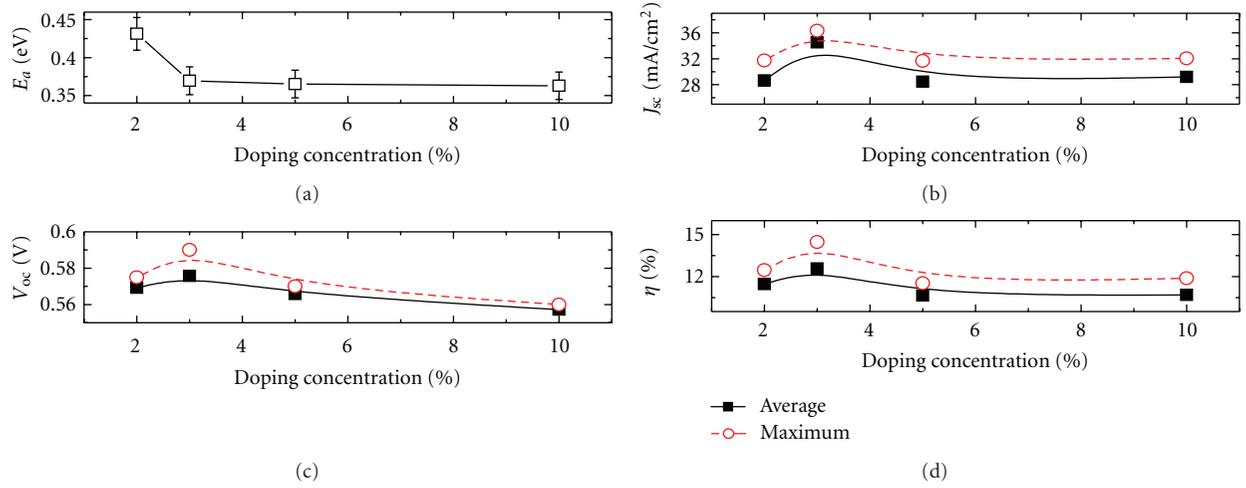


FIGURE 2: The activation energy, E_a , of a-Si:H(p) deposited on glass (a) and performance of Al/Ag/ITO/a-Si:H(p)/c-Si(n)/Al solar cells (b-d) with varying gas phase doping concentration of the a-Si:H(p).

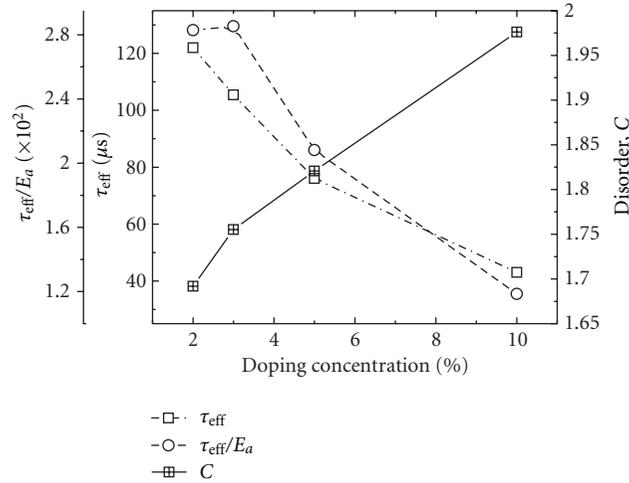


FIGURE 3: Minority carrier lifetime, τ_{eff} , measured on a-Si:H(p)/c-Si:H(n) structures, the degree of disorder in the a-Si:H(p), C, and trade-off factor, $Opt = \tau_{eff}/E_a$, as a function of the gas phase doping concentration.

deposited on c-Si(n) as a function of gas phase doping concentration of emitter layer. It is note that the C value is obtained from a well fit of the dielectric function of a-Si:H(p) using Tauc-Lorentz model, as discussing in the experimental part. It is clear that the trend of τ_{eff} and C displays a contrary direction and hence this also could be the reason for the reducing of V_{oc} when X_g is increased. As reported by R. A. Street, substitutional doping of a-Si:H(p) leads to the creation of deep defects [13]. This

leads to a self-compensation effect in a-Si:H(p). Hence, the disorder in the a-Si:H(p) leads to a higher amount of interface states and thus a decreased minority carrier lifetime of a-Si:H(p)/c-Si(n) heterojunction. By increasing gas phase doping concentration, eventually, on the one hand the band bending increases with increasing gas phase doping concentration, on the other hand the disorder in the a-Si:H layer and interface states (decrease in τ_{eff}) increases. Therefore, we suggest a new factor ($Opt = \tau_{eff}/E_a$) that may

