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Temperature Effect on the Performance of N-type μc -Si Film Grown by Linear Facing Target Sputtering for Thin Film Silicon Photovoltaic Devices

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Abstract- In this work, the effect of temperature on performance of (Al+Ag)/n^+- μ c -Si/ p-Si/Al thin Film Grown by Linear Facing Target Sputtering thin Film solar cells devices has been investigated. μ c n+-Si type is used as donor whereas p-type used as an acceptor. The optimised device has an efficiency of ~23.5% at room temperature. Investigations on the optimized device show that temperature has significant effect on the photovoltaic performance. Short circuit current density (J_{sc}) and fill factor (FF) increase whereas open circuit voltage (V_{oc}) increases with reduction in temperature. The increasing in J_{sc} has been attributed to the temperature dependent electronic properties of the active μ c n+-Si layers while the increment in the V_{oc} has been attributed to the reduction in band bending and increment in built in voltage (V_{bi}) on lowering of temperature. In overall the efficiency first increases and then decreases with reduction in temperature.

Keywords- thin film solar cells, electrical performance, Electronic properties, Fill factor, Short circuit current density, Open circuit voltage, series and shunt resistances.

1. Introduction

In the last two decades a new branch of photovoltaic research, known as thin film-Silicon (TF-Si) photovoltaic devices has evolved which is now considered to be an alternate to conventional inorganic solar cells. Thin film solar cells devices are considered to be the most promising alternative sources of energy as they can play an important role in generating cost effective long term and clean energy along with other potential features, such as light weight, flexibility, and ease in fabrication of large area devices. These technological potentials are now driving the attention of researchers towards further improvement in the performance of these devices. The performance of TF-Si devices has improved a lot in the last decade through various device designs, different physical treatments and variation of materials and processing techniques. Power conversion efficiency (η) of ~ 21 % has been achieved in tandem TF-Si multi- junction devices based on silicon at illuminations of 100 mW/cm^2 [1]. In recent years, power conversion efficiencies of thin-film organic photovoltaic cells have been increased steadily and rapidly [2, 3]. .It should be emphasized that high efficiency and long lifetime has not been observed for the same device, and one of the current challenges is the combination of all the desirable properties in the same material (efficiency, stability, processability and low cost). The separate demonstration of these properties for different materials, however, does show that it should be possible and from this point of view, the TF-Si could become a true competitor to the silicon-based PV. Stability and reliability are the major concerns for these devices and lots of research is being done in this area as well. Because of continuous efforts and hard work of the researchers, several thousand hours life time of TF-Si devices has been achieved

[4-6]. Under light illumination the absorbed light photons generate excitons, which diffuse to the donor acceptor interface and dissociate there. The efficient dissociation of photo-generated excitons and rapid transportation of the separated charge carriers through the active layers leads to the high efficiency in these devices.

Depending upon the materials to be used, the TF-Si devices can be prepared by thermal evaporation of the materials in vacuum. For reliability of these devices in different environmental conditions it becomes very important to investigate the effect of various physical parameters, e.g., temperature, humidity, electric field, magnetic field and illumination intensity on their performance. In this paper, the effect of temperature on the performance of on n+-Si has been investigated. These studies have been carried out in dark. The interesting results along with their interpretations have been discussed. This research throws adequate light on elucidating the mechanism governing the charge carrier transport and generation of photocurrent/photo-voltage in the thin film solar cells devices as a function of working temperature.

2. Experimental

The devices were prepared from the Al+Ag/ n$^+$-Si/ p-Si/Al configuration, where n$^+$ -Si μc thin film works as exciton blocking layer. Application of exciton blocking layer reduces the exciton quenching at cathode and improves the cell performance [7]. Fig. 1 shows the schematic structure of the device. The p -Si substrates were coated from one side by mc n+-type Si thin film using linear target sputtering coating process. The fabricated cells were annealed in air at 400 ^{0}C for 1h to complete the junction formation.

