Materials Today: Proceedings xxx (xxxx) xxx

Contents lists available at ScienceDirect

Materials Today: Proceedings

journal homepage: www.elsevier.com/locate/matpr

The use of back surface field and passivation layer to enhance the performance of silicon heterojunction solar cells

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ARTICLE INFO

Article history:
Available online xxxx

Keywords:
Back surface field
Simulation
Passivation
Silicon heterojunction solar cells

ABSTRACT

c-Si/a-Si:H heterojunction solar cells (Si-HJSCs) are simulated by AFORS-HET to study their performance with the back surface field (BSF) and passivation layer. Si-HJSCs(*ninip)* with the best open circuit voltage (V_{oc})(760.8 V), short circuit current density (J_{sc})(36.97 mA/cm^2), fill factor (*FF*) (85.22%), and efficiency (η) (24.17%) were achieved. Whereas, estimated values of 675.2 mV, 33.5 mA/cm^2, 83.34%, and 18.98% for a basic Si-HJSC (*np*) SC, which corresponds to the V_{oc}, J_{sc}, *FF* and η. The intrinsic -a-Si:H layer on both sides of the c-Si wafer has passivated the dangling bond density on the silicon, and the defect density at the interface between the c-Si and a-Si:H layers and improved the performance of Si-HJSCs. These simulation results were compared with experimental data for accuracy and validation. It was observed that the simulation results are highly promising and almost match experimental data.

Selection and peer-review under responsibility of the scientific committee of the 2nd International Conference on Multifunctional Materials.

1. Introduction

In a homojunction, the band gap is formed between materials with the same band gap, while in a heterojunction, the band gap is formed between materials with different band gaps [1]. Recombination losses are decreased by the heterojunction due to the separation of carriers moving in opposite directions [2,3]. In a result, the photocurrent produced by the SC is increased [4]. By improving surface passivation and reducing charge carrier recombination, silicon HJSCs can generate better V_{oc} and η than c-Si SCs. The conversion η is like that of c-Si SCs when it comes to turning sunlight into energy [5–7].

In 1974, the a-Si/c-Si HJSC was reported initially by Fuhs et al. [8]; the a-Si/poly c-Si HJSC was reported by Okuda et al. in 198 with an η of 12% [9]. In 1992, Sanyo introduced its cutting-edge silicon HJSC PV technology, which has since reached an η of 18.1% [10]. Heterojunction with intrinsic thin layer (HIT) SHJSCs use an i-a-Si:H layer inserted between the c-Si and doped a-Si:H layers to generate a heterojunction. Passivation of the c-Si interface and surface is accomplished by utilizing this layer [10]. Many groups are currently studying Si-HJSCs with the goal of improving efficiency of solar cell [11–15].

The effectiveness of Si-HJSCs was studied here by employing the AFORSHET modelling software. The performance of Si-HJSCs was evaluated by measuring their efficiency, quantum efficiency, and spectrum responses. Simulated results were compared with experimental data for validation and correctness.

2. Details of simulation

AFORS-HET is used for modelling Si-HJSCs. Different configurations of Si-HJSCs are shown in Fig. 1(a-c). Reliable references are used for the density of states distribution, layer density and thermal velocity in all layers and other parameters [17–19,22–28]. The remaining parameters in AFORS-HET are used with their default settings [16,20,21,24].

3. Results and discussion

3.1. J-V characteristics of Silicon HJSCs

Current density against voltage (J-V) for Si-HJSCs is shown in Fig. 2. Silicon HJSC performance was evaluated in three different setups, as indicated in Fig. 2. V_{oc}, J_{sc}, *FF*, and η of the estimated SC properties shown in Table 1. A fixed 5 nm thick a-Si:H layer was used throughout. These a-Si:H layers having a constant bandgap value. The ITO layer thickness of these SCs is only 70 nm. The

