ISSN: 2633-4828 Vol. 5 No.4, December, 2023

International Journal of Applied Engineering & Technology

OPTIMIZATION OF INTRINSIC AND DOPED HYDROGENATED AMORPHOUS SILICON LAYERS FOR HETEROJUNCTION INTRINSIC THIN SOLAR CELLS

Nagesh M[1], Jayapal R[2] and Suresh R[3]

[1, 2] Department of Electrical & Electronics Engineering, R.V. College of Engineering, Bengaluru, India

[3] Department, Chemical Engineering, R.V. College of Engineering, Bengaluru, India

Visvesvaraya Technological University, Belgavi, India

[1] nageshm@rvce.edu.in

ABSTRACT

The optimization of process parameters and material properties of intrinsic and doped Hydrogenated amorphous silicon (a-Si:H) layers in Heterojunction Intrinsic Thin (HIT) solar cell is of significant in obtaining high efficiency HIT Solar cells. a-Si:H materials were deposited using 13.5 MHz RF PECVD system and optimization of depositing parameters of the individual layers i) passivation or intrinsic ii) emitter layer (p-type) and iii) back reflection layer (n) layers of amorphous a-Si:H material initially on glass substrates for achieving the required thickness, electrical and optical characteristics were studied.

For intrinsic a-Si:H layer, an average optical transmittance of 84%, optical band gap of 1.88 eV, photo gain of order 10^{5} ^{5}(photoconductivity= 9.20×10^{-5} Scm^{-1} and dark conductivity=2.78×10^{-10} Scm^{-1})for a dilution ratio R=9 (=SiH_4/H_2) were obtained and an optimized layer thickness was 5 nm.

In our experiments, The obtained highest minority carrier lifetime of the Si wafer before and after passivation (a-Si:H) are 220 and 410 µs and the surface recombination velocity (SRV) obtained for c-Si wafer is 63.63 cm/s and the lowest SRV obtained is 50.54 cm/s after a-Si:H films passivation.

p-layer studies has been carried out to achieve high conductivity and wider optical band gap to perform as emitter layer allowing more blue light in to the device. Results revealed that the p-a-Si:H films of 20 nm thick exhibited conductivity of 3.08×10^{-6} S/cm and band gap of 1.97eV

For n-layer, as a current collector or back surface layer, the optimized PH_3 gas (%) is of 10% with silane (SiH_4) resulted with thickness is in the range 42 to 90 nm. We have obtained good quality n-type a-Si:H films with a band gap of 1.73eV, high conductivity of 1.66×10^{-2} Scm−1 at the thickness of ~20nm. By incorporating Optimized layer properties, HIT solar cell was developed with an efficiency of 16.18%.

Keywords: HIT Solar Cell, PECVD, Passivation Studies, Effective Minority Carrier Lifetime, Surface recombination velocity (SRV), Conversion efficiency.

INTRODUCTION

Hydrogenated amorphous silicon and crystalline silicon (a-Si:H/c-Si) heterojunction solar cells are focused in current research studies due to their combined technological advantages of using low cost a-Si:H material and high efficiency c-Si material.

When the light incident on solar cell, an internal electric field is present across i- layer. The electron-hole pairs that are generated in the intrinsic a-Si:H layer immediately experience the internal electric field that separates electrons and holes from each other. The separated carriers, drift under the influence of the electric field towards the extrinsic layers (electrons towards the n+ layer and holes towards the p-layer) and are collected by the electrodes. Hence, the intrinsic- layer band gap and conductivity plays an important role in the a-Si:H HIT solar cell efficiency.

The thickness of the i-layer has been defined to ensure uniform passivation with low interfacial defect density, high optical bandgap and higher charge carrier lifetime that makes it as the ideal buffer layer for effectively passivating the crystalline silicon surface and interface region.

In this study, HIT solar cells was developed by using optimized intrinsic and doped a-Si:H layers properties. Intrinsic and doped a-Si:H was deposited on both float glass and c-Si wafer to study electrical , optical and surface passivation properties.

Intrinsic hydrogenated amorphous silicon (i-a-Si:H) were studied on Silicon wafers and compare for better surface recombination and increased lifetime of minority charge carriers in order to enhance the conversion efficiency of HIT Solar cells.