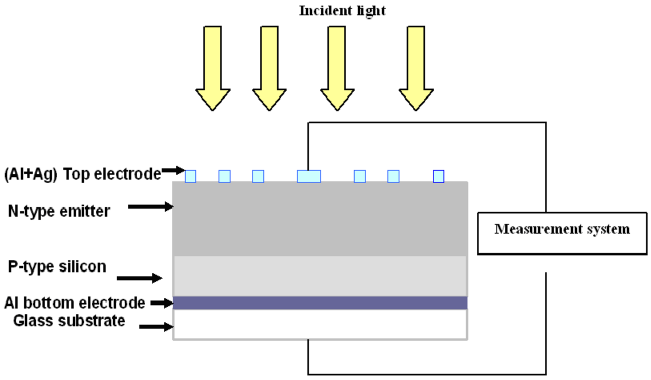


Fig. 1. Schematic diagram of (Al+Ag)/n$^+$- Si/ p-Si/Al solar cell.

To eliminate the performance variance due to fabrication conditions, the devices were fabricated in a controlled way under identical conditions. The current density- voltage (J-V) characteristics were carried out in dark and under halogen lamp illumination with irradiance of 100 mW/cm^2. The electrical measurements were performed using a conventional d.c. technique and a high-impedance Keithley 610 electrometer.

3. Results and Discussion

3.1. Electrical properties of (Al+Ag)/ n$^+$-Si/ p-Si/Al thin film silicon solar cell in the dark

The power conversion efficiency of TF-Si device depends on the absorption efficiency, exciton dissociation efficiency, transport of charge carriers and charge collection efficiency. Absorption of incident photons and exciton dissociation are decided by the thickness of the photoactive layers. The best performance can only be achieved by the optimization of various parameters. The current-voltage characteristics at different temperatures in the range 300-420K are presented in Fig. 2, and it exhibits a semiconductor / semiconductor multijunction thin film behavior with the forward direction to the positive potential on p-Si. This exponential dependence at this voltage range can be attributed to the formation of depletion region between n+-Si active layer and Si due to the high work function of the two ohmic contacts for active layer and n-Si. The I-V characteristics presented in Fig. 2 can be described as follows [8]:

$$I = I_{01}\left[\exp\left(\frac{qV}{n_1 kT}\right)-1\right]+I_{02}\left[\exp\left(\frac{qV}{n_2 kT}\right)-1\right]+\frac{q(V-IR_s)}{R_{sh}} \tag{1}$$

where I_0 is the reverse saturation current, q the electronic charge, V the applied voltage, k the Boltzmann's constant, T the temperature and n is the ideality factor, R_s and R_{sh} are series and shunt resistances, respectively. The subscripts1 and 2 indicated that two possible contributions to the diode current can be presented.

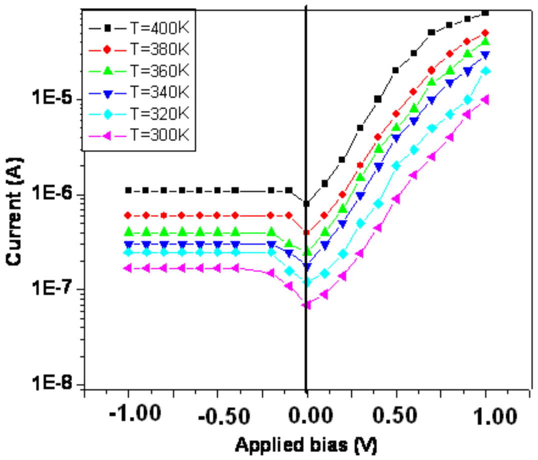


Fig. 2. The current-voltage characteristics of (Al+Ag)/n$^+$-Si/ p-Si/Al thin film solar cell in the temperature range 300-400K.

In order to understand which mechanisms control the device behaviors in the high-voltage region 0.50< V < 0.62V, the I-V characteristics of (Al+Ag)/n$^+$-Si/p-Si/Al thin film solar cells are presented in log-linear scale (at different temperatures) in Fig. 3. The dependencies become close to

IVm, where m>2, for (Al+Ag)/n^+-Si/p-Si/Al thin film solar cells. The observed transition to super-linear dependence of the current with increase in the bias voltage usually indicates the onset of a space charge limited current (SCLC) regime. The value of exponent m decreases with increasing temperature [9].

