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Study and Optimization Optical and Electrical properties of the p, i and n- Layers of Single Junction a:Si-H Solar cell in an Indigenously Developed PECVD Cluster System.

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Abstract: Hydrogenated amorphous silicon solar cells have been one of the principle drivers of large area and flexible microelectronics. Hence the effort is to develop single junction hydrogenated amorphous silicon solar cells, using an indigenously developed Plasma Enhanced Chemical Vapour Deposition system and also leverage plasmonics to further enhance the efficiencies. The software controlled PECVD system enables deposition and optimization of layers and solar cell device using a cluster 5 process chambers. In the present work, several experiments have been carried out by varying the critical process parameters in order to optimize the p and n-layers for obtaining efficient hydrogenated amorphous silicon (a-Si:H) p–i–n solar cell. The p-layer conductivity and band gap were found to have high influence on the efficiency of a-Si:H, p–i–n solar cell in addition to the i and n-layer properties. Single junction thin film a-Si solar cells have been fabricated with a maximum efficiency of around 5.89 %. The current band gaps of p-layer,i-layer and n-layers are 1.95 eV, 1.73 eV and 1.7 eV respectively. Presented in this paper are the details of the two above activities.
Key words: a:Si:H, PECVD, bandgap, conductivity.

1. Introduction

Thin film based solar cells such as CIGS and CdTe have shown great improvement in their efficiency during last decade. Moreover, organic, polymer and dye sensitized solar cells are also exhibited great response towards improvement of their efficiencies. Thus, in order to involves Hydrogenated amorphous silicon, a-Si:H, in competition with other solar cells, it is significant to improve the efficiency of solar cell which will strongly depend on the optical and electrical properties of p, i and n layers of a-Si:H solar cell [1-3]. Recently, studies are performed for optimizing the parameters in order to enhance the efficiency of a-Si:H p–i–n solar cells. The simplest semiconductor junction that is used in solar cells for separating photo generated charge carriers is the *p-n* junction, an interface between the *p*-type region and *n* type region of one semiconductor [4]. Therefore, the basic semiconductor property of a material, the possibility to vary its conductivity by doping, has to be demonstrated first before the material can be considered as a suitable candidate for solar cells.

This study reports on developing the p-layer of solar cell application using PECVD. The deposition processes with the variations of the gas ratios (B_2H_6 and CH_4) were investigated. The thickness, deposition rate, conductivity and band gap at various deposition conditions are reported. Among various parameters,p, i and n layer conductivity and band gaps have great influence on the efficiency of solar cells. Recently, theoretical studies for optimization of p, i and n-layers band gaps for improving the efficiency of a-Si:H p–i–n solar cells with hydrogenated amorphous carbon as p-layer are also carried out by our group.

Keeping all these points into the mind, the p, i and nlayer conductivity and bandgaps of a-Si:H and acceptor and donor concentrations are optimized by carrying out several experiments. With these optimized values, the experimental realization of efficient a-Si:H p–i–n solar cell is possible.

2. Experiment

a-Si:H p–i–n solar cells were prepared using an indigenously designed and developed capacitive coupled 5-chamber RF-PECVD deposition system working with an excitation frequency of 13.56 MHz.SCADA software integrated with PLC/user interface enables the operation and control of the machine and process in auto mode. The system is provided with independent magnetic arms to the chambers in order to transfer the substrates between the process chambers during deposition of the p-i-n layers. Dry mechanical pumps (Edwards) are used for the process chambers. The maximum possible substrate size in this deposition system is 100 X 100 mm^2. Various glass substrates (float glass, schott glass etc.) of size 25 X 25 mm^2 have initially been used for deposition of solar cell layers. A base pressure of 1 X 10^{-3} torr has been maintained throughout the study. SEREN make RF power supply of 600 W has been used to power the electrode size of 130 mmΦ X 8 mm thick.

Figure1 shows the schematic diagram of solar cell construction with its layer parameters. The superstrate arrangement allows the light to enter through the glass/TCO (Transparent Conductive Oxide). TCO acts as front contact, which enables the large percentage transmission of the incident light. The individual layers of device have been deposited using gases such as H_2, SiH_4,B_2H_6 and CH_4 for p-layer; H_2 and SiH_4 for i-layer; H_2, SiH_4 and PH_3 for n layer.

