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INVESTIGATIONS ON THE PHOTOVOLTAIC PROPERTIES OF INDIUM TIN OXIDE (ITO)/n-GaAs HETEROJUNCTIONS

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Summary

This paper deals with the photovoltaic behaviour of indium tin oxide (ITO)/n-GaAs heterojunctions. Earlier studies on these junctions have shown that they are either non-rectifying or exhibit very low values of open-circuit voltage and short-circuit current. However, here an efficiency of 6.8% (under ELH simulation) has been reported. The junctions are prepared by depositing ITO on n-GaAs by a simple reactive thermal evaporation of In–Sn alloy. The substrate temperature has been found to play an important role on the device performance. The *I–V* characteristics and the spectral response in conjunction with previous knowledge of these junctions suggest that the possible formation of an interfacial layer of $In_xGa_{1-x}As$ could affect the device performance considerably, particularly at higher fabrication temperatures.

1. Introduction

Solar cells based on thin films of transparent and conducting indium tin oxide (ITO) deposited onto absorber semiconductor substrates have drawn much interest among various research groups. Considerable photoconversion efficiencies have been exhibited by ITO/n-Si [1], ITO/p-Si [2] and ITO/p-InP [3]; however, conspicuously, the system ITO/GaAs has not been observed to show much promise. The highest efficiency of only 7% has been achieved in ITO/p-GaAs solar cells in which case ITO was deposited by r.f. sputtering [4] and the ITO/n-GaAs junctions have been reported to exhibit non-rectifying characteristics [3]. Junctions prepared by chemical vapour deposition of indium oxide (IO) on n-GaAs at 450 °C have yielded observable photovoltage and current [5] but the values are very low. Hence the question: is the poor performance of ITO/GaAs an inherent property of the interface or is it induced during fabrication?

It is a known fact that one of the major uncertainties encountered in heterojunction devices is the chemical interactions at the interface which can either be beneficial or detrimental, depending upon the applications and

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materials involved. Such interactions are expected to depend upon the methods and conditions of preparation. Therefore, a study of the properties of the junctions prepared at different conditions may yield constructive information about the interface.

This paper reports the photovoltaic properties of ITO/n-GaAs heterojunctions: an efficiency of 6.8% (as determined by ELH simulation as described later) has been achieved for the first time. The method of ITO deposition is a simple reactive thermal evaporation of In–Sn alloy. The effect of substrate temperature on the behaviour of the junctions has been studied with the help of their I–V characteristics and spectral response.

2. Junction preparation

The GaAs wafers (single side polished, n-type, (100)) used in this work were supplied by M/s Wacker. The doping concentration was 4×10^{15} cm^{-3} (confirmed by Hall measurements). The wafers were chemically cleaned following standard procedures which include etching with H_2SO_4–H_2O_2–H_2O (5:1:1 by volume) solution and with boiling HCl, and rinsing in methanol. The wafers were dried in nitrogen before being loaded in a vacuum chamber for back ohmic contact metal deposition. Indium (purity, 99.999%) was the metal used and was evaporated at a chamber pressure of 3–5×10^{-6} Torr. The contacts were annealed in an argon atmosphere at 300 °C for 4 min. Before ITO deposition on the polished front side, the wafers were once again chemically cleaned following the same procedures as described earlier. During this cleaning step, the back contact was protected with a layer of apiezon wax which was later removed by a brief dip in trichloroethylene. After a final rinse in methanol, the wafers were dried in nitrogen and loaded in the deposition chamber. The ITO was deposited by evaporating an In–Sn (90:10) alloy in a controlled atmosphere of oxygen using a procedure optimized to produce high quality ITO films [6]. A metal shadow mask was used during deposition to form ITO dots of diameter 4 mm. The substrate temperature was controlled to an accuracy of ±2 °C. ITO films deposited at room temperature were given post-annealing treatment in an argon atmosphere at 150 °C for 2 min to make them transparent. Front contacts to the cells were made with silver paste (air dry quality) in the form of a dot of diameter 1 mm on ITO films. The active area of the cells was about 0.12 cm^2. Clean glass substrates were also kept along with GaAs wafers to confirm the quality of ITO films. The thickness of the films was about 90 nm (measured by multiple beam interferometry). The properties of these ITO films are presented in Table 1.