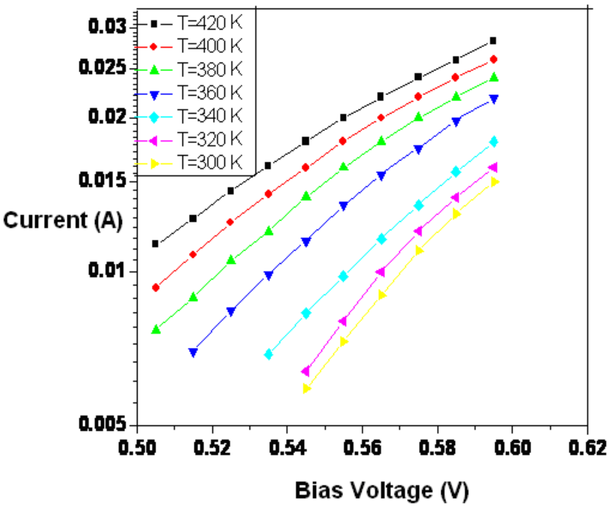


Fig. 3. Junction current under high bias voltage region of Al+Ag/n^+-Si/p-Si/Al thin film solar cell in the temperature range 300-420K.

3.2. Photovoltaic properties of the (Al+Ag)/n^+- μ c Si/p-Si/Al structure

The power conversion efficiency of a thin film silicon photovoltaic device depends upon the absorption efficiency, exciton dissociation efficiency, transport of charge carriers and charge collection efficiency. Absorption of incident photons and exciton dissociation are decided by the thickness of the photoactive layers. The best performance can only be achieved by the optimization of various parameters. For the same objective we varied the thicknesses of the active layer n+-type mc -Si film. To optimize the thickness of n-type mc -Si first of all was kept at 700 nm. The device exhibited a short circuit current (Jsc) = 36 mA/cm^2, open circuit voltage (Voc) = 0.58 V, fill factor (FF) = 82% and the cell efficiency is 22.2%. The increment in Jsc can be attributed to the enhanced absorption of incident light in n+-type mc-Si film due to increased thickness resulting large photo-current.

The illuminated I-V characteristics of the (Al+Ag)/n^+-Si/p-Si/Al thin film silicon solar cell are shown in Fig. 4 and 5. The current value at a given voltage for this device under illumination is higher than in the dark. This indicates that the absorption of light by the active layer n-type mc -Si generates carriers contributing photocurrent due to the production of excitons and their subsequent dissociation into the free charge carriers at the barrier, i.e. n^+-type mc-Si interface. It is observed that the photocurrent in the device in reverse direction is strongly enhanced by photo illumination. This behavior yields useful information on the electron-hole pairs, which were effectively generated in the junction by incident photons. Under the influence of the electric field at the junction, the free electrons and holes were accelerated towards the electrodes along the potential barrier at the interface. As observed from Fig. 4, the device shows photovoltaic characteristics at different illumination levels (i.e., 20 mW/cm^2 to 100 mW/cm^2), with short-circuit photocurrent density (J_{sc}) (The current flowing freely through an external circuit that has no load resistance; the maximum current possible.) of 35.5 mA/cm^2, open circuit voltage (V_{oc}) (the difference of electrical potential between two terminals of a device when there is no external load connected) of 0.6V (at illumination 100mW/cm^2), fill factor (FF) (The ratio of a solar (photovoltaic) cell's actual power to its power if both current and voltage were at their maxima.) of 0.75 and power conversion efficiency (The amount of energy produced as a percentage of the amount of energy consumed. In the case of a photovoltaic device, the ratio of the electric energy n produced by the device, under one-sun conditions, to the energy from sun light incident upon the cell) of 22.2%. The variation of short-circuit photocurrent (J_{sc}) with the incident light intensity (Pin) for n+-Si/p-Si device is shown in Fig. 5. The J_{sc} follows the power law, i.e. Jsc a (Pin) s, with exponent(s) has a range from 0.53 to 0.58 .The s values for 0.5 and 1.0 Correspond to bimolecular recombination and monomolecular recombination mechanism, respectively [10]. The value of the exponent lies between 0.5 and1.0 for continuous distribution of trapping centers [10]. The obtained s value for the (Al+Ag)/n^+-Si/p-Si/Al diode indicates the presence of continuous distribution of traps. This value suggests that life time of the photocarriers is controlled by trap centers.