EXPERIMENT & RESULTS

Optimization of Individual layers:

i-a-Si:H layer

Intrinsic a-Si:H layers were deposited using silane (SiH4) and H2 Gases with PECVD RF Source power. Depending on the characterization to be performed on samples, i-a-Si:H films have been deposited on float glass and polished c-Si wafers. Float glass substrates (75 x 75mm) were used to perform wider characterization such as layer thickness, electronic and optical properties of deposited of intrinsic a-Si:H material (i-a-Si:H).

Prior to each deposition, Wet chemical process was .carried out. For float glass substrates, glass was soaked in soap solution, 15 min ultrasonic bath in IPA solution followed by same amount of time in a DI bath.

For n-type c-Si wafer,wet chemical process (RCA-1,RCA-2 and 2% HF dip) has been carried out for c-Si wafers. This effective cleaning of c-Si wafer surfaces ensures, high lifetime and good passivation effect.

Then, n-type c-Si wafers are subjected to ultrasonic bath with IPa Solution for 10 min, rinsing with DI Water, RCA-1 Solution is prepared by using DI: NH4OH: H2O2 (5:1:1) ratios and heated for about 80-85ºC, where the c-Si wafers are dipped for 10 min in RCA-1 Solution.

After RCA-1, wafers are rinsed with DI water and dipped in prepared RCA-2 (Metal contamination removal) with DI:HCL:H2O2 (6:1:1) ratios at about 80-85ºC for 10 min. Finally, the wafers are subjected to 2% HF Dip to remove native oxide. Observation: hydrophobic nature of c-Si wafers.

Deposition parameters such as chamber pressure, substrate temperature and RF power are kept constant to 1 Torr, 250˚C and 7W respectively. Dilution ratio R, defined as the ratio between silane and H_2 gas flow, SiH_4:H_2, is varied from 1 to 15 by keeping SiH_4 at a flow rate of 5 sccm to study the effect of hydrogen dilution on thickness, conductivity, photo gain and band gap of i-a-Si:H layer**.** The snapshot of i-a-Si:H layers on glass and wafer was shown in Fig.1 & 2 respectively.

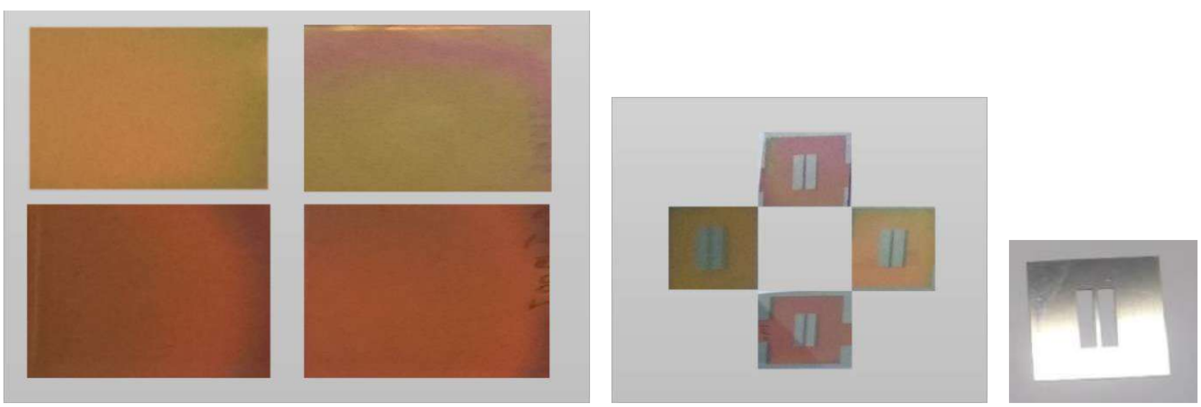
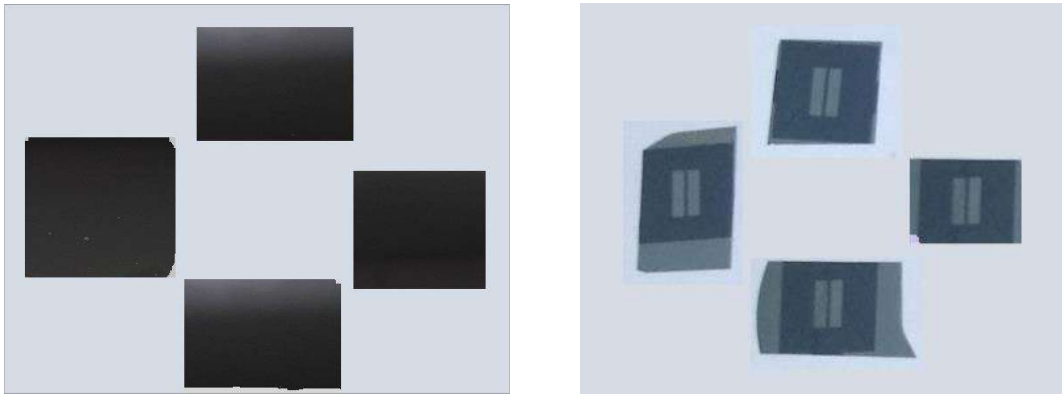