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https://doi.org/10.1016/j.matpr.2023.04.583
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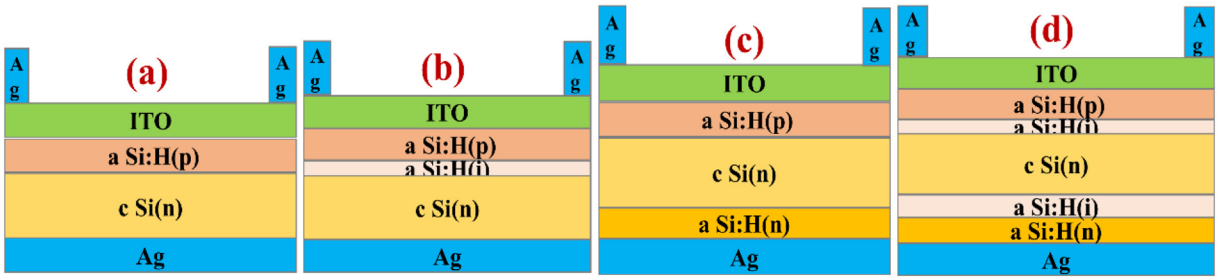

Fig. 1. Schematic structure a) *np*, b) *nip*, c) *nnp*, d) *ninip* of Si-HJSCs.

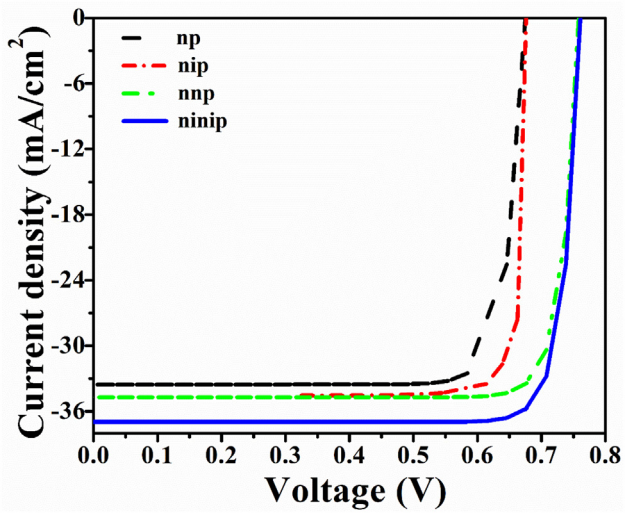

Fig. 2. Current density of SCs measured with voltage.

V_{oc} of 675.2 V, J_{sc} of 33.53 mA/cm^2, *FF* of 83.34%, and η of 18.98% are the computed parameters for a *np* solar cell (Fig. 1a) (Table 1). Due to a high recombination density and many dangling bonds, c-Si wafers have an extremely low V_{oc} and J_{sc}. There is a loss of η because the internal electric field is weak at the semiconductor junction, charge carriers recombine, and fewer e-h's collected at Ag contacts. Incorporating an intrinsic passivation layer (Fig. 1b) somewhat improves the solar cell characteristics (Table 1). In the *nnp* structure, the n-a-Si:H BSF is superimposed on the *np* structure (Fig. 1c). Table 1 shows that the nnp solar cell has a V_{oc} of 757.9 V, a J_{sc} of 34.71 mA/cm^2, an *FF* of 85.85%, and an η of 22.62%. Fig. 2 displays the enhanced V_{oc} and J_{sc} of 757.9 V and 34.71 mA/cm^2 for *nnp* SCs with n-a-Si:H BSF layers. The improved electric field at the junction is mostly due to the BSF's ability to reduce recombination losses. The i-a-Si:H layer has been implanted on both the top and bottom of the c-Si wafer to boost the electric field across the junction (Fig. 1d). Along with increasing the electric field at the junction, this i-a-Si:H layers also serve to passivate dangling bonding density on the surface of c-Si and the interface between c-Si and the p-a-Si:H/n-a-Si:H layer [29–32]. While both V_{oc} and J_{sc} have increased, the *FF* has remained relatively unchanged. A value of 24.17% is attained by SCs with a *ninip* structure, i-a-Si:H passivation layer, and a BSF.

Table 1
Solar cell characteristics of Si-HJSCs.

