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High efficiency In_2O_3/c-Si heterojunction solar cells produced by rapid thermal oxidation

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In this paper, Indium oxide (In_2O_3)/n-Si junction solar cells were prepared by novel rapid thermal oxidation (RTO) technique using halogen lamp at 300 ºC/25 sec condition at static air. The fabricated solar cells subjected to post-deposition annealing at 450 ºC/30 min and 450 ºC/35 min. High conversion efficiencies ranging between 11.5% and 14.5% at AM1 condition for unannealed an annealed cells respectively were obtained without using frontal grid contact. The photovoltaic properties of solar cells before and after annealing are characterized and analyzed. Furthermore, the stability conditions and reliability of these cells have been tested.

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1. Introduction

The monocrystalline silicon junction solar cells have high conversion efficiency (~20%). These cells fabricated by large –scale integration (LSI) [1,2]. LSI procedure produce high-cost solar cells.Heterojunction solar cells based on silicon like transparent conductive oxide (TCO) represents one of good solutions for producing simple, low-cost, large area, and high efficiency solar cells [3]. Indium tin oxide (ITO)/Si and Indium oxide (IO)/Si solar cells are subjected under extensive studies [4-7]. Different methods used to prepare high quality In_2O_3 such as sputtering, spraying, CVD, sol- gel, and vacuum evaporation [8-13]. The film produced by these methods is polycrystalline in nature. The recent publications confirm that in the highly oriented films is important to minimize the effects of the texture that in turns affect the transport properties of grown films [14]. The previous study of the authorsshowed the possibility of formation highly oriented In_2O_3 grainsin the direction of (222) by RTO technique [15]. From this point of view, we have studied In_2O_3/Si junction solar cells in this paper. The study included also the effect of post-deposition heat treatment on characteristics of solar cells.

2. Experiment

In this study n-type mirror like single crystal (111) silicon substrates having resistivity of 1-3 Ωcm are used. These substrates are cut into 49 cm^2 pieces, first washed with acetone and then etched in CP4-A solution for 2 min and then in 12% HF for 2 min to remove the native oxide. High purity indium thin film was deposited by thermal evaporation under vacuum pressure of 10^{-7}Torr on Si and cleaned glass substrates through special mask. Rapid thermal oxidation technique using halogen lamp was used to oxidized inium film at static air and hence produced In_2O_3 layer on Si and glass substrates. The experimental set-up and details are presented elsewhere [15]. After formation of In_2O_3 film with thickness of 100 nm on both silicon and glass the samples are transferred into annealing system using tube furnace. The annealing process was carried out under vacuum pressure down 10^{-4} Torr at conditions 450 ºC/30 min and 450 ºC/35 min. Ohmic contacts were made on In_2O_3 and Si by depositing Al and In-Ga alloy thick films, respectively. For point probe FPP5000 system and thermoelectric measurements were used to investigate the conductivity of In_2O_3 film. The film transmittance was measured in the range (300-900) nm using Shimadzu spectrophotometer. Dark and illuminated current-voltage (I-V) characteristics were measured with a potentiostat and a potential sweeper sun simulator at AM1 condition was used as light source. Capacitance-voltage (C-V) properties were measured using LCZ meter at the frequency of 1 kHz.

3. Results and discussion

The XRD spectrum of In_2O_3 that presented elsewhere [15] confirms that the film has high orientation grains in the (222) direction with very sharp peak which better than that for films prepared by other methods .The optical transmittance spectrum of film is presented in Fig. 1 The significant increasing in film transmittance was found after annealing. A high average transmittance over 80% in the visible region

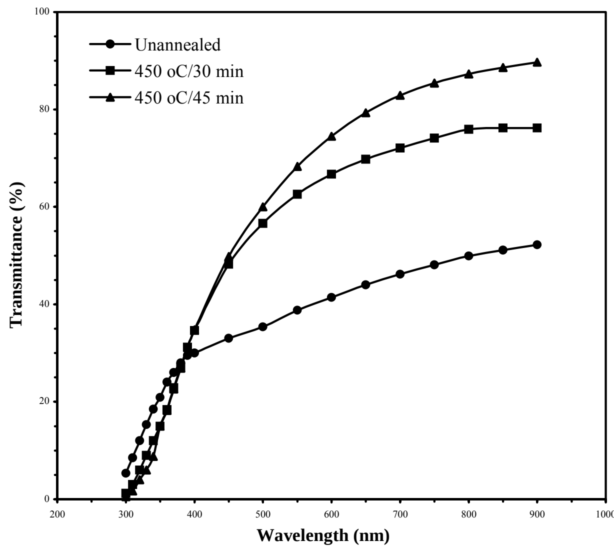

Fig. 1. Transmittance spectrum of film before and after annealing.

was obtained for film annealed for 45 min. Fig. 2 shows $(\alpha h\upsilon)^2$ versus photon energy, where α is absorption coefficient which determined from transmittance data.

