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Design and Optimization of High-Efficiency Amorphous/Crystalline Silicon Heterojunction (HIT) Solar Cells Using SCAPS-1D Simulation

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Abstract

The heterojunction structure of amorphous/crystalline silicon solar cells, a-Si:H(p)/a-Si:H(i)/c-Si(n)/BSF (a-Si:H(n⁺)/Au, was analyzed using numerical computer simulations. The study examined how the thickness, charge carrier concentration, and band gap of the a-Si:H layers affect solar cell performance. Additionally, the impact of defect density in the bulk material and at the emitter/wafer interface was explored. The study discusses the effect of incorporation of an intrinsic a-Si:H(i) buffer layer and a n-doped a-Si:H(n) back surface field layer, modeled solar cell structures with the configuration a-Si:H(p)/a-Si:H(i)/c-Si(n)/a-Si:H(n⁺)/Au. This study establishes design criteria for a-Si:H/c-Si heterojunction solar cells, identifying the optimal emitter thickness, band gap of emitter, buffer, and back layer.

Keywords: HIT solar cell; simulation; efficiency; AMPS; BSF

1. Introduction

The heterojunction with intrinsic thin layer (HIT) solar cell is a highly promising solar cell design that combines high efficiency with low cost. Its simple structure and excellent energy conversion ability attract significant interest in both theoretical and experimental research[1–3]. Low-temperature fabrication of HIT solar cells is favorable for using thin silicon wafers, which is mainly responsible for the major cost of crystalline silicon (c-Si)-based solar cells [4–7]. For HIT solar

cell, Sanyo company reported a conversion efficiency of 24.7 % in 2013 [8]. After that, in 2017, Yoshikawa et al. demonstrated record efficiency exceeding 26% for a c-Si solar cell with an IBC structure and an a-Si/c-Si Si HJ [9]. To achieve high-efficiency HIT solar cells, it is essential to understand and carefully optimize several key parameters.

In a typical HIT solar cell, the BSF layer is a heavily doped region located at the back of the crystalline wafer. In the BSF film, an amorphous silicon layer is deposited on the backside of the crystalline silicon. This configuration helps passivate the silicon wafer, and the doped a-Si:H provides a back field to the cell. It has been known that the BSF extends up to 1 μm with a higher doping level compared to the c-Si substrate[10]. Advantages to use a-Si:H layer because of its tunable band gap that can be adjusted during the deposition process, typically a-Si:H band gap varies from 1.6 eV to 1.8 eV[11]. In this study, we optimize with numerical simulation a HIT cell fabricated on n-c-Si wafer. The HIT solar cell structure consider as a-Si:H(p)/a-Si:H(i)/c-Si(n)/BSF/Au.

2. Numerical Modeling and Solar Cell Parameters:

To optimize the HIT solar cell for high efficiency, simulations were performed using the SCAPS-1D software [12–15]. This software was developed by Professor Mark Burgelman. SCAPS allows the study of semiconductor-based devices by solving the Poisson equation (Eq. 1) and the continuity equations for free electrons and holes (Eq. 2 and Eq. 3).

$$\frac{dE}{dx} = -\frac{\partial^2 \psi}{\partial x^2} = \frac{q}{E} [p(x) - n(x) + N_D^+(x) - N_A^-(x) + p_t(x) - n_t(x)] \quad \text{--- 1}$$

$$\frac{1}{q} \left(\frac{dJ_n}{dx} \right) + G_n(x) - R_n(x) = \frac{dn}{dt} \quad \text{--- 2}$$

$$\frac{1}{q} \left(\frac{dJ_p}{dx} \right) + G_p(x) - R_p(x) = \frac{dp}{dt} \quad \text{--- 3}$$

$G(x)$ is the electron and hole generation rate while the electron and hole recombination rates are $R_n(x)$ and $R_p(x)$, respectively.

3. HIT cell structure with a-Si: H/c-Si heterojunction

The HIT solar cell is a technology pioneered by SANYO, including an internal (i-type) amorphous silicon (a-Si) layer and a p-type a-Si layer laminated on top n-wafer. It adopts unique structure. The n heterojunction is made of textured n-type CZ crystalline silicon (c-Si) wafer [16].

For this simulation study the HIT solar cell structure is considered including layers of a-Si:H(p)/a-Si:H(i)/c-Si(n)/BSF/Au, the schematic of HIT cell is represented in Fig.1. It consists of an n-type crystalline silicon substrate (c-Si(n)) with a thickness of 165 μm on which is deposited by buffer intrinsic amorphous silicon (a-Si:H(i)) with a thickness of 8 nm. For the crystalline c-Si(n) absorber, a doping concentration of $N_D = 3 \times 10^{16} \text{ cm}^{-3}$ total defect density $N_t = 10^{10} \text{ cm}^{-3}$ was assumed across the entire bandgap. The intrinsic layer passivates the surface defects that existed on c-Si(n) surface. Then a emitter layer of p-type amorphous silicon (a-Si:H(p)) is deposited of thickness of 10nm forming a p-i-n heterojunction.

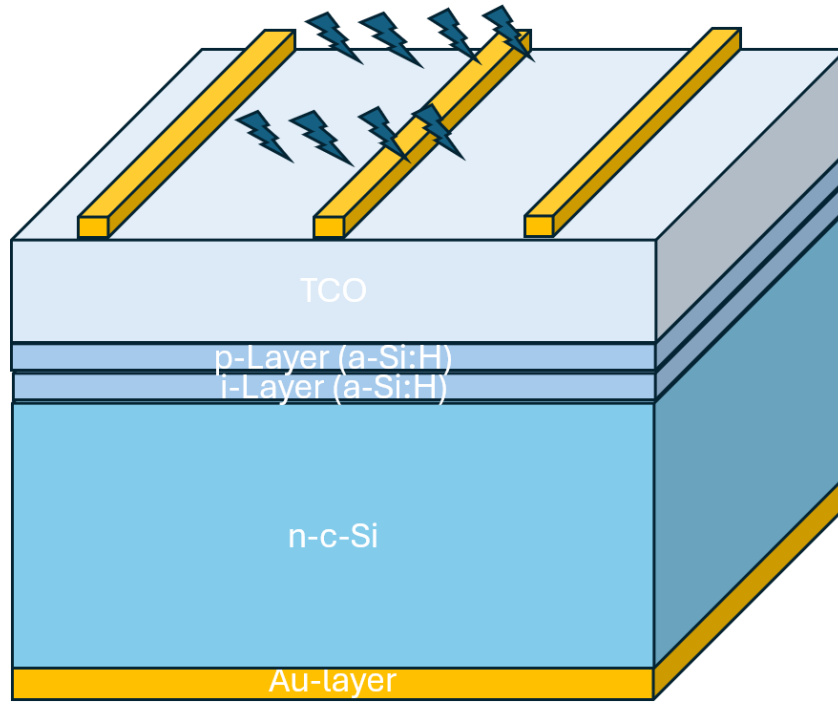


Figure 1. Schematic of HIT solar cell structure.