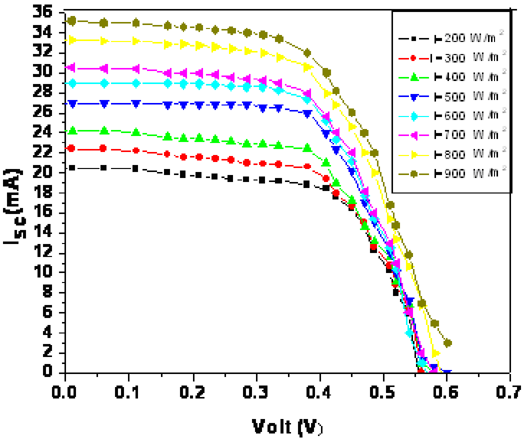


Fig.4. Current - Voltage characteristics for (Al+Ag)/n^+- Si/ p-Si/Al thin film solar cell at different illumination levels.

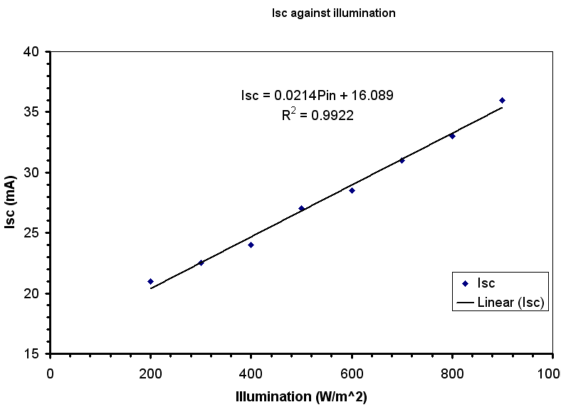


Fig. 5. Short-circuit current- illumination characteristics.

3.2.1. Temperature effect on the electrical performance of the cell

The current supplied by a solar cell to a load is that given by the difference between the photocurrent I_L and the recombination current $I_D(V)$,according to the equation:- $I = I_L - I_D(V)$ the latter being due to the bias from the generated voltage. If we assume, to simplify things, that a single exponential can express the current in the diode, the characteristic equation for the device is:

$$I = I_L - I_0\left[\exp\left(\frac{eV}{nkT}\right) - 1\right] \quad (2)$$

Fig.6 illustrates the relation between the I-V characteristics of the fabricated thin film solar cell under different temperatures. As it is clear from Fig.6 that as the cell temperature increases the cell J_{sc} slightly increases.