Fig.1: Deposited i- Layers of a-Si:H on Float Glass

1(a). i-a-Si:H deposition on 75x75mm glass. 1(b). Electrode mask with 20mm electrode length and 1mm distance apart 1(c). i-a-Si:H glass substate with electrode deposition for conductivity measurements



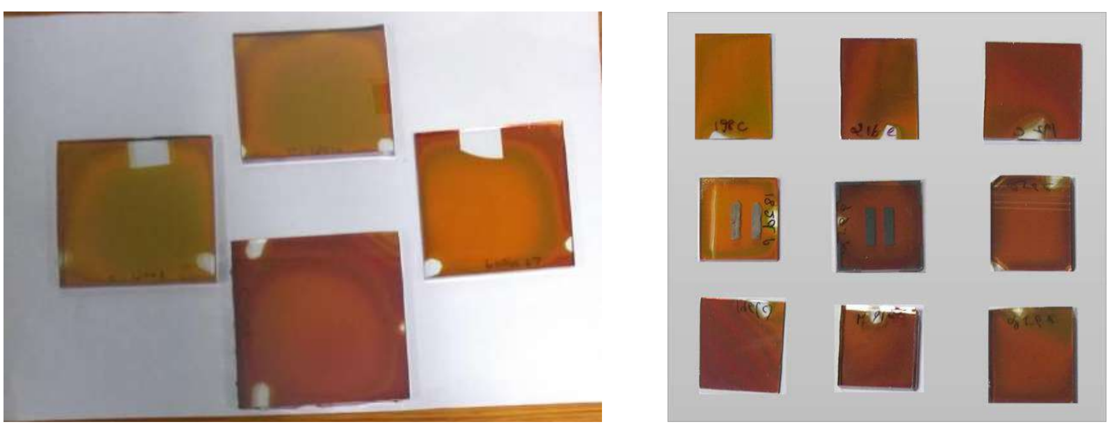
2(a) 2(b)

Fig.2: Deposited i- Layers of a-Si:H on c-Si wafer

2(a). i-a-Si:H material on c-Si wafer for Passivation studies. 2(b). i-a-Si:H material on c-Si wafer for Conductivity studies

Optimization of Emitter Layer (P Layer)

The p- Layer of a-SiC:H films were deposited in a PECVD chamber system using SiH_4, H_2 and B_2H_6. The boron content was controlled by varying the flow ratio of B_2H_6/SiH_4. In order to facilitate the analysis, we defined *Rx* as the flow ratio of B2H6/SiH4 . The value of *Rx* was from 0.2 to 1, The flow of SiH4 (hydrogen dilution 10%) was fixed to 10 sccm. All relevant parameters are shown in Table 1: Optimized individual layers properties summarized The p-layer has been deposited on the glass substrates, at a constant temperature =250ºC, pressure 1=Torr, RF power =7W and deposition time =10min. The B_2H_6 was dopant gas, whose flow rate is 2-10 sccm varied with an increment of 1 sccm along with constant H_2 dilution ratio R to obtain maximum conductivity and optimum band gap value. Deposited p-layer samples for HIT Solar cells are shown in the Fig 3.The thickness measured using stylus profiler was in the range of 60 nm- 275nm. Initially thicker films have been deposited on glass in order to measure the optical properties and later thickness of the films has been decreased by controlling the H_2 Dilution Ratio R, Diborane doping ratio (R_x) with respect to Deposition rate.



3a 3b.

Fig. 3a. Deposited p-layers on 75 x 75 mm float glass, Fig. 3b p-a-Si:H glass substate with and without electrode deposition for electrial and optical measurements.

Back Surface Field (BSF) Layer / (n-layer) Studies for HIT Solar Cell

To study and optimize the influence of n-a-Si:H layer as BSF layer, films were prepared using silane (SiH_4) as the source gas, hydrogen (H_2) as the diluent gas and phosphine (PH_3) as the dopant gas. Fig.4 shows the deposited n-a-Si:H layers.