After that on top a Transparent Conductive Oxide (TCO) of ITO (Indium Tin Oxide) film is deposited on the p-layer. On the back of the solar cell, a heavily doped n-layer creates the Back Surface Field (BSF) layer is form by depositing highly doped amorphous a-Si:H(n) layer on

back side of c-Si, which creates a high potential barrier that pushes minority carriers back toward the bulk, enabling more effective collection of photogenerated carriers [17].

In our measurement for the amorphous silicon layers, including a-Si:H(p), a-Si:H(i), and a-Si:H(n), a band gap of $E_g = 1.6\text{-}1.7\text{eV}$ and an electron affinity of $\chi = 3.93$ were assumed. The doping concentration for the doped films was set to $N_A = 10^{17}\text{ cm}^{-3}$. The defect-state distributions within the band gap consist of exponential tail states and Gaussian dangling bond states. Moreover, this model assumes a constant total interface-state concentration, $N_t [\text{cm}^{-2}]$, at the a-Si:H/c-Si interface during the calculation. This simulation study optimizes layer parameters of HIT solar cell for the high performance. Moreover, establish the design criteria for a-Si:H/c-Si heterojunction solar cells, and identify the optimal emitter thickness, band gap of emitter, buffer, and back layer.

4. Results and Discussions

To optimize the layer parameters in HIT cells, a series of simulations was performed at room temperature using the SCAPS-1D software. The required parameters for the simulation study are available in literature and tabulated in Table 1.

Table-1: Input parameters of various layers of the HIT cell for simulations.

Parameters	a-Si:H(p)	a-Si:H(i)	c-Si(n)	BSF a-Si:H(n+)
Thickness	10nm	8nm	165 μm	20-50 nm
$E_g(\text{eV})$	1.72	1.72	1.12	1.12/1.7-2
ϵ	11.9	11.9	12	4.05/11.9
$\chi(\text{eV})$	3.8	3.8	4.05	3.9/3.8
$N_D(\text{cm}^{-3})$	--	--	1×10^{14}	$10^{15}/10^{20}$
$N_A(\text{cm}^{-3})$	1×10^{19}	--	--	--
$\mu_n(\text{cm}^2/\text{Vs})$	20	30	1450	1450/20
$\mu_p(\text{cm}^2/\text{Vs})$	5	10	450	450/5
$N_C(\text{cm}^{-3})$	1×10^{20}	1×10^{20}	1×10^{19}	$10^{19}/10^{20}$
$N_V(\text{cm}^{-3})$	1×10^{20}	1×10^{20}	1×10^{19}	$10^{19}/10^{20}$
$N_t(\text{cm}^{-3})$	1×10^{21}	1×10^{13}	1×10^{11}	1×10^{11}

Vth(cm/s)	1×10^7	1×10^7	1×10^7	1×10^7
Capture cross-section donor state e, h, (cm²)	$10^{-17}, 10^{-15}$	$10^{-17}, 10^{-15}$	$10^{-17}, 10^{-15}$	$10^{-17}, 10^{-15}$
Capture cross-section acceptor state e, h, (cm²)	$10^{-17}, 10^{-15}$	$10^{-17}, 10^{-15}$	$10^{-17}, 10^{-15}$	$10^{-17}, 10^{-15}$

Different layer parameters are optimized and used for the construction of HIT cells, which give photovoltaic (PV) characteristics, including Short Circuit Current Density (J_{sc}), Open Circuit Voltage (V_{oc}), Fill Factor (FF), and Conversion Efficiency (η). The simulation involved varying one parameter while keeping the others constant and then fixing the studied parameter at its optimal value for subsequent simulations. We also studied the effect of BSF on cell performance.

4.1 Effect of the BSF layer on the cell performance

Initially, cell performance was studied with and without BSF layer. All the photovoltaic parameters (V_{oc} , J_{sc} , FF, and η) with and without the BSF layer are tabulated in Table 2. It has been observed that after introducing the 100 nm BSF layer, cell efficiency improves from 17% to 27%, as shown in Figure 2. It shows that by including the BSF V_{oc} , ISC and FF have significantly improved, which is reflected in the performance of the solar cell.

Rahal et al. clearly explains the role of the BSF layer [18]. They note that with the BSF layer present, a strong electric field appears at the c-Si(n)/BSF junction. This field is negative, directed from the BSF layer toward the active layer, which enhances the cell performance. When the BSF layer is removed, the junction of c-Si(n)/BSF no longer exists, leading to the absence of an electric field ($E=0$ V/cm) and resulting in reduced performance [18].

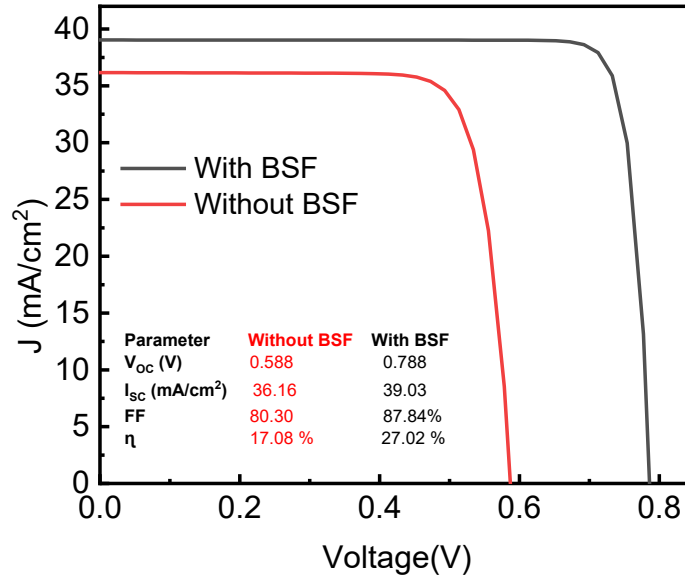


Figure 2: Effect of the BSF layer on the cell parameters.