Structures	V_{oc}(mV)	J_{sc}(mA/cm^2)	*FF*(%)	η(%)
np	675.2	33.53	83.34	18.98
nip	676.3	34.54	83.91	19.62
nnp	757.9	34.71	85.85	22.62
ninip	760.8	36.97	85.92	24.17

3.2. Si-HJSCs: Spectral response

Fig. 3 depicts the Si-HJSC's spectral response (SR) for the wavelengths 300–1200 nm. The SR of *ninip* SCs increased steadily with wavelength, from 30% at 350 nm to 71% at 950 nm. The *nnp* SCs have a somewhat lower spectrum response than *ninip* SCs. At 1000 nm, the SR% dropped to 30%, and at 1100 nm, it dropped to practically nil, without any discernible change in intensity. The spectral response of *np* SCs has been reduced by around 10% to 12% from 800 to 1050 nm. Applying a BSF and covering silicon HJSCs with a thinner i-a-Si:H may improve their spectrum responsiveness.

3.3. Si-HJSCs: Quantum efficiency

The external quantum efficiency (*EQE*) of Si-HJSCs is shown in Fig. 4 to be between 300 and 1200 nm. For *np* SCs, 80% *EQE* is located between 350 and 900 nm. When compared to np SCs, the external quantum of *ninip* and *nnp* SCs is larger in the 350–1100 nm range. For *ninip* SCs, the *EQE* is closest to 85% at 430 nm, somewhat lower at 550 nm, and gradually increasing at 950 nm. Improvements in spectral performance between 350 and 450 nm may be seen when comparing spectra from np and nip cells. In the same way, the *EQE* of *nnp* SCs has dropped by about 2% between 400 and 1000 nm. The *ninip* and *nnp* SCs are more costly but have better *EQE* spectra than *np* SCs. When a passivation layer and BSF are applied to SCs, the *EQE* significantly increases.

In Fig. 5 depicts internal quantum efficiency (*IQE*) Si-HJSCs. The number of internal quantum fluctuations is proportional to the number of free charge carriers captured per incident photon. The *np* SCs have an *IQE* of around 80% between 350 and 900 nm. In comparison to *np* SCs, the *IQE* of *ninip* and *nnp* SCs is increased around 350–1100 nm. Improvements in spectral performance between 350 and 450 nm may be seen when comparing spectra from np and nip cells. The *ninip* SCs obtain about 87% *IQE* at 430 nm, somewhat less at 550 nm, and gradually more at 950 nm. The *EQE* spectrum is narrower and less strong than the *IQE* spectrum when it comes to *ninip*, *nnp*, and *np* SCs. When a passivation layer and BSF are applied to SCs, the *IQE* significantly increases.

4. Experimental validation

Table 2 displays the results of a comparison between the simulated SCs, and the experimental reports used to validate the simulations. We have previously reported that we have successfully built n-type wafer-based single-sided c-Si/a-Si:H HJ (*nip*) structured SCs with an η of 17.3% [30]. The simulation results for *nip* structured SCs were found to be slightly higher than the experimental values. It is also observed that the results are very encour-

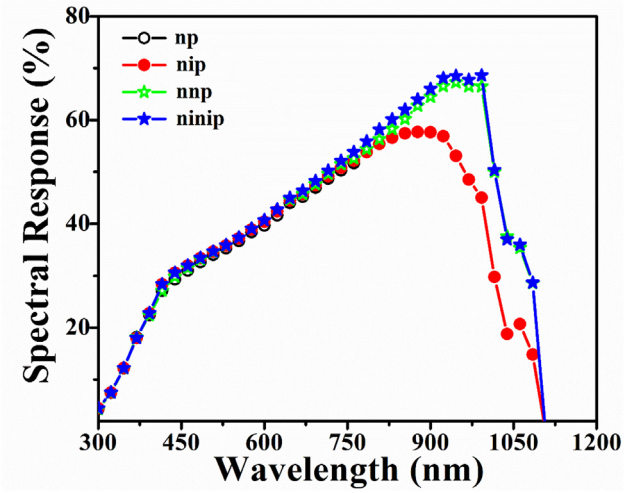

Fig. 3. SR of SCs measured by wavelength.