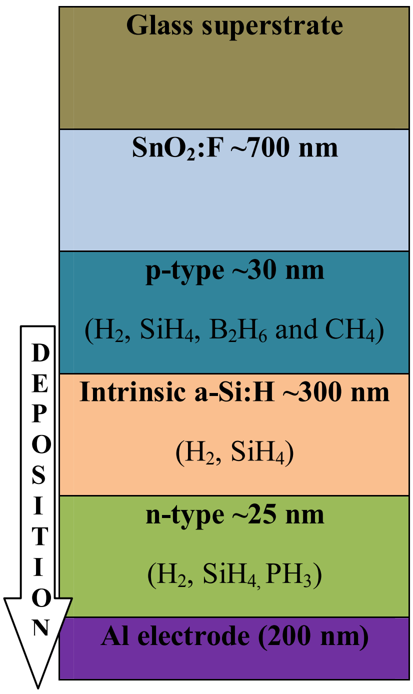

Figure 1: The schematic diagram of a-Si:H p-i-n solar cell.

Thickness of the films were measured using stylus profiler (veeco Dektak 6M). Electrical properties of the deposited films were studied by co-planar conductivity measurements (Keithley 6487 and AgilentB-1500 semiconductor device analyzer) using sputtered and evaporated aluminum electrodes with 12mm length and 3mm gap. Optical measurements are recorded using UV-VIS spectrophotometer (perkin Elmer Lambda 35) in the wavelength range of 250-2500nm. After optimizing the individual layers solar cells of size 10 x 10

mm^2have been fabricated on SnO_2:F coated glass substrates. The IV measurements of the above cells were measured using a Spectranova SN series solar simulator [5].

3. Results and Discussions

Optical Studies

The optical properties of *a*-Si:H are usually considered by its absorption coefficient αand a value of the optical band gap (Eg).Figure2 shows that p- layer (window layer) is more transparent to the sunlight hence better the optical properties of individual layers. Table 1 shows the transmittance values of p-layer and i-layer thin film on glass substrate. Figure 3a shows the absorption coefficient of *p*-type *a*-SiC:H, i-type *a*-Si:H, and n-type. From the absorption coefficient of *a*-Si:H based materials tauc plot is developed from which optical band gap is determined as shown in Figure 3b. The optical band gap allows the comparison of *a*-Si:H based materials concerning their light absorption properties. Higher the band gap lesser is the absorption.

Table 1: Average % Transmittance and % Transmittance@ 750 nm of p and i layer of solar cell.

Layer	Average %Transmittance (500 ~ 800nm)	% Transmittance @ 750 nm
p	43.48	44.64
i	37.07	35.72

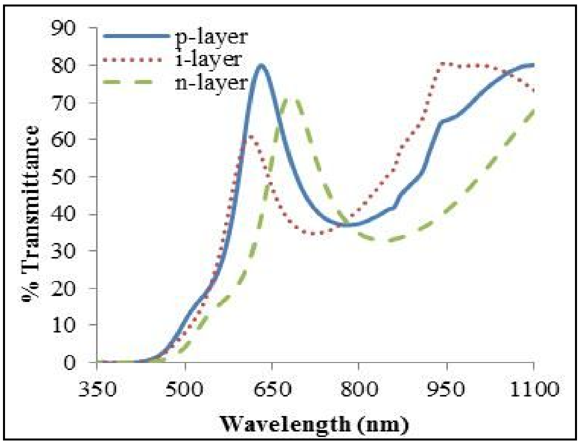

Figure 2: The average % transmittance of p, i and n-layers.