Table-2: Cell parameters with and without BSF.

Parameter	Without BSF	With BSF
V_{oc} (V)	0.588	0.788
I_{sc} (mA/cm ²)	36.16	39.03
FF	80.30	87.84%
η	17.08 %	27.02%

4.2 Effect of the BSF Layer band gap on the cell performance

It is known that the band gap of hydrogenated amorphous silicon (a-Si:H) typically ranges from 1.6 to 1.8 eV. A major advantage of amorphous silicon is its ability to adjust, or "tune" its optical band gap by alloying it with other elements. Adding carbon (a-SiC:H) or nitrogen increases the band gap. Adding Germanium (a-SiGe:H) decreases the band gap [19]. Similarly, the hydrogenated form of microcrystalline silicon (μ c-Si:H) used in thin-film photovoltaics often possesses an optical band gap ranging between 1.2 eV and 1.5 eV, which can be optimized based on deposition conditions[20].

The BSF layer band gap can range from 1.2 eV to 1.8 eV, depending on whether the materials used are microcrystalline or amorphous. Therefore, the effect of the bandgap on solar cell parameters, such as V_{OC} , I_{SC} , FF, and η , was studied by varying the bandgap from 1.2 to 1.8 eV.

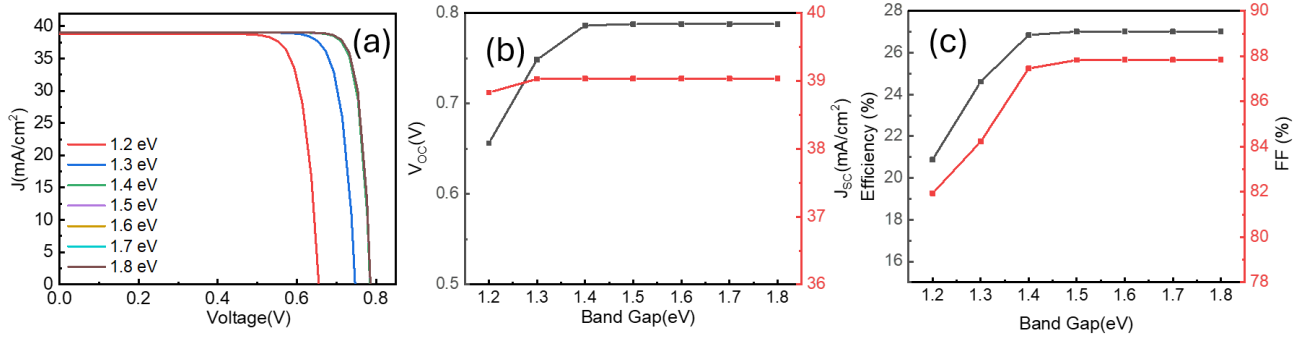


Figure 3. HIT cell characteristics of different BSF layer band gaps.

Figure 3a shows the JV characteristics curve of the HIT solar cell for different BSF layers of different band gaps. It is observed that V_{OC} increases with BSF band gaps, as shown in Fig. 3b. Figure 3c indicates that at 1.2 eV, the efficiency is 20.88%, and it increases significantly up to 1.5 eV, after which it saturates at 27.02%. It has been known that the wide band gap creates an energy barrier (band offset) in the valence or conduction band, depending on the cell polarity, as shown in Fig. 4. A higher band gap of BSF creates a valence band offset at the c-Si(n)/BSF interface. This barrier acts as a "field" that repels minority carriers (e.g., holes in an n-type wafer) away from the back metal contacts. This will enhance hole confinement, reducing recombination at the rear contact. Improves open-circuit voltage (V_{OC}) and fill factor (FF). A lower bandgap in BSF provides weaker confinement. Allows minority carriers to diffuse into the rear contact, increasing recombination losses. Results in lower efficiency compared to optimized heterojunction BSF designs [18]. Band diagram of n-type c-Si bulk with HIT BSF layer (p-i-n-n⁺) is shown in fig-4 [21]. When the BSF layer is added to the back side of c-Si(n), the front field at the heterojunction allows holes to easily overcome the valence-band barrier. Similarly, the electrons, the majority carrier in an n-type wafer, have higher mobility in a-Si than holes can easily be separated by the electrode[22].

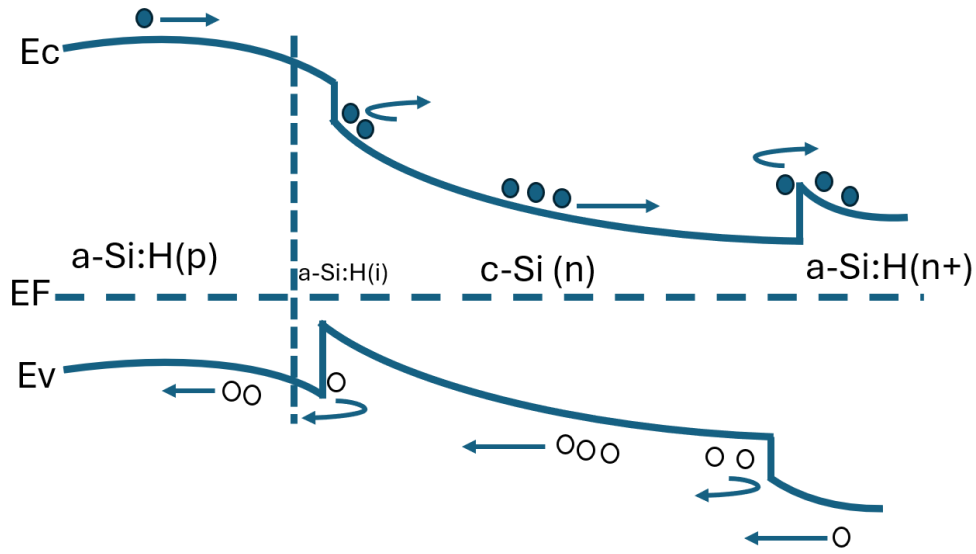


Figure 4. Band diagram of the HIT solar cell with BSF.