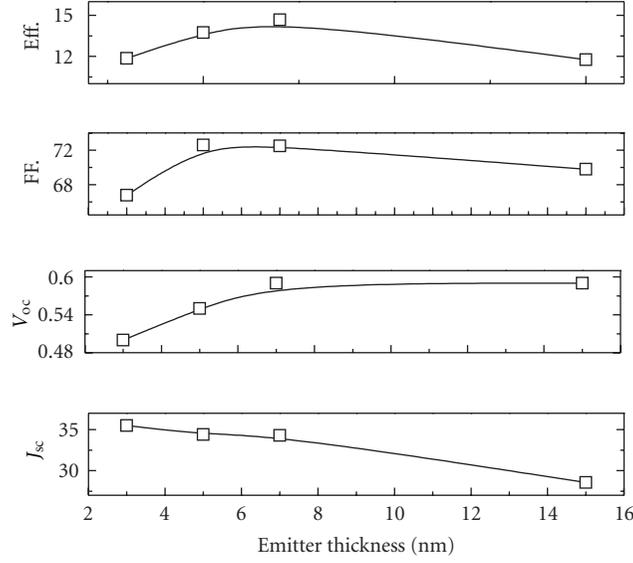


FIGURE 4: Solar cell parameters, short-circuit current density, open-circuit voltage, fill factor, and efficiency, as a function of a-Si:H(p) thickness for a-Si:H(p)/c-Si(n) heterojunction solar cells.

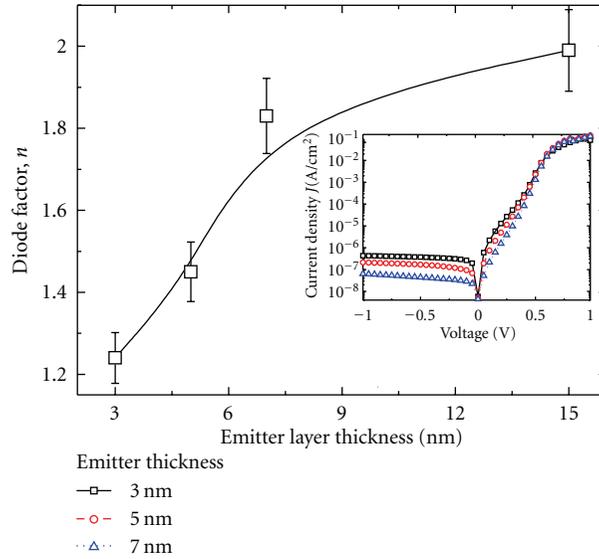


FIGURE 5: The diode factor n versus emitter layer thickness obtained from dark-current density versus voltage (DIV) with a-Si:H(p)/c-Si(n) solar cells shown in Figure 4. The inset shows DIV for a-Si:H(p)/c-Si(n) solar cells having different emitter layer thickness.

be presented as a trade-off between interface states and the position of the Fermi energy as showed in Figure 3. The highest Opt value is achieved at gas doping concentration of 3% and it is also point of merit for achieving highest device performance.

The parameters of an a-Si:H(p)/c-Si(n) solar cell, plotted as a function of the a-Si:H(p) emitter-layer thickness are shown in Figure 4. With increasing emitter-layer thickness up to 7 nm, V_{oc} increases linearly and then saturates beyond this layer thickness. It should be mentioned that for thickness smaller than 7 nm the open circuit voltage drops down to values around 500 mV. According to the usual junction rectification models for HIT solar cell at high forward bias

voltage region ($0.4 < V < 0.6$ V), a relation between J and V is presented simply by [9]

$$J = J_0 \left[\exp\left(\frac{qV}{nKT}\right) - 1 \right] - J_{ph}, \quad (2)$$

where J_0 and J_{ph} are the saturation current density and photocurrent density, respectively. q , n , k , and T denote electron charge, diode factor, Boltzmann's constant, and temperature, respectively. Since $\exp[qV/kT] \gg 1$ at $V \sim 0.5$ V and $T = 300$ K, J_0 and n can be determined directly from the intercept and slope of J - V characteristics by applying (2) with using dark-current density versus voltage, as shown in the inset of Figure 5. From Figure 5 we observed that