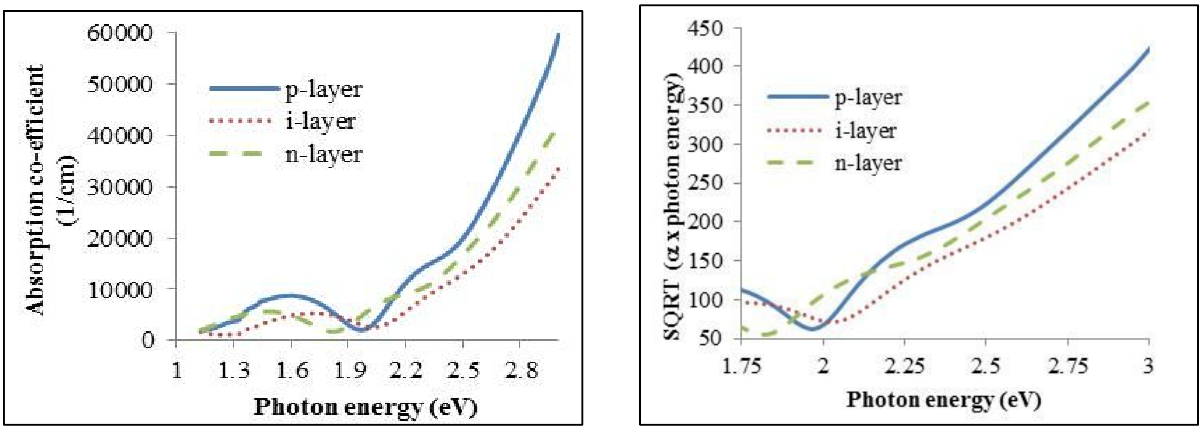

Figure 3: (a) Absorption coefficient as function of photon energy for *p*-type *a*-SiC:H, i-type *a*-Si:H, and n-type *a*-Si:H. (b) Tauc plot to determine the Tauc optical band gap for *p*-type *a*-SiC:H, i-type *a*-Si:H, and n-type.

Electrical Studies

The electrical properties of *a*-Si:H are usually characterized in terms of dark conductivity and photoconductivity. Photoconductivity measured using the AM1.5 light spectrum and the incident power of100 mW/cm^2.

i. Optimization of p-layer.

Usually, thinner and wide-optical bandgap p-type hydrogenated amorphous silicon car-bide (a-SiC:H) layer is used in high-efficiency a-Si solar cells as a window layer. The performance of the window layer affects the open-circuit voltage (Voc)as well as conversion efficiency of solar cells. The influence of B_2H_6 concentration on conductivity of p-layer has been studied by keeping the parameters such as RF Power = 7W, temperature = 250^{o}C, pressure = 1 torr and results are shown in Figure 4a. The conductivity increases from 2.28X 10^{-8} S/cm and reaches to a maximum value of 3.15 X 10^{-6} S/cm with increase in B_2H_6 concentration from 3 sccm to 6 sccm and then after decreases. The Figure4b shows the effect of CH_4 concentration on the bandgap of p-layer. The bandgap increases from 1.72 eV to 1.95 eV with increase in the CH_4 concentration from 2 sccm to 10 sccm. From the above studies p-layer is optimized for a maximum conductivity of ~3 X 10^{-6} S/cm and bandgap of 1.95 eV at a deposition rate of 7.5 nm/min.In this work the averageEgis about 1.95 eV, which is higher than that of common p-type a-Si:H films (Eg = 1.6–1.8 eV) and close to general a-SiC:H (Eg=2.04 eV) window-layer material has good agreement with the previous work [5].The wider optical band gap of the doped window layer or the top p-layer allows more light to enter into the active region (i-layer) of the device [6-7]. The higher optical band gap of the window layer reduces the absorption loss at the p-type layer. However, it is observed from Fig. 4 that with increased carbon content within the material, optical band gap increases and the wider optical band gap is usually associated to lower dark conductivity of order 10^{-6} S/cm. As a result the higher optical band gap of the p-layer may lead to lower output voltage from the device. The carbon-silicon bonds lead to higher optical gap of the material and thus the increased carbon fraction leads to higher optical gap of the material. This higher optical gap results in higher optical transparentwindow layerof a p-i-n type solar cell.