4.3 Influence of buffer layer (a-Si: H(i))

In a HIT silicon solar cell, the intrinsic amorphous silicon (a-Si:H(i)) layer is one of the most important parts of the device. It is placed between the crystalline silicon (c-Si) wafer and the doped amorphous silicon layers. The crystalline silicon surface contains many dangling bonds and defects that act as recombination centers. The intrinsic a-Si:H layer contains hydrogen, which passivates these dangling bonds, greatly reducing surface recombination. This results in higher carrier lifetime and higher solar-cell efficiency. Similar cell performance observed in our case for with and without a-Si:H(i) layer, cell efficiency is higher after the incorporation of an i-layer in HIT cells. Highest efficiency obtained 27.02% is shown in fig.-5. In addition, if the doped amorphous silicon layer were placed directly on crystalline silicon, Interface defects would increase, thereby increasing recombination. The intrinsic layer acts as a buffer between the crystalline wafer and the doped layers, creating a high-quality heterojunction interface. The intrinsic layer helps maintain favorable band alignment between c-Si absorber and the doped a-Si: H emitter/contact layers. This assists charge separation at each contact while minimizing recombination losses.

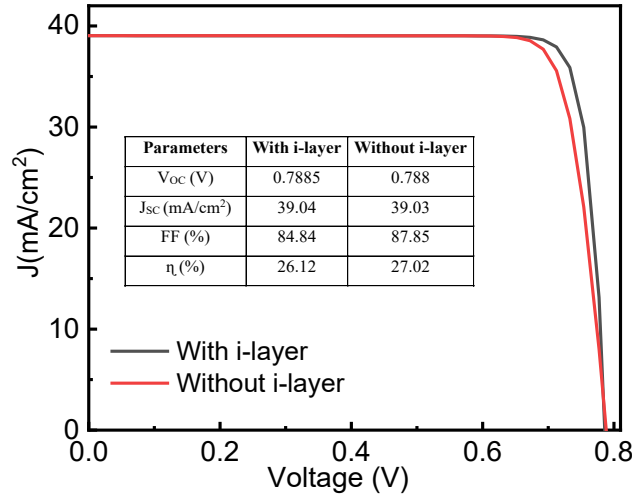


Figure 5. JV curve of HIT cell with and without buffer layer (a-Si:H(i)).

4.4 Influence of the thickness of the intrinsic Layer (a-Si:H(i))

In HIT solar cells, the intrinsic layer serves a dual role: it provides chemical surface passivation to reduce defects and allows carriers to tunnel more easily. Therefore, the 'i' layer must be adjusted to balance excellent passivation with optimal charge carrier extraction. The influence of the buffer layer (a-Si:H(i)) thickness on cell parameters was studied by varying it from 4 nm to 50 nm. Figure 6a displays the J–V curves of HIT cells with buffer layers of different thicknesses, which indicates up to 20 nm cure overlap on each other. Consequently, the efficiency ($\sim 27\%$) for these cells remains constant up to 20nm. However, with further thickness increments, efficiency decreases to 22.3% at 50nm, as shown in Fig. 6c. A slight increase in V_{oc} with a thickness, while J_{sc} decreases sharply with increasing layer thickness, displayed in Fig. 6b. The efficiency drops with a thicker intrinsic (i) layer mainly due to increased series resistance and higher recombination rates [23]. If the layer is made too thick, it creates a physical barrier that restricts the movement of charge carriers toward the electrodes. This increases the internal resistance of the cell, which directly reduces the Fill Factor (FF) and overall power output.

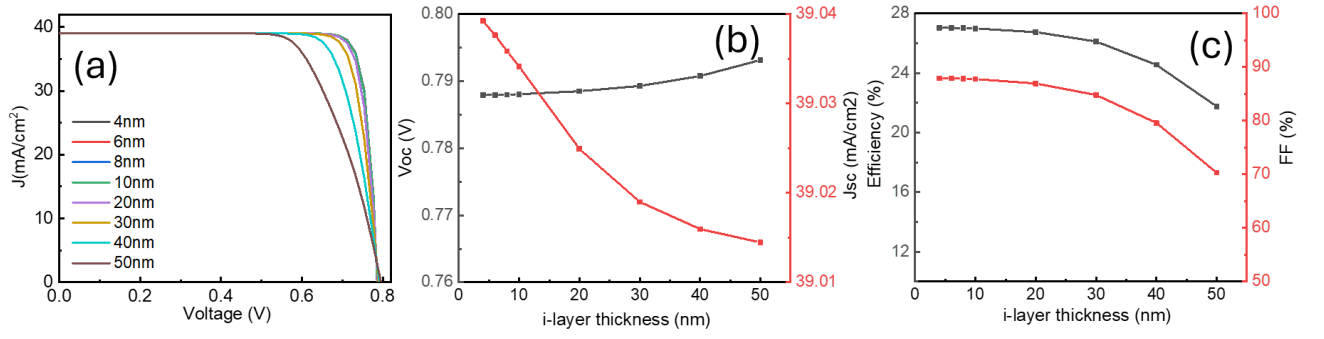


Figure 6. HIT cell characteristics with different i-layer thicknesses.

4.5 Influence of the Band gap of the Intrinsic (a-Si:H(i)) layer

The effect of the buffer (a-Si:H(i)) layer's band gap on cell parameters was studied by varying it from 1.6 eV to 1.8 eV. Figure 7a represents the JV characteristics curves of HIT cells of different i-layer band gaps, showing high value of FF for 1.6 -1.65 eV and decreases for band gap >1.65eV. It is known that on further increasing the band gap enlarges the heterojunction band offsets, creating carrier extraction barriers and increasing series resistance, which lowers the fill factor despite potentially better passivation [24]. Therefore, a high efficiency cell observed for a band gap of 1.6 -1.65 eV and declined sharply to < 2% for a band gap of 1.8 eV is shown in Fig. 7c.