3. I–V characteristics

The light I–V characteristics of the junctions were studied under GE-ELH simulation. The input intensity was 100 mW cm^{-2} as measured

TABLE 1

Properties of ITO films and ITO/n-GaAs junctions prepared at different temperatures

	Sample				
	I	*II*	*III*	*IV*	*V*
Substrate temperature (°C)	30[a]	170	200	250	300
ITO Sheet resistance (ohms/□)	500	135	90	45	35
Transmittance of ITO films at 500 nm	0.82	0.85	0.90	0.91	0.91
Open-circuit voltage (V)	0.570	0.575	0.430	0.255	0.135
Short-circuit current density (mA cm^{-2})	7.25	24.75	23.04	22.53	5.81
Fill factor	0.32	0.48	0.55	0.47	0.32
Efficiency (%)	1.32	6.83	5.45	2.70	0.25
Diode ideality factor, n	1.68	1.51	1.16	1.05	—[b]
Reverse saturation current density, J_0 (μ A cm^{-2})	0.0163	0.0084	0.013	1.67	—[b]
Series resistance (ohms)	288.8	45.5	18.1	14.4	—[b]

[a]Deposited at room temperature (30 °C) and post-annealed at 150 °C for 2 min.
[b]Junctions exhibit non-rectifying characteristics.

using a silicon reference cell. The temperature of the samples during measurements was maintained strictly at 25 ± 0.5 °C by keeping them on a water-cooled metal block. The temperature was measured by placing a copper–constantan thermocouple on a dummy GaAs wafer kept very close to the test cell. Figure 1 shows the light I–V characteristics of the test cells. The related cell parameters are listed in Table 1. The series resistance (R_s) of the cells was calculated by noting the value of forward voltage (V') for which the current is same as the short-circuit current (I_{sc}), following the relation [7]

$$R_s = \frac{V' - V_{oc}}{I_{sc}} \qquad (1)$$

To determine the diode ideality factor n and the saturation current density J_0, the variable illumination technique was followed in order to avoid series resistance effects. Figure 2 shows the V_{oc} *vs.* J_{sc} plots whose slope and y intercept correspond to n and J_0 following the equation,

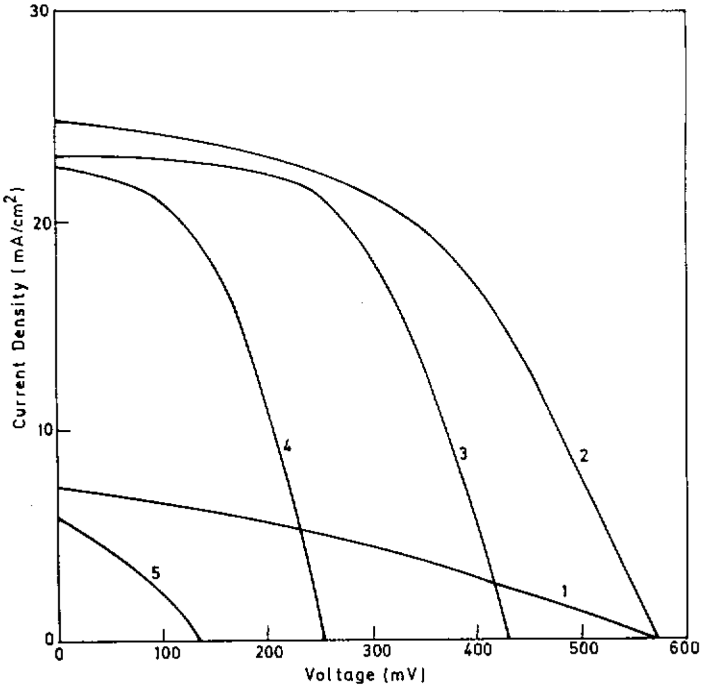

Fig. 1. Illumination I–V characteristics of ITO/n-GaAs junctions prepared at different temperatures: (1) 30 °C (post-annealed); (2) 170 °C; (3) 200 °C; (4) 250 °C; (5) 300 °C.