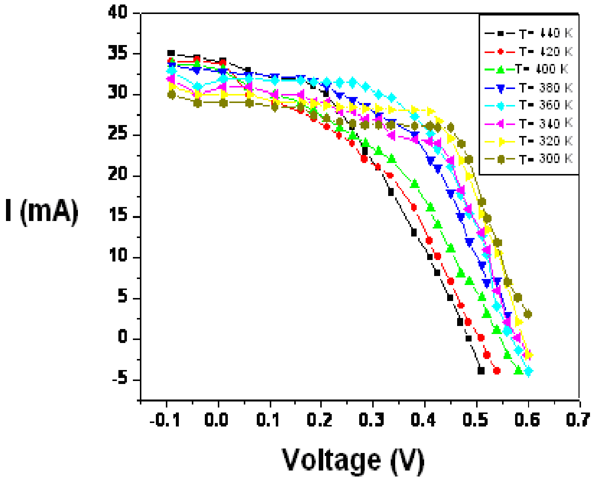
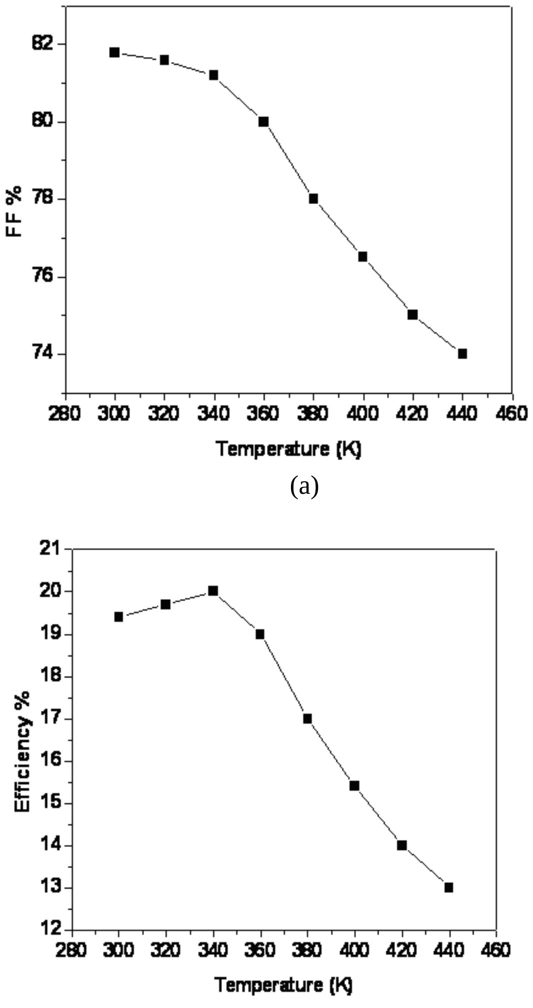


Fig. 6. I-V characteristics for the (Al+Ag)/n$^+$-Si/p-Si/Al thin film solar cell under different temperatures .



(a)

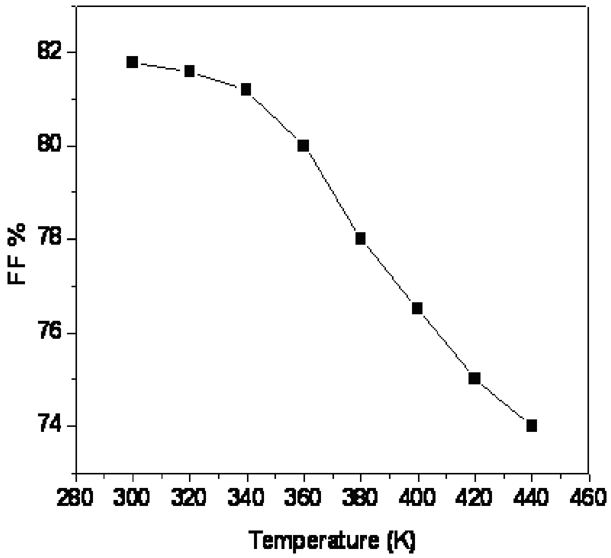
(b)

Fig. 7. Electrical parameters versus temperature of (Al+Ag)/n$^+$-Si/p-Si/Al thin film solar cell.