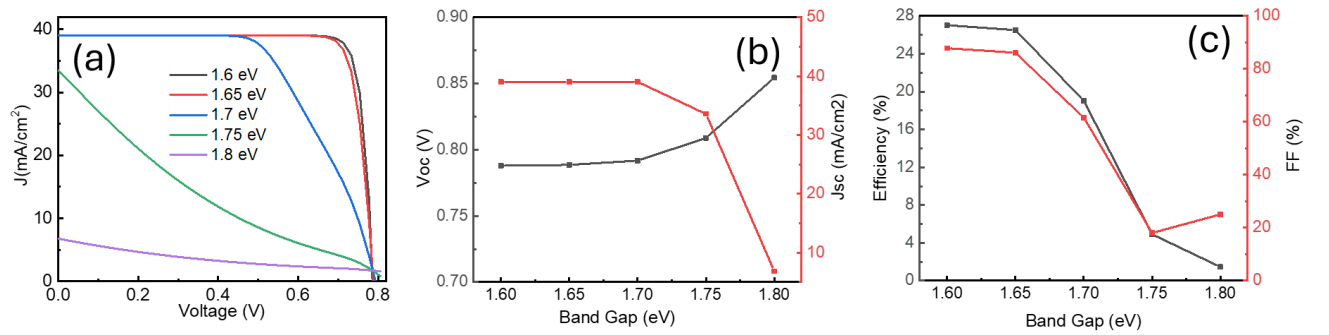


Figure 7. HIT cell characteristics for different a-Si:H(i) layers of variable band gap.

4.6 Influence of Donor density of c-Si(n)

In the literature, for HIT cells, the silicon wafer used has resistivity values considered optimal, in the range of 0.1 Ω cm to 0.5 Ω cm, which can be adjusted with doping [12, 16]. Therefore, to optimize the solar cell parameters, the doping density of the c-Si layer varied between $1 \times 10^{13} \text{ cm}^{-3}$

³ and $1 \times 10^{18} \text{ cm}^{-3}$, and cell characteristics were analyzed and are shown in Fig. 8. Out characteristics of HIT cell indicate, as the doping level increased from $1 \times 10^{13} \text{ cm}^{-3}$ to $1 \times 10^{16} \text{ cm}^{-3}$, a slight improvement observed in J_{sc} , V_{oc} , and fill factor (FF) that gives efficiency $>27\%$ (shown in fig 8b and 8c). As the concentration increased further, efficiency sharply declined to 19% observed at 10^{18} cm^{-3} .

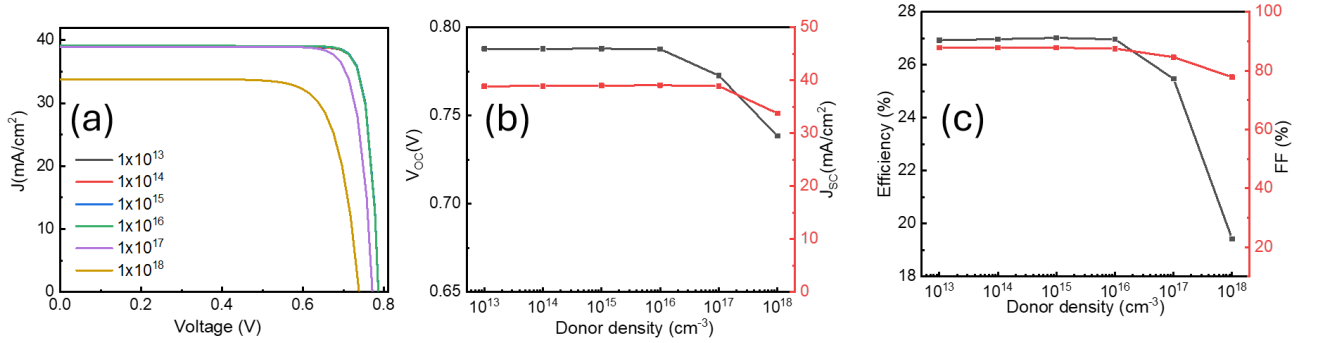


Figure 8. HIT cell characteristics of various c-Si with different donor concentrations.

That is because of higher doping increases recombination losses, reduces minority-carrier lifetime, and worsens band bending at interfaces, thereby limiting open-circuit voltage (V_{oc}) and fill factor. High doping increases band bending and interface defect density, potentially weakening passivation and increasing surface recombination[25]. Therefore, the optimal doping concentration of the c-Si wafer was determined to be $10^{15} - 10^{16} \text{ cm}^{-3}$. The present simulation results also suggest that the optimized doping level for c-Si (n) is in the range 10^{14} cm^{-3} to 10^{15} cm^{-3} .

4.7 Influence of defect density of c-Si(n)

Crystalline silicon is the active layer in a HIT solar cell, where light is absorbed, and charge generation occurs. Therefore, the quality of c-Si decides the cell performance. Therefore, the impact of defect density in the bulk (N_t) of the crystalline silicon active layer on the photovoltaic parameters (I_{sc} , V_{oc} , FF and efficiency) was studied by varying the defect density from 10^{11} cm^{-3} to 10^{15} cm^{-3} . Figure 9a shows the JV curve at different defect densities. It has been observed that as defect density increases, V_{oc} and I_{sc} decrease, as shown in Fig. 9b, thereby reducing the solar cell efficiency is shown in Fig. 9c. The highest efficiency is achieved at low defect density is 27.02% observed at 10^{10} cm^{-3} . This reduction in cell efficiency is mainly due to a decrease in minority-carrier lifetime, which is determined by defect density; it is high at low concentrations

and vice versa. It has been suggested that, to maintain high efficiency, τ should ideally exceed 1ms (corresponding to very low defect levels, typically in the range of 10^9 to 10^{10} cm^{-3}) [26]. Therefore, an optimum defect density of 10^{10} cm^{-3} was maintained for all simulation analyses in this study.

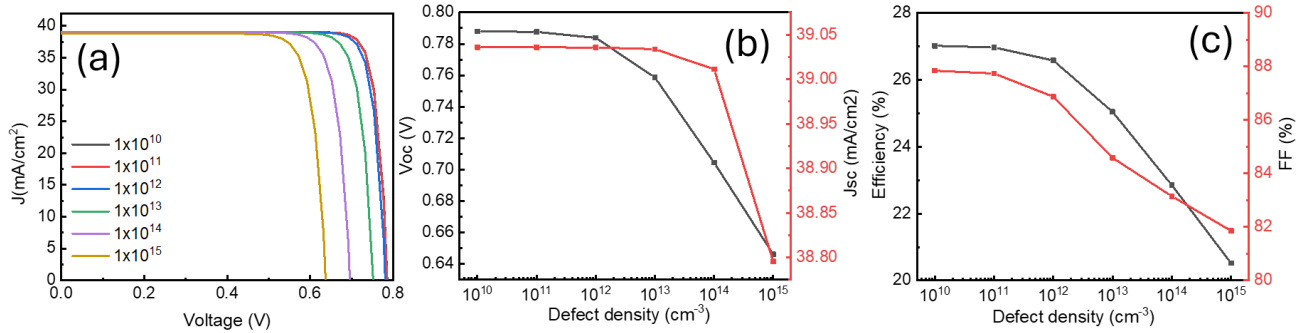


Figure 9. HIT cell characteristics for c-Si (n) with different defect densities.