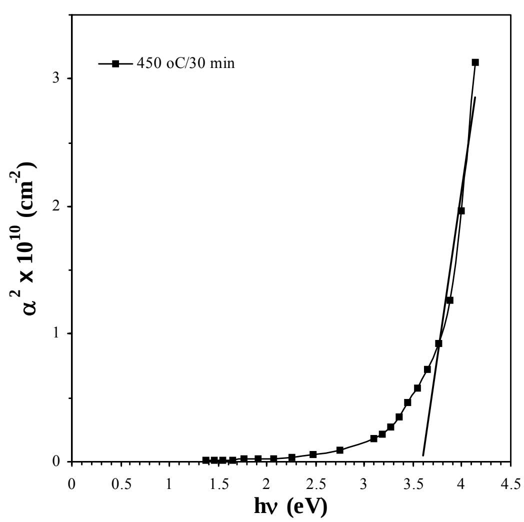

Fig. 2 $(\alpha h\upsilon)^2$ versus hυ plot.

The optical band gap has been found to be 3.67eV for unannealed film while found to be 3.77 eV and 3.8 eV for films annealed at 450 ºC/35 min and 450 ºC/45 min conditions, respectively.

The values of band gap after films annealing are larger compared to the intrinsic band gap, this can be attributed to the BM shift [14,16].The resistivity of the films before and after annealing are tabulated in Table 1.

Table 1. Resistivity of In_2O_3 thin film at 300K.

Sample	ρ (Ω.cm) × 10^{-3}
As-Oxidized	0.2
450 ^{o}C/30 min	0.14
450 ^{o}C/45 min	0.1

The decrease of the resistivity was observed after annealing due to the decrease the density of defects which in turns increases the carrier mobility of the film [17,18], these values are lower than that obtained by other methods [19-22]. Fig. 3 depicts the thermoelectric voltage data for films, all films have negative Seebeck coefficient and therefore are n-type. Dark I-V characteristics of isotype In_2O_3/Si heterojunctions are presented in Fig. 4, good rectification characteristics was observed after annealing. The ideality factor deduced from I-V plot was decreased after annealing and found to be around 2 at V_f < 1.5 V. This high value of ideality factor suggests the domination of recombination process in these devices which occurs in the junction region and /or at the junction [23]. Fig. 5 presents $1/C^2$ versus reverse bias, a

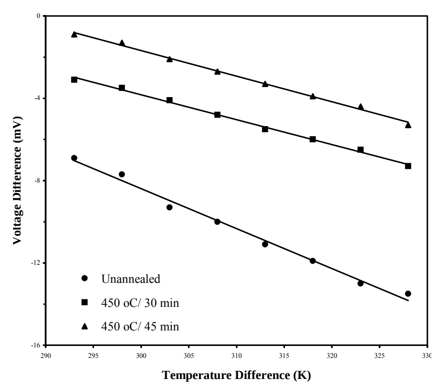

Fig. 3. Thermoelectric characteristics of films.

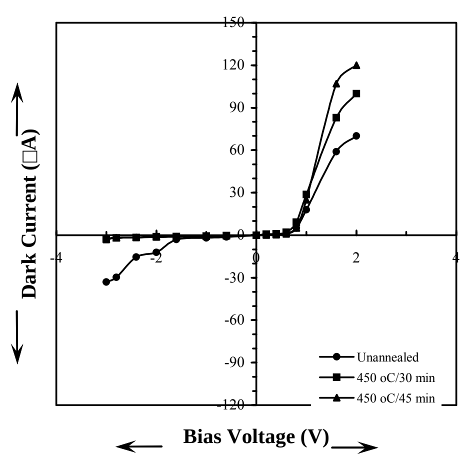

Fig. 4. Dark I-V characteristics of cells.

voltage interface plot of In_2O_3/Si cells. This linear relationship suggests the junctions are abrupt type, and the interception of $1/C^2$ curve with voltage axis gives the diffusion potential V_{bi}. The diffusion potential increased significantly after post-deposition heat treatment and found to be 0.82 V which is in good agreement with the published results [24]. This improvement can be attributed to the reduction in surface states and film resistivity. The main parameters of heterojunctions extracted from I-V and C-V characteristics are listed in Table 2.