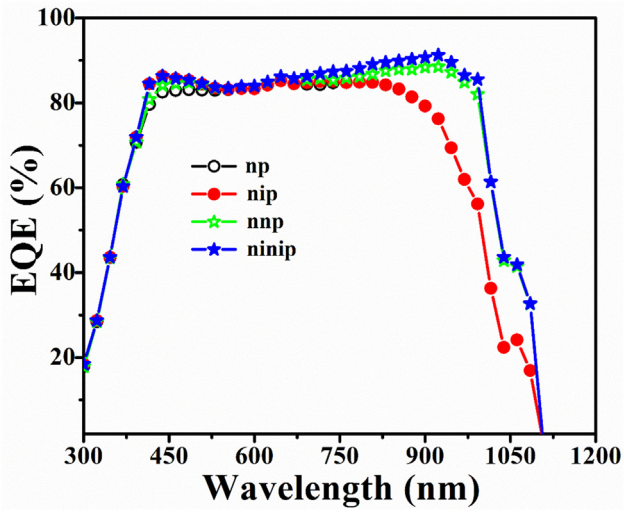

Fig. 4. *EQE* of SCs as a function of wavelength.

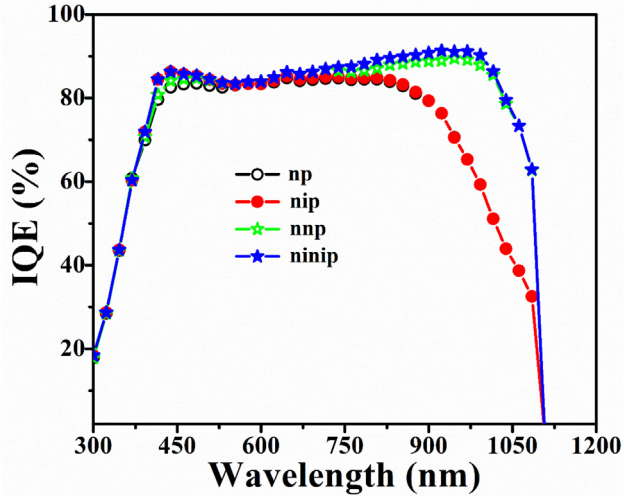

Fig. 5. *IQE* of SCs as a function of wavelength.

Table 2
Characteristics of simulated and experimental Si-HJSCs.

Structures	V_{oc}(mV)	J_{sc}(mA/cm^2)	*FF*(%)	η(%)
**nip (Simulation)*	676.3	34.54	83.91	19.62
#nip (Experimental)	705	32.72	75	17.30 [30]
**ninip (Simulation)*	760.8	36.97	85.92	24.17
ninip (Experimental)	750	39.50	83.2	24.70 [33]
ninip (Experimental)	740	41.80	82.7	25.60 [6]

(* this work; # our previously reported work).

aging and nearly matching with experimental results when compared the results from simulated cells of *ninip* structured Si-HJSCs to those from the reported work.

5. Conclusions

Performance of the different structured Si-HJSCs have been studied by AFORS-HET tool. The BSF and passivation layer were added to the Si-HJSCs to assess its performance. High V_{oc} of 760.8 V, J_{sc} of 36.97 mA/cm^2, *FF* of 85.22% and η of 24.17% were achieved with *ninip* SCs. It is observed that SC parameter values are 757.9 mV, 34.71 mA/cm^2, 85.85 % and 22.62 % corresponding to V_{oc}, J_{sc}, *FF* and η for *nnp* SCs. A basic *np* solar cell is expected to have an V_{oc} of 675 mV, an J_{sc} of 33.53 mA/cm^2, *FF* and an η of 83.44% and 18.98% respectively. There has been a significant increase in the performance of *ninip* SCs owing to the extremely thin layer of a-Si:H on both sides of c-Si that passivates most of the dangling bonding density and interface defect density. The internal electric field at the junction was enhanced by adding sufficient BSF with n-a-Si:H layer to separate free charge carriers and rapidly access metal contacts. This electric field with n-a-Si:H significantly reduced recombination density at the interface. It was found that these simulation results are highly promising and almost match experimental results.

CRediT authorship contribution statement

Venkanna Kanneboina: Conceptualization, Methodology, Software, Data curation, Writing – original draft, Investigation, Writing – review & editing. **Hemambika Sadasivuni:** Writing – review & editing.

Data availability

Data will be made available on request.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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