4.8 Influence of band gap variation of the window a-Si:H(p) layer

The window layer of an amorphous silicon (a-Si:H(p)) solar cell requires a wide optical band gap to minimize light absorption. Standard amorphous silicon has a band gap of amorphous silicon is in the range 1.6 eV to 1.8 eV, and that can be adjusted by tuning the process parameters[19,27]. The performance of the HIT solar cell was evaluated by varying the band gap of the window layer (a-Si:H(p)). Fig. 10a displays the JV curve of a HIT cell with a different band-gap p-layer. It shows that V_{oc} and J_{sc} are nearly constant for all cells, therefore, it displays an overlapped curve observed in Fig. 10a. A similar result is observed in Fig.10b, which illustrates that V_{oc} and J_{sc} are steady over the entire band gap range. In Fig. 10c, a slight increase in efficiency with a band gap is observed at the beginning, then reaches a maximum of 27.02%, and remains steady afterward. A larger band gap in the window layer prevents from absorbing visible sunlight, allowing most of the solar spectrum to pass through to the active absorber layer (c-Si), where electron-hole pairs are generated. If the band gap were smaller, the window layer would absorb some sunlight, reducing the number of photons reaching the absorber and decreasing overall efficiency. A wide band-gap window layer also maintains better band alignment with the absorber, minimizing recombination at the front interface and increasing V_{oc} .

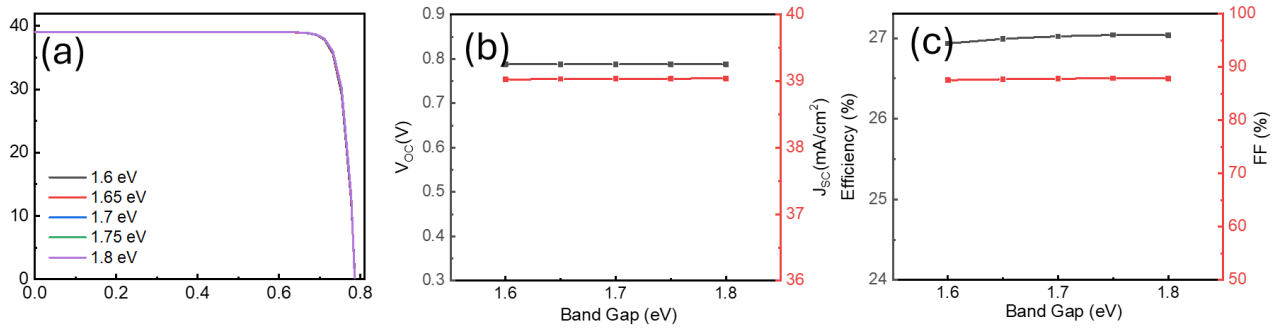


Figure 10. HIT cell characteristics for window layer a-Si:H (p) of various band gaps.

4.9 Influence of thickness of window layer (a-Si:H (p)) on HIT cell parameters.

The dependence of the cell parameters on the thickness of the p-layer is studied by varying the p-layer thickness from 4 nm to 50 nm, as presented in Fig. 11. When the p-layer thickness increases, a minimal change is observed up to 10 nm visible in the J-V curve, as shown in fig 10a. Further increasing the thickness the efficiency start decreasing. When the Voc increases up to 30 nm cell, and Isc remains ready up to 10 nm, then decreases rapidly, as shown in Figure 11b. The maximum efficiency recorded for HIT solar cell is 27.02% thinner cell remains constant at 10 nm, and afterward, it reduces to 25%. It has been suggested that increasing the thickness of the window layer increases its absorption of incoming photons before they reach the crystalline silicon absorber. Since it is an amorphous layer, generated electron-hole pairs in such a layer easily recombine without contributing to the current. While a thin layer allows light to pass through to the active absorber and reach the electrodes before recombining [26,28,29]. Moreover, heavily doped layers have a high concentration of defects, which attract and trap electrical charges. Amorphous silicon has relatively low electrical conductivity. If the window layer is too thick, it increases the cell's series resistance and lowers the fill factor (FF), reducing overall power output [29]. Therefore, the results suggest that 10 nm is an optimal p-layer thickness and that is maintained throughout the analysis.

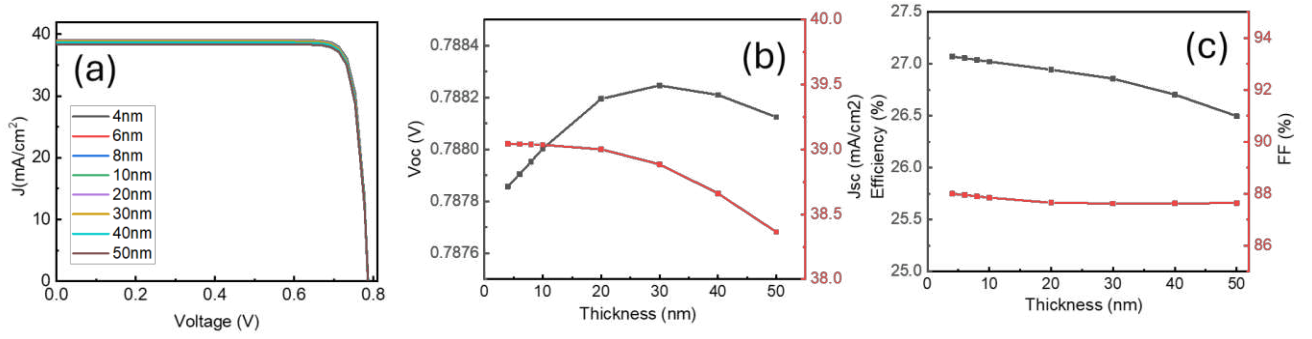


Figure 11. HIT characteristics for different a-Si: H(p) layers with various thicknesses.