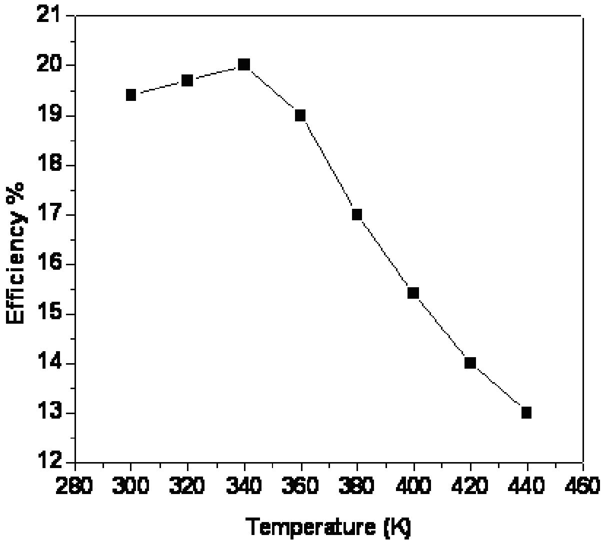
Fig. 7 (a & b) shows the effect of temperature on J_{sc} and V_{oc} of the μc -n-type Si TF-Si solar cells based devices. It is observed that Jsc increases with increasing in temperature, but Voc decrease with increasing in temperature. The temperature dependence of J_{sc} can be attributed to the electronic transport properties of the active μc n-type Si materials. Their charge carrier mobilities are very low and depend on the temperature. One would expect that the lowering of temperature will enhance the current [11]. Therefore, raise in Jsc can be interpreted in terms of trapping effect and the reduction of charge carrier mobility with temperature. Regarding the variation of V_{oc} with temperature, the origin of V_{oc} itself is not well understood. Different models have been presented to explain the experimental observations [12, 13]. However, the temperature variation of V_{oc} could not directly be explained by these models. In conventional Si solar cells the temperature dependence of V_{oc} is given by:-

$$V_{OC} = \frac{nkT}{q}\ln\left(\frac{J_{SC}}{J_0} + 1\right) \quad (3)$$

where J_0 is the reverse saturation current in the device and n is the diode ideality factor. Here both the J_{sc} and J_0 also depend on temperature and increase with increase in temperature [14, 15]. Though increase in J_{sc} would slightly increase V_{oc} but due to large increase in J_0 (J_0 is proportional to n_i^2, where n_i is intrinsic charge carrier density) would rapidly decrease Voc with increment in temperature [14]. V_{oc} was observed to increase linearly with temperature reduction and Eq. (3) was used to explain the temperature dependence of V_{oc}. Alternatively the temperature dependence of the V_{oc} in the present case has been attributed to the temperature dependence of built-in voltage (V_{bi})[14,16,17,18]. The structure of a TF-Si solar cell device contains an active μ C n^+-type Si layer sandwiched between two metal electrodes. For the devices containing electrodes with different work- functions, in thermal equilibrium the Fermi level alignment takes place and an electric field is developed which is known as built-in electric field. The corresponding voltage between the two electrodes is known as the built-in voltage (V_{bi}). The built-in electric field for electrons is directed from anode to cathode. Generally, V_{bi} is given by the difference of the work-function of the two electrodes (ΔW). But if electrodes make ohmic contact with the active materials, an accumulation of charge carriers takes place in the vicinity of the electrodes and band bending takes place. Because of this band bending V_{bi} now becomes less than the (ΔW). As the temperature increases V_{bi} decreases and because of increment in V_{bi}, V_{oc} decreases. Fig. 8 (a &b) shows the variation of FF and η of the TF-Si solar cell based on μ C n^+-type Si layer with temperature. The observed temperature dependence of FF is almost similar to that of Jsc. This behaviour can qualitatively be understood in terms of temperature dependent series resistance of the TF-Si devices



(a)



(b)

Fig. 8. Solar cell fill factor and efficiency versus temperature.

4. Conclusion

The current-voltage characteristics at low forward bias of the fabricated (Al+Ag)/n^+-μc-Si/ p-Si/Al thin Film device showed that the thermionic is the dominant charge transport mechanism through the device as well as space charge limited conduction at high forward bias. Temperature has been found to have a significant effect on device performance. The dark current under reverse bias and at low temperatures has been attributed to be governed by the tunneling of the charge carriers through large injection barriers. The overall efficiency of the device increases first and then decreases with reduction in temperatures. Various photovoltaic parameters were obtained from the analysis of loaded I-V characteristics under illumination. The highly enhanced value of the fill factor and power conversion efficiency can be attributed to the low recombination rate of carrier and consequently unlimited the collection efficiency of the charge carriers.

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