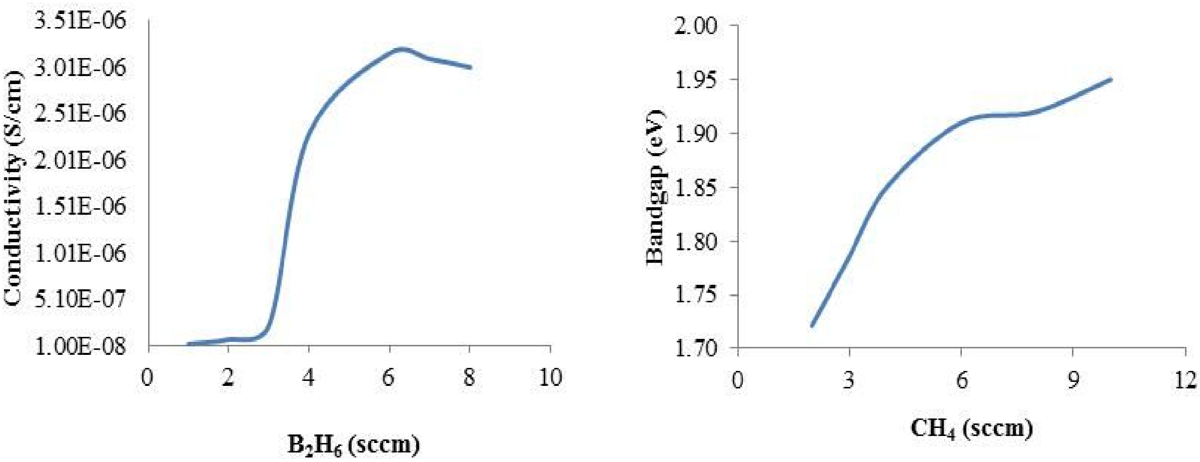

Figure4:(a) The effect of B_2H_6 concentration on p-layer conductivity. (b) The Effect of CH_4 concentration on p-layer bandgap.

ii. Optimization of i-layer.

As we discussed in our earlier work [8] to optimize the i-layer band gap of a-Si:H single-junction solar cells, band gap has been varied between 1.6 to 1.9, Figure5 represents the variation of dark conductivity with the change in band gap of i-a-Si: H layer. The optimum band gap has been observed at ~1.73 eV which corresponds to the maximum dark conductivity of order 4.87x10^{-10} Scm^{-1} (- log (4.87x10^{-10}) = 9.31) and a gain of order 10^5. As the high energetic photons will be absorbed at the window layer, the band gap can be gradually decreased for successive absorber layers. During this process, the p-layer and the n-layer band gaps are kept 1.9 eV and 1.95 eV, respectively. Since p-layer band gap is retained as 1.9 eV, the light of solar spectrum with energy less than 1.9 eV should reach i-layer. At low i-layer band gap more photons will be absorbed, which may cause significant absorption losses and hence, lower dark conductivity which in turn decreases the efficiency. With the increase of i-layer band gap from1.65 eV to 1.73 eV absorption losses should be reduced and hence, comparatively higher conductivity is obtained. Further increase in band gapbeyond 1.73 eV, it is realized that sufficient light absorption is reduced in i-layer which causes lesser electron–hole pair generation and therefore, decrease in conductivity.

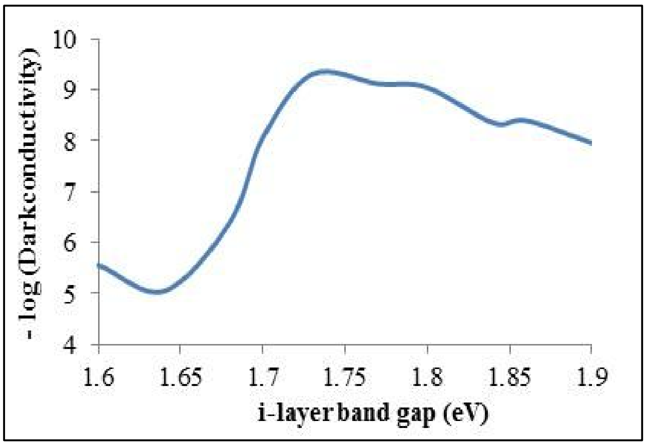

Figure 5: Variation of Conductivity with i-layer band gap.

iii. Optimization of n-layer.

The effect of flow ratio on deposition rate and conductivity has been studied, by keeping RF power of 7W. The doping efficiency in *a*-Si:H, which is defined as the fraction of dopant atoms with fourfold coordination, is in the range of 10^{-2} - 10^{-3} in *a*-Si. This means that relatively high concentrations of phosphorous atoms must be introduced in order to obtain material with high conductivity. As shown in the Figure 6 the deposition rate decreases with increase in flow ratio (H_2/PH_3) and the conductivity increases from the order of 10^{-6} to an order of 10^{-2} with the flow ratio.