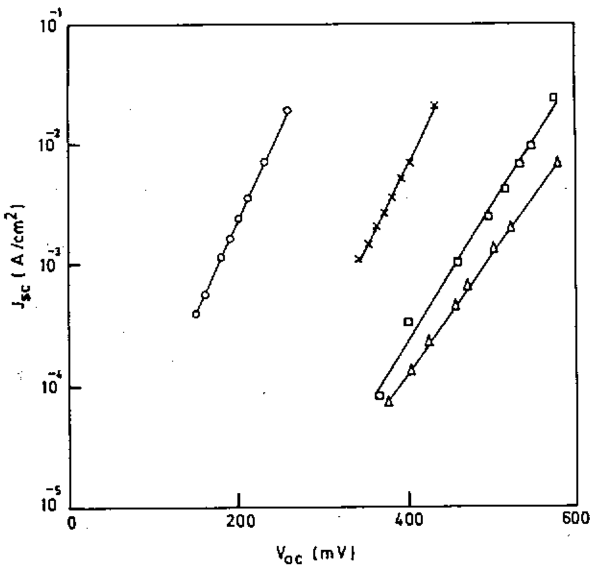

Fig. 2. V_{oc} *vs.* J_{sc} plots for ITO/n-GaAs junctions prepared at different temperatures: (△) 30 °C (post-annealed); (□) 170 °C; (×) 200 °C; (○) 250 °C.

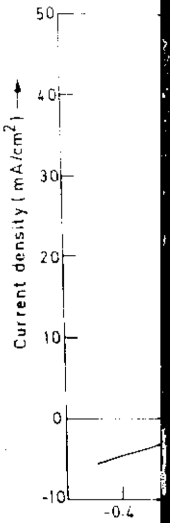

Fig. 3. Dark I-

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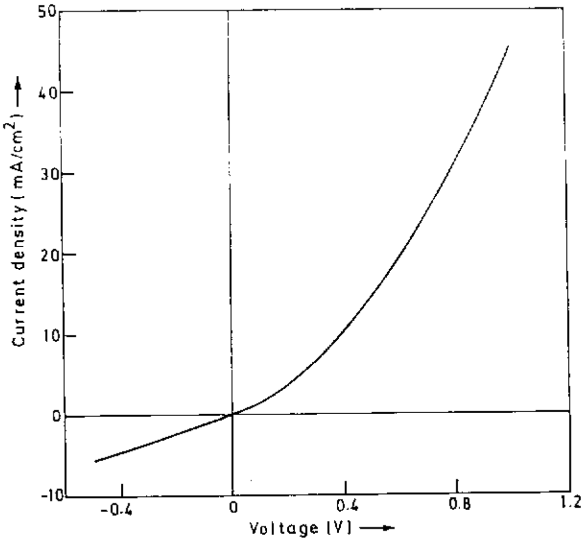

Fig. 3. Dark I–V characteristics of ITO/n-GaAs junctions prepared at 300 °C.

$$V_{oc} = n V_T \ln\left(\frac{J_{sc}}{J_0}\right) \tag{2}$$

where V_T is the thermal voltage.

It may be seen from Table 1 that the properties are sensitive to the ITO deposition temperature. The cell prepared at 170 °C exhibits the maximum efficiency of 6.83%; incidentally, the highest reported for this system (ITO/n-GaAs). It may be noted that though the ITO film quality increases with substrate temperature, the photoconversion efficiency of the junction diminishes. The rectifying characteristics of the junction prepared at 300 °C are poor (Fig. 3). The junction prepared at room temperature and post-annealed has a high series resistance to affect the I_{sc} and fill factor, and this may be attributed to high sheet resistance of ITO films.

The reduction in V_{oc}, and hence in efficiency, with increased ITO deposition temperature is clearly due to the increase in the value of J_0. This is accompanied by a reduction in the value of n which approaches unity. The n values suggest a change in dominant current transport mechanism as the substrate temperature is increased, *i.e.* from a "depletion region recombination process" to an "over the barrier process". The decrease in n in conjunction with an increase in J_0 indicates a reduction in "effective barrier height" before the non-rectifying behaviour takes over.