4.10 Influence of the a-Si:H(p)/c-Si(n) interface defect

The influence of interface defect concentration is studied by varying defect concentration from $N_t = 10^{10}$ to 10^{16} cm⁻². Figure 12a shows the JV curve of the HIT solar cell made with different defect densities (N_t) at the interface a-Si:H (p)/c-Si(n) after passivation with an a-Si: H(i) layer. Figure 13a shows the JV characteristics curves of HIT cells with different interface defects. It is observed that most JV curves overlap up to 10^{15} cm⁻²; thereafter, the curves change shape and decrease toward lower voltages for higher interface defect levels (10^{16} - 10^{18} cm⁻²). No significant changes in V_{oc} and J_{sc} up to 10^{16} cm⁻², then decreased slightly at higher values, as shown in Figure 12b. Similarly, the efficiency of HIT cells with different interfacial defects shows a relatively stable value up to a concentration of 10^{13} cm⁻², then decreases with increasing interface defect density, as shown in Figure 13c. It decreases to 22.4% at 10^{18} cm⁻², and the maximum efficiency obtained for the HIT cell is 27.02%.

The photovoltaic effect mainly occurs at the interface layer, making it very sensitive to the distribution of defect states in that region. During the optimization process of the crystalline silicon (c-Si) absorber layer, the defect density was lowered to 10^{10} cm⁻³. Additionally, the resistivity of crystalline silicon is a vital parameter that greatly affects solar cell performance. It has been found that interface states at the emitter/wafer interface significantly reduce the open-circuit voltage of the solar cell [30,31], due to additional interface recombination.

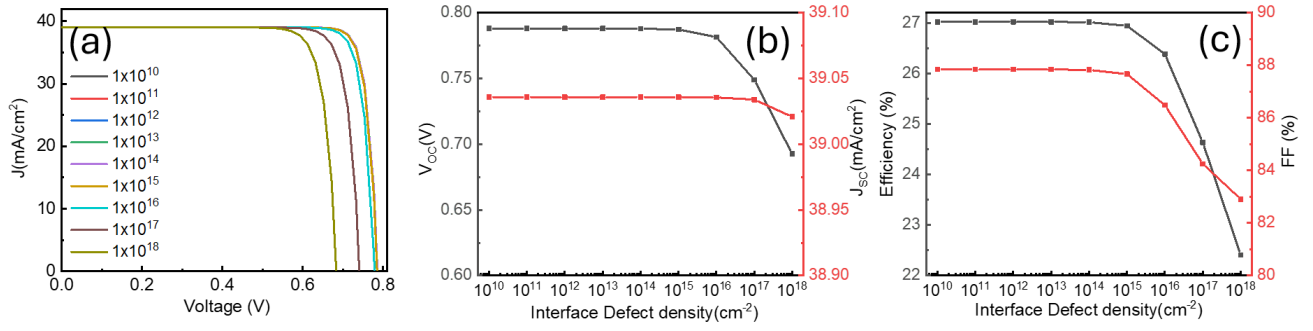


Figure 12. HIT characteristics for variable interface defects at the emitter/wafer interface.

This can be minimized by ensuring a strong band bending in the crystalline absorber. Also, it has been suggested that the interface defects concentration should be less than $N_t \approx 10^{11} \text{ cm}^{-2}$. This can be achieved through excellent surface passivation, which is observed with intrinsic a-Si:H(i), which passivates c-Si surface dangling bonds, minimizes surface defects, and enhances the V_{OC} of the cell [32]. In this case, incorporating an 8 nm intrinsic a-Si:H buffer layer between the crystalline silicon absorber and the p-doped emitter further improves the cell's performance. Carrier recombination at the a-Si:H/c-Si interface is a critical factor that influences the device's open-circuit voltage and overall efficiency. Therefore, the optimal value for interface defect density is possible to keep in the range 10^{10} - 10^{13} cm^{-2} .

4.11 Influence of series resistance (R_s) and shunt resistance (R_{sh}) in HIT

In HIT solar cells, defects are inevitably present and may arise within individual layers or at the interfaces between adjacent layers, significantly influencing device performance. Therefore, the series resistance (R_s) and shunt resistance (R_{sh}), which are essential factors influencing the performance of the HIT device. The output current of the HIT solar cell depending on R_s and R_{sh} is understood using the following equation, [33].

$$I = I_{ph} - I_0 \left[\exp \left(q \frac{U + IR_s}{kT} \right) - 1 \right] - \frac{U}{R_{sh}}$$

Where, (I_{ph}) is a photo-induced current, I_0 is the reverse saturation current (U) is the output voltage, k is the Boltzmann constant, q is the electron charge, and T is the temperature.

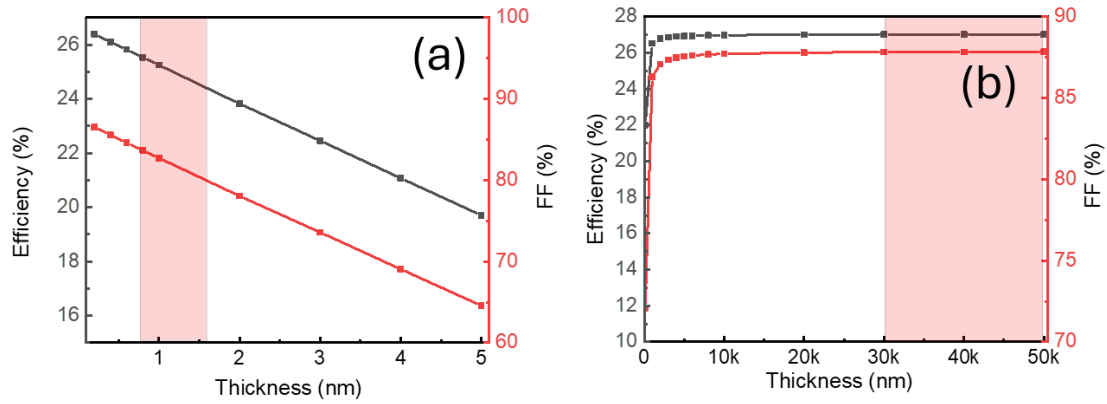


Figure 13. Effect of R_s and R_{sh} on efficiency and FF of HIT solar cell.