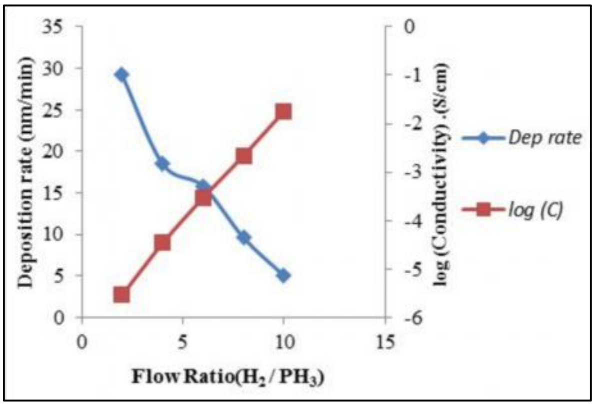

Figure 6: The effect of flow ratio on deposition rate and conductivity.

After achieving the above independent p-, i- and n-layer properties, Table 2, experiments have been conducted to fabricate complete a-Si:H solar cell devices using fluorine doped tin oxide and aluminum as bottom and top electrodes respectively. As on today, we have fabricated and characterized a-Si:H solar cells. TheI-V characteristics of the fabricated solar cells are obtained as shown in Figure 7having maximum efficiencyof5.89% with open circuit voltage Voc = 0.80 V, short circuit currentJsc =0.01070A/sq.cm, and fill factor FF = 0.68.

Table 2: Optimized individual layer's Band gap and Conductivity values used in the fabrication of single junction a-Si:H p-i-n solar cells.

Layer	Band gap(eV)	Conductivity (S/cm)
p	1.95	9.8×10^{-6}
i	1.73	**Dark Conductivity:** 3.38×10^{-10} **Photo Conductivity :** 1.23×10^{-5}
		Gain : 3.83×10^{4},
n	1.7	1.8×10^{-2}

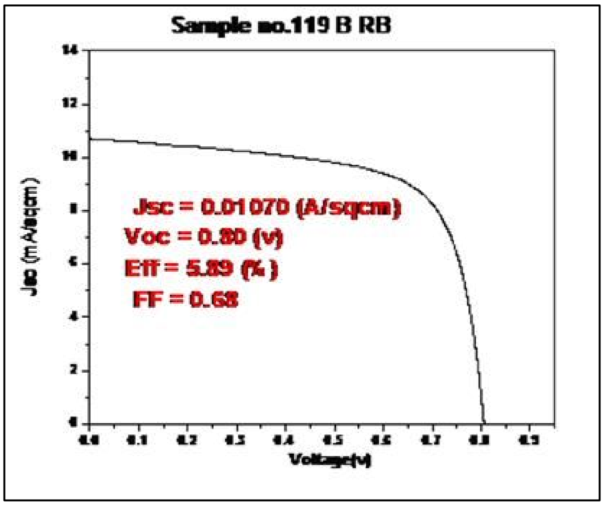

Figure 7: I-V results of solar cell.

Conclusion

In the present study, the role of p, i and n-layers conductivity and band gaps on the efficiency of a-Si:H p–i–n solar cells have been investigated experimentally. At first, the acceptor (PH_3) and the donor (B_2H_6) flows, 7 sccm and 6 sccm respectively are optimized to obtain the conductivity in the order of 10^{-2} S/cm and 10^{-6} S/cm respectively.i-layer has been optimized to a gain of order 10^{+4} (photoconductivity = 10^{-5}, Darkconductivity = 10^{-10}). The optimized bandgaps of p-layer,i-layer and n-layersare1.95eV, 1.73 eV and 1.7eV respectively. The maximum efficiency offabricated a-Si:H solar cells is found5.89% with Voc = 0.80 V, Jsc =0.01070 A/sq.cm, and FF = 0.68. We are now in the process of incorporating buffer layer and nano-metal layers in experimental studies in order to enhance the efficiency of a-Si:H p–i–n solar cells.

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