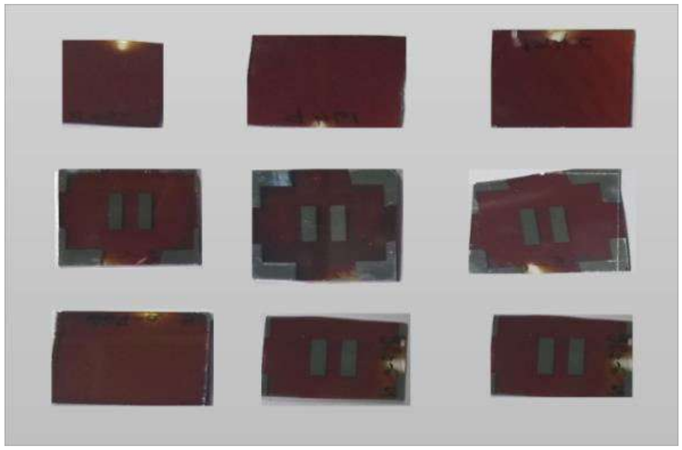


Fig.4 Deposited n-a-Si:H layers on float glass

The thickness of deposited samples were measured by stylus profilometer and it is found to be in the range 42 to 90 nm respectively by keeping constant time of 7 mi

Table.1 Optimized individual layers properties summarized (A4-A5)

Device Layers	Parameters Varied	Optimized Properties	Remarks
i-layer	Max.H_2 Dilution ratio SiH_4:H_2 (1:15) Optimum ratio is 1:9	Dark Conductivity=2x10^{-10} cm-Ω^{-1} Photo Conductivity=2x10^{-10} cm-Ω^{-1} Photo Gain=3.31 x 10^5 Band Gap=1.88 eV Min. Thickness=5nm	Chamber pressure=1Torr; RF Power=7W; Temperature=250˚C. Electrode distance=25mm
p-layer	Max. Doping ratio B_2H_6:SiH_4 is (1:10),Optimum Ratio is 0.4:10;	Conductivity=3.08x10^{-6} cm-Ω^{-1} Optimum Band Gap=1.97 eV Min. Thickness=20 nm	Chamber pressure=1Torr; RF Power=7W; Temperature=250˚C. Electrode distance=25mm H_2 Dilution ratio SiH_4:H_2 (1:9)
n-layer	PH3 concentration (%) 2 to 26%; Optimum % is 10%	Conductivity=1.66x10^{-2} cm-Ω^{-1} Band Gap=1.73 eV Min. Thickness=20nm	Chamber pressure=1Torr; RF Power=7W; Temperature=250˚C. Electrode distance=25mm H_2 Dilution ratio SiH_4:H_2 (1:9)
TCO (AZO material)		Thickness=80nm	
Metal Contact		Thickness=300nm	Temperature=70˚C

Note: The above table shows the optimized average values obtained by conducting repetitive experiments of each layer.

Fabrication of HIT Solar cell:
An intrinsic thin a-Si layer followed by a p-type a-Si layer is deposited on a n type c-Si wafer to form a p/n heterojunction. The front TCO films were then deposited on p-layer. On the other side of the c-Si, intrinsic and n-type a-Si layers are deposited to obtain a Back Surface Field (BSF) structure and finally, metal grid electrodes are formed using a screen-printing method/Evaporation method for good ohmic contacts.

The structure and layer details of the HIT cell fabricated in this study has been shown in Fig.5