Series resistance R_s contribution in HIT solar cells appears from the interface and metal contacts. Resistive amorphous silicon and crystalline wafers contribute their own resistance, affecting the solar cell performance. Moreover, the resistance of the amorphous layer is determined by its quality, and it can be tuned by optimizing the deposition process. Similarly, shunt resistance R_{sh} is coming from the cell design, charge recombination process and leakage currents between the layers. For high-efficiency HIT devices, it has been suggested that the series resistance should be below $0.2\text{--}0.3 \Omega \text{ cm}^2$ and the shunt resistance should exceed $10^5 \Omega \text{ cm}^2$ to ensure optimal performance and minimize energy losses[34].

To understand the individual effect of R_s and R_{sh} on the designed HIT cell structure resistance changes and observe the effect on the cell parameter. Initially, R_s varies from 0.2 to $1 \Omega \text{ cm}^2$ for this R_{sh} kept constant at $5000 \Omega \text{ cm}^2$. It can be seen that as the R_s value increases, the fill factor and efficiency decrease continuously, as shown in Figure 13a. which is due to reduced output power from insufficient charge collection in the device, leading to a continuous drop in FF, as shown in Figure 13b. A maximum efficiency of 27.02% was obtained at $R_s = 0.2 \Omega \text{ cm}^2$, which decreased to 20% at $R_s = 1 \Omega \text{ cm}^2$.

Similarly, shunt resistance (R_{sh}) varied from $100 \Omega \text{ cm}^2$ to $50000 \Omega \text{ cm}^2$ by keeping series resistance (R_s) constant at $0.2 \Omega \text{ cm}^2$. Figure 13b shows the changes in cell parameters due to R_{sh} variation. It is observed that FF and efficiency increase with higher R_{sh} , as shown in fig 13b. A maximum efficiency of 27.02% was obtained when the R_{sh} value increased above $5000 \Omega \text{ cm}^2$. This is mainly

due to a reduction in leakage current at higher shunt resistance, which improves solar cell efficiency. The optimal R_s and R_{SH} values are $0.2 \Omega\text{cm}^2$ and $5000\Omega\text{cm}^2$ respectively.

Table 3: Different HIT layer parameters.

Layer	Thickness (nm)	Doping density (cm^{-3})	Doping density (cm^{-3})	Band gap (eV)	Defect density (cm^{-3})
a-Si:H(p)	10	6×10^{17}	--	1.7	10^{16}
a-Si:H(i)	8	--	--	1.62	10^{16}
c-Si (n)	165000	--	3×10^{15}	1.12	10^{10}
BSF (a-Si:H(n))	10-50	--	5×10^{17}	1.72	10^{16}

4.12 Optimizes HIT solar cell

Finally, based on the above observations, the optimized HIT device structure is considered with p-i-n configuration of layer a-Si:H(p)/a-Si:H(i)/c-Si(n)/BSF. Different optimized parameters for the HIT cell are tabulated in Table-3. For the cell fabrication, thicknesses of the different layers set as a-Si:H(p)(10nm)/a-Si:H(i)(8nm)/c-Si(n)(165 μm)/BSF (20nm).The doping concentrations in a-Si:H(p) and c-Si(n) are taken as $N_A = 6 \times 10^{17} \text{ cm}^{-3}$ and $N_D = 1 \times 10^{15} \text{ cm}^{-3}$, respectively.

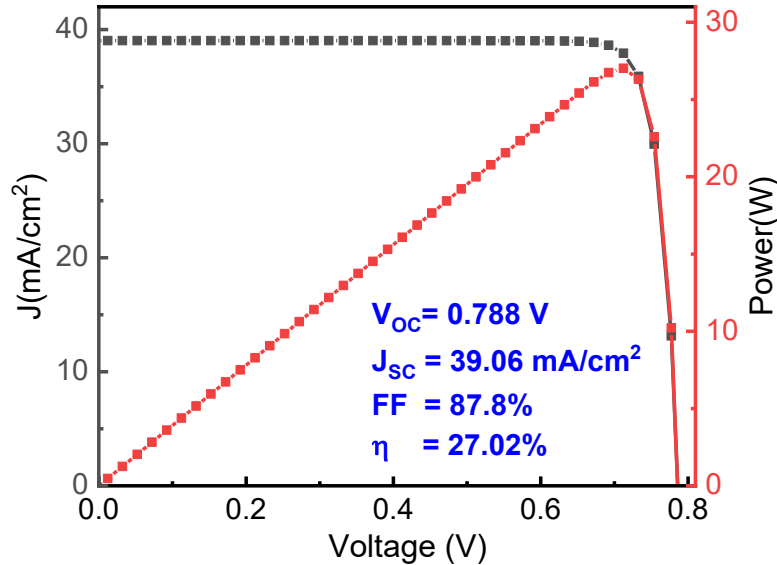


Figure 14. JV characteristics of optimized HIT cell

In optimized HIT cell, various defects are taken into account e.g. bulk defect in each layer and interfacial defects at a-Si:H(i)/ c-Si(n) interface. By considering all these factors, the cell efficiency obtained is 27.02% with J_{SC} of 39.06 mA/cm², V_{oc} of 0.788 V, FF of 87.8%. In the optimize perovskite cell R_s and R_{SH} values are 0.2 Ω cm² and 5000 Ω cm² taken respectively (as shown in fig-14).

Conclusions:

The SCAPS-1D simulations study was done to optimize amorphous and c-Si HIT solar cells. This indicated that using hydrogenated amorphous silicon is crucial for producing high-quality photovoltaic cells. In this simulation study, the solar cell structure is considered as a-Si:H(p)/a-Si:H(i)/c-Si(n)/BSF/Au, where the hydrogenated amorphous layer ($E_g=1.7$ eV) with n-doping is used as a BSF layer. Moreover, the influence of the BSF layer on the photovoltaic parameters of a HIT solar cell was studied. A significant improvement in photovoltaic parameters was observed after incorporating the BSF layer into the HIT cell. Similarly, for HIT cell formation, intrinsic a-Si:H (8nm) is required for passivation to c-Si and as a buffer layer between two doped layers. Optimizing the thicknesses of the p-type and intrinsic layers is also important for improving efficiency. A thick p-type layer reduces efficiency. The acceptor density drastically affects efficiency when it is below 10^{15} cm⁻³. Moreover, reducing defects can suppress the recombination. A maximum efficiency 27.02% could be achieved after the optimization of all the layers constituting the HIT cell of structure a-Si:H(p)/a-Si:H(i)/c-Si(n)/BSF/Au.

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