The transformation from a rectifying barrier to an ohmic contact as the deposition temperature is increased may be explained if one assumes diffusion of indium from the ITO side to the GaAs side forming an interfacial layer of $In_xGa_{1-x}As$ whose bandgap (E_g) depends upon In:Ga ratio ($E_{g(InAs)} < E_{g(InGaAs)} < E_{g(GaAs)}$). It has been shown that the formation of

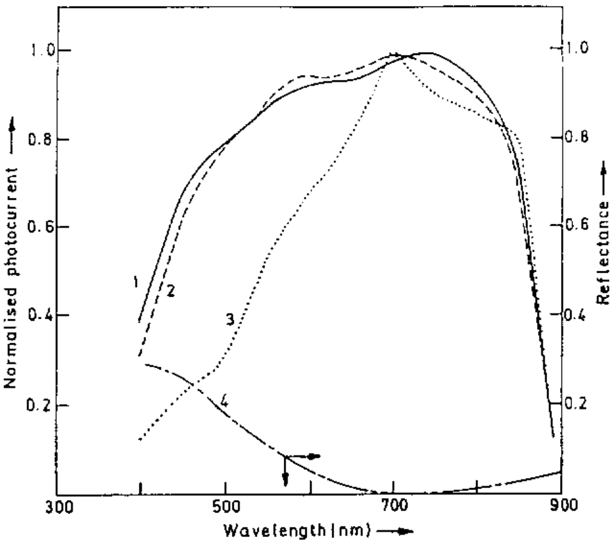

Fig. 4. Spectral response of ITO/n-GaAs junctions prepared at different temperatures: (1) 170 °C; (2) 250 °C; (3) 300 °C: curve (4) represents the reflectance of ITO film of thickness 90 nm on GaAs substrate.

this layer can lower the Schottky barrier height [8]. The exact nature of the interfacial layer in the present case is not clear, but the diffusion of indium is a likely process as it has been observed in ITO/GaAs junctions prepared by sputtering of ITO on GaAs even at room temperature [3]. However, a detailed understanding of the ITO/n-GaAs interface prepared under different conditions, may be had from the depth profiling studies with X-ray photoelectron spectroscopy or UPS.

4. Spectral response

The spectral response of the cells was measured in the wavelength range 400 - 900 nm using narrow bandwidth interference filters (Ealing), the transmittance of which are nearly equal. Since the photon flux obtained from the lamp is not the same for all the wavelengths, a correction factor was found for each of the wavelengths using a standard silicon photodiode detector. This correction factor was incorporated in the measured spectral response illustrated in Fig. 4 for three of the cells. The photocurrent for each of the wavelengths was normalized to the maximum value of the individual cells. The cut-off at the higher wavelength side corresponds to the bandgap of GaAs. The calculated reflectance of the ITO film of thickness 90 nm on GaAs is also shown in Fig. 4. The reflectance was calculated using Fresnel coefficients by considering the effects of air/ITO and ITO/GaAs interfaces [9]: the refractive index of ITO was taken as 2 in this case [6] and the optical constants of GaAs were obtained from ref. 10. The cells show a peak response around 700 nm, where the reflectance is minimum.

The degradation in the short wavelength response for the cells prepared at higher temperatures indicates an increase in the junction depth with substrate temperature: this suggests the formation of an interfacial layer (possibly $In_xGa_{1-x}As$) which does not contribute to I_{sc}.

5. Conclusions

ITO/n-GaAs heterojunction solar cells have been prepared for the first time using a simple reactive thermal evaporation method. The estimated active area efficiency measured using a non-standard source (GE-ELH) and a reference silicon cell was 6.8%. It has been observed that the maximum efficiency is obtained by depositing ITO on GaAs kept at 170 °C. Higher deposition temperatures yield better ITO films but poorer rectifying junctions marked by higher values of J_0. Junctions prepared at 300 °C show non-rectifying characteristics. Analysis of the I–V characteristics and spectral response suggest that the possible formation of an interfacial layer of $In_xGa_{1-x}As$ could be responsible for the decrease in rectifying behaviour and the degradation of the short wavelength response.

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