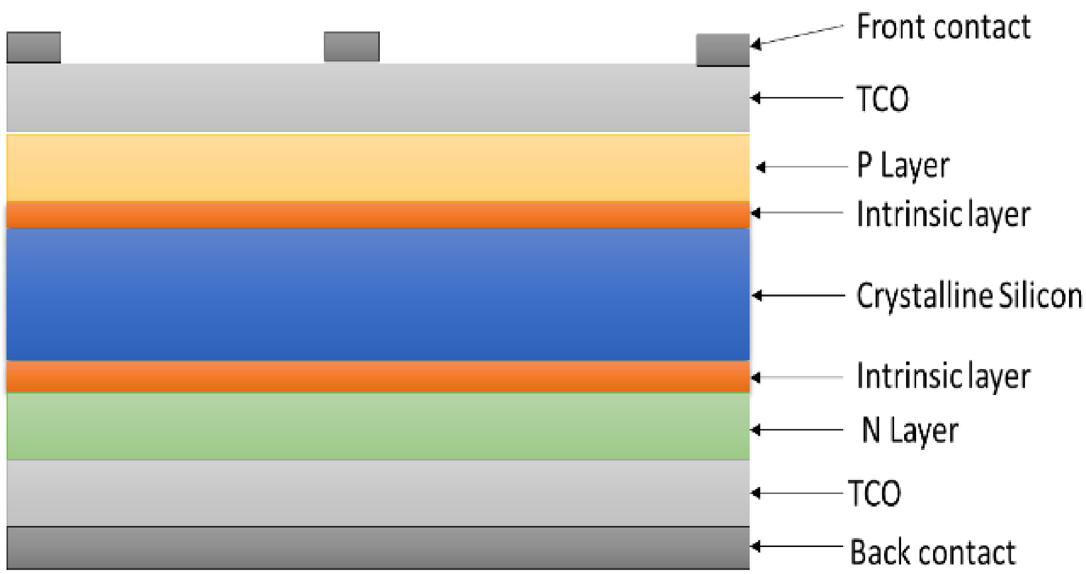


Fig.5 Schematic of developed HIT Solar cell

By incorporating the above optimized properties (Table.1) HIT solar cells have been fabricated using the double sided polished FZ n-type CZ c-Si wafer (1–2Ω, 280µm thick, (1 1 1) oriented)

The wafers were cleaned by RCA 1 (H_2O_2:NH_4OH:H_2O) and RCA 2 (H_2O_2:HC: H_2O) followed by HF dip after an ultrasonic treatment. The prepared wafer is then transferred to a PECVD multi-chamber deposition system to deposit the amorphous layers. The substrate is preheated to 250ºC for about 50 minutes after which the 5 nm thick intrinsic, 20 nm thick p-type a-Si:H layer were deposited on the front side of the wafer. Similarly 5 nm thick intrinsic, 20 nm thick n^+ a-Si:H layers were deposited on the rear-side of the silicon wafer at 250˚C.

Subsequently, the front TCO films were then deposited from the AZO target composed of 2wt% Al and 98 wt% ZnO with 99.99% purity using sputtering technique. The substrate temperature and the RF power density were held at 250˚C and 7 Wcm^{-2}, respectively. Using an turbo pump, the chamber of the sputtering unit was evacuated to pressure of 10^{-5} Torr before admitting argon (99.99% purity) at a pressure of 3×10^{-3} Torr. The thickness of AZO films was measured by stylus profilometer at room temperature and was fixed at 80 ± 5 nm for all films. The AZO deposition was performed by a metal mask with 1x1cm^2 opening and and 0.4x0.4 cm^2 areas which was directly placed on the p-a-Si:H surface to form square-shaped AZO layers on the a-Si:H films.

Metal contacts aluminum(Al) are deposited with suitable electrode mask on top of front TCO layer and rear of n^+ layer using Thermal evaporation technique.

The **experimental flow/Important steps** carried out while depositing. Starting with n-type FZ Si wafer (Fig.6).

Fig.6 Experimental Flow for HIT solar cell development

The **Important steps** carried out while depositing is shown in Fig 6 . The snap shot of the developed HIT solar cell is shown in Fig 7. The n-type FZ Si wafer was used as the base material.

The important steps carried out are:

- RCA Cleaning-1
- RCA Cleaning-2
- 2% or 5% HF Dip
- Loading wafers in PECVD immediately after HF Dip
- Deposition of Passivation layer followed by p- layer
- Take out the wafers outside to flip
- Flip and Loading the same wafers to PECVD
- Depositing Passivation layer followed by n-layer deposition on rear side
- Deposition of TCO on front side by using sputtering technique.
- Metal contacts on both sides