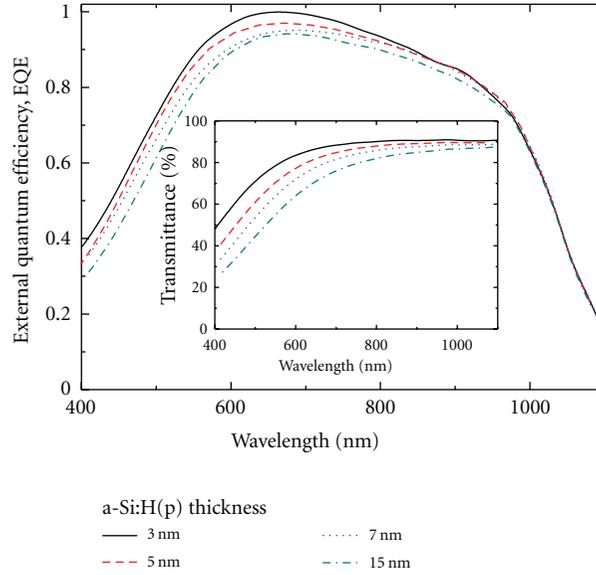


FIGURE 6: Variation of external quantum efficiency (QE) spectrum with a-Si:H(p) thickness. The inset shows that transmittance of a-Si:H(p) with different thickness was deposited on glass substrate.

$n \approx 1.25$ was obtained for a-Si:H(p) thickness of 3 nm and then this values increase with further increasing in layer thickness. The maximum of $n \approx 1.9$ was observed for layer thickness of 15 nm. Thus conduction mechanisms in our device are shifted from diffusion-recombination to recombination for thicker in emitter layer. The diffusion-recombination dominated for thinner emitter layer could be attributed to a smaller built-in potential in the ITO/a-Si:H(p)/c-Si(n) structure [9], leading to low V_{oc} . A similar variation with V_{oc} is also observed for FF with emitter thickness less than 7 nm; however, after passing through an optimum where the FF was maximized, a further increasing in emitter layer thickness resulted in a significant decrease of FF . This could be owing to the serial resistance component and also a lesser probability of tunneling of holes through a-Si:H(p) layer as thickness increases.

In contract to V_{oc} , J_{sc} reduces with increasing emitter-layer thickness. As a result, we obtained a solar cell efficiency of 14.6% ($V_{oc} = 590$ mV, $FF = 0.72$, and $J_{sc} = 34.3$ mA/cm²) at the optimum thickness of $p = 7$ nm without the incorporation of surface texture, intrinsic hydrogenated amorphous silicon. In Figure 6, the external quantum efficiency (QE) spectrum as a function a-Si:H(p) thickness was depicted. For convincing, transmittance of a-Si:H(p) layer with difference thickness was also measured and shown in the inset of Figure 6. It is clear that the thicker in emitter layer leads to lower in transmittance due to Lambert-Beer law. Thus, the QE of the thinner film is enhanced especially in the short wavelength region where the absorption of the a-Si:H films is low. Hence, the reduction in J_{sc} shown in Figure 4 may come from the degradation of the short wavelength response. It is well known that heavily doped a-Si:H layers generally exhibit quite high defect densities of $\sim 10^{18}$ cm⁻³, which is close to the defect densities of our a-Si:H(p) layer ($2.33 \sim 3.70 \times 10^{18}$ cm⁻³), separately

estimated by ellipsometry measurement on a-Si:H(p) films deposited on glass substrate. Due to its structure disorder and high doping, on the one hand, the diffusion length of the carrier in amorphous silicon layer is so small that only drifts current but no diffusion current can occur. On the other hand, the penetration depth of the space charge region in the a-Si:H side is so small that there is no electric field inside the layer. Thus, a heavily doped a-Si:H(p) layer incorporated into the heterojunction solar cells acts as a “dead layer”. For that reason it has to be as thin as possible.

4. Conclusion

In conclusion, the a-Si:H(p)/c-Si(n) heterojunction solar cell was set up for future development of high efficiency heterojunction with intrinsic thin (HIT) layer solar cells. The correlation between doping concentration, a-Si:H(p) layer thickness, and cell performance was discussed. An optimum value for gas phase doping concentrations of a-Si:H(p) was found to be 3%. For high gas phase doping concentrations, on the one hand the band bending increases with increasing gas phase doping concentration, on the other hand the disorder in the a-Si:H layer and interface states (decreases in τ_{eff}) increases. Hence, solar cell efficiency degrades. The a-Si:H(p) thickness of 7 nm is optimum for a-Si:H(p)/c-Si(n) heterojunction solar cell. Degradation of open-circuit voltage or short-circuit current density and hence efficiency was observed for thinner or thicker layers. Using optimized conditions, we obtained 14.67% efficiency for the a-Si:H(p)/c-Si(n) structure.

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