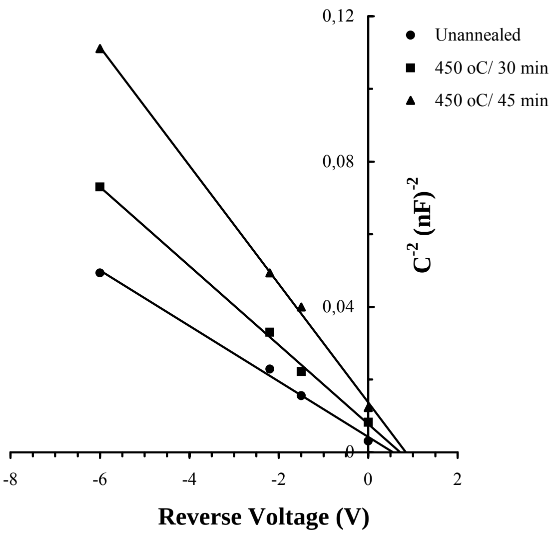

Fig. 5. Dependence of $1/C^2$ on reverse bias.

Table 2. Main parameters of heterojunctions.

Heterodiode	Rectification Factor at 1 Volt	I_S (μA)	V_{bi} (eV) from CV
As-oxidized	10	0.2	0.52
450 ºC/30 min	48	0.12	0.72
450 ºC/45 min	35	0.07	0.82

Fig. 6 shows I-V characteristics under AM1 white light illumination condition of cells before and after annealing. The open-circuit voltage V_{oc} was 463 mV before annealing and increases to 488 mV after annealing, and the short-cicuit current density J_{sc} has been found strongly depended on annealing condition. Superior value of J_{sc} (57.1 mA/cm^2) was obtained after annealing at 450 ºC for 45 min.

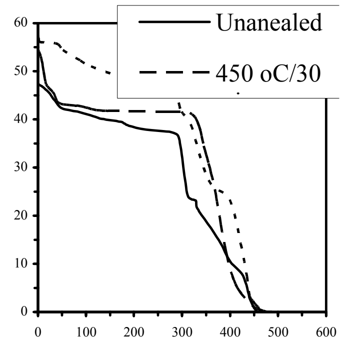

Fig. 6. Typical I-V characteristics curve under sunlight of air mass1,93mW/cm^2.

This enhancement is due to decreasing the sheet resistance of In_2O_3 after annealing [13,17]. The filling factor of the cells are comparable to that for others In_2O_3/Si cells prepared by other methods [25]. Table 3 gives the main characteristics of cells before and after annealing. The conversion efficiency of 14.2% was obtained for annealed cells at 450 ºC/45 min, This value is higher than that for other cells prepared by other methods [26-28]. Fig. 7 shows the spectral responsivity of cells, it is obvious that all the cells have peak response at 900 nm and no shifting in peak response have been noticed after annealing. The responsivity at peak response was increased significantly after annealing and found to be 0.7 A/W which represent the highest value for heterojunctions solar cells so far.

Table 3. Solar cells parameters.

The Cell	J_{SC} (mA/cm^2)	V_{OC} (mV)	J_m (mA/cm^2)	V_m (mV)	FF	η %
As-oxidized	47.4	463	36.1	294	0.48	11.5
450 ºC/30 min	54.4	488	41.3	316	0.49	14.1
450 ºC/45 min	57.1	488	46.4	283	0.47	14.2

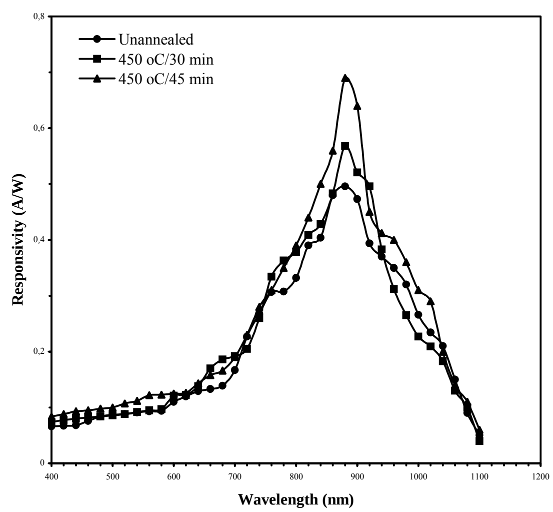

Fig. 7. Spectral responsivity curve.

The determination of cell parameters was repeated after three hours of illumination at 93 mW/cm^2 and after storage in air for six months. No serious degradation has been noticed in these parameters.

4. Conclusion

The optical and electrical properties of highly oriented In_2O_3 thin films before and after heat treatment prepared by simple rapid thermal oxidation and their application to In_2O_3/c-Si solar cells were studied. Conversion efficiency as high as 14% at AM1 condition was obtained for post-deposition heat-treated In_2O_3/Si cells without using SiO_2 layer. No degradation in efficiency has been noticed after three hours of illumination and/or after storage in air for six months. These results reflect the high quality of undoped In_2O_3 film grown by novel RTO technique. These results confirm that the In_2O_3 film prepared by this method is very a promising material for crystalline silicon solar cells applications.

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