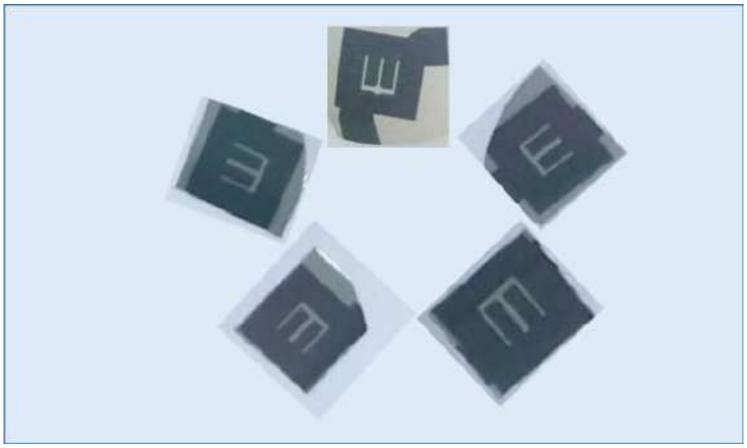


Fig.7 Developed HIT Solar Cell

Thickness Measurement:

The thickness of the developed i-a-Si:H layers are measured using bruker dektak thickness stylus profilometer with 1000µm length at 10 sec duration. The thickness is found to be in the range of 70-120 nm.

Life Time Measurements & Surface Recombination Study:

The process at which charge carriers combine to form electron-hole pair at the surface is known as surface charge carrier recombination. The high number of defects at the bare silicon surface makes surface recombination the dominant mechanism in silicon wafers. The reduction of such recombination is achieved by surface passivation by using i-a-Si:H material. Hence, to study surface recombination the effective minority carrier lifetime was measured using a Sinton Consulting WTC-120 quasi-steady-state photo-conductance (QSSPC) lifetime tester in the transient mode. The effective lifetime is extracted at an excess carrier density of 10^{15} cm^{-3}

Table 2: Results of minority carrier lifetime

Results description	After RCA Cleaning	After passivation
Measured effective lifetime(τ_{eff})	220µs	410µs
Measured Sheet Resistance Ω/sq	87.74	90.52

The passivation effect of the films on the c-Si surface is shown by the effective lifetime of the samples that bifacial covered by the films with same deposition parameters, tested by QSSPC method. The highest lifetime of the Si wafer and after passivation (a-Si:H) are 220 and 410 µs.

Surface Recombination velocity (SRV) Seff can be deduced by Eq. (1):

$$S_{eff} = \left(\frac{1}{\tau_{eff}} - \frac{1}{\tau_{bulk}}\right) \times \frac{w}{2} \qquad \ldots\ldots\ldots \quad (1)$$

w= Thickness of the n-Si wafer (~280µm)

τbulk is set to infinity

Hence, from Eq.(1)

Seff of the wafer without a-Si:H passivation layer is 63.63 cm/s

Seff of the wafer with a-Si:H passivated is 50.54 cm/s

In our experiments, the lowest surface recombination velocity of the c-Si wafer is 50.54 cm/**s** after a-Si:H films passivation in our study. By reducing surface recombination losses, the Voc has been improved from 0.715 to 0.720 V.

Electrical Studies:
I-V Measurements with solar cell parameters such as short circuit current density (Jsc), Open circuit voltage (Voc), Fill Factor (FF) and photovoltaic conversion efficiency η were calculated using indigenously developed I-V System with AM1.5 equivalent Light Source for solar illumination.

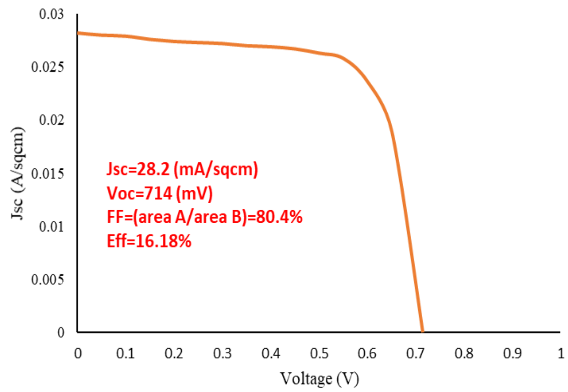


Fig.8. I-V Curve for developed HIT Solar cell

Fig.8 shows I-V Characteristics a-Si:H HIT Solar cell. The maximum efficiency of the cell obtained is 16.18%.

CONCLUSION
In this study, Optimization of intrinsic and doped a-Si:H individual layer properties was done to develop HIT Solar cell.

In our experiments, The obtained highest minority carrier lifetime of the Si wafer before and after passivation (a-Si:H) are 220 and 410 μs and the surface recombination velocity (SRV) obtained for c-Si wafer is 63.63 cm/s and the lowest SRV obtained is 50.54 cm/s after a-Si:H films passivation.

For intrinsic a-Si:H layer, an average optical transmittance of 84%, optical band gap of 1.88 eV, photo gain of order 10^{5} ^{5}(photoconductivity= 9.20 x 10^{-5} Scm^{-1} and dark conductivity=2.78 x 10^{-10} Scm^{-1})for a dilution ratio R=9 (=SiH_4/H_2) were obtained and an optimized layer thickness was ~5 nm.

p-layer studies has been carried out to achieve high conductivity and wider optical band gap to perform as emitter layer allowing more blue light in to the device. Results revealed that the p-a-Si:H films of of ~20 nm thick exhibited conductivity of 3.08 x 10^{-6} S/cm and band gap of 1.97eV

For n-layer, as a current collector or back surface layer, the optimized PH_3 gas (%) is of 10% with silane (SiH_4) resulted with thickness is in the range 42 to 90 nm. We have obtained good quality n-type a-Si:H films with a band gap of 1.73eV, high conductivity of 1.66 x 10^{-2} Scm−1 at the thickness of ~20nm.

A conversion efficiency of 16.18% of heterojunction with intrinsic thin layer (HIT) solar cell on 10 mm × 10 mm FZ-c-Si wafer has been obtained.

STATEMENTS & DECLARATIONS

Funding:
The authors are thankful to Department of Science and Technology, Govt of India for the funding (grant no:DST / TMD / SERI / S46); and to Rashtreeya Vidyalaya College of Engineering, Bengaluru for support.

Competing Interests:

The authors have no relevant financial or non-financial interests to disclose

REFERENCES

[1] J. Ge et al. “Optimisation of Intrinsic a-Si:H Passivation Layers in Crystalline-amorphous Silicon Heterojunction Solar Cells” ELSEVIER Energy Procedia V15,pg 107-117.2012

[2] Thomas Muellar et al. “Heterojunction Silicon Wafer Solar Cells using Amorphous Silicon Suboxides for Interface Passivation” ELSEVIER Energy Procedia V15,pg 97-106.2012

[3] T. Schutz-Kuchly and A. Slaoui, “Double layer a-Si:H/SiN:H deposited at low temperature for the passivation of N-type silicon,” Appl. Phys. A, vol. 112, p. 863, 2013.

[4] Pysch DMB, Zimmermann K, Schetter C, Hermle M, Glunz SW. “Comprehensive study of different PECVD deposition methods for deposition of thin intrinsic amorphous silicon for heterojunction solar cells” . Proc. 24th European Photovoltaic Solar Energy Conf., Hamburg, Germany, p. 1580-5,2009.

[5] Schüttauf et al. “Excellent crystalline silicon surface passivation by amorphous silicon irrespective of the technique used for chemical vapor deposition”. Appl. Phys. Lett.; 98:153514,2011.

[6] C. Voz et al. “Surface passivation of crystalline silicon by Cat-CVD amorphous and nanocrystalline thin silicon films” ELSEVIER Thin Solid Films V- 430,270–273, 2003

[7] T. Mishima, M. Taguchi, H. Sakata, and E. Maruyama, “Development status of high-efficiency HIT solar cells,” Sol. Energy Mater. Sol. Cells, vol. 95, pp. 18–21, 2011.

[8] S. DeWolf, A. Descoeudres, Z. C. Holman, and C. Ballif, “High-efficiency silicon heterojunction solar cells: Areview,” Green, vol. 2, pp. 7–24, 2012.

[9] Rodrigo Garcıa Hernansanz et al. “Deposition of Intrinsic a-Si:H by ECR-CVD to Passivate the Crystalline Silicon Heterointerface in HIT Solar Cells” IEEE Journal of Photovoltaics,Vol.6 No.5, 2016

[10] Honda S, Mates T, Ledinsky M, Oswald J, Fejfar A, Kocka J, Yamazaki T, Uraoka Y, Fuyuki T. Effect of hydrogen passivation on polycrystalline silicon thin films. Thin Solid Films **487**:152-6,2005.

[11] Hsiao JC, Chen CH, Lin CC, Wu DC, Yu P. “Effect of hydrogen dilution on the intrinsic a-Si:H film of the heterojunction silicon-based solar cell”. J. Electrochem. Soc. 158:H876-H878, 2011.

[12] Jeon M, Yoshiba S, Kamisako K. “Hydrogenated amorphous silicon film as intrinsic passivation layer deposited at various temperatures using RF remote-PECVD technique” Curr. Appl. Phys. 10:S237-S240.2010.