STUDY OF SPUTTER DEPOSITION OF ITO FILMS FOR A-SI:H N-I-P SOLAR CELLS

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ABSTRACT: We studied rf sputter deposition of indium tin oxide (ITO) films for use as the top electrodes and antireflective coatings in substrate-type a-Si based solar cells. ITO films were deposited on glass substrates for the evaluation of sheet resistance and transmission and on n-i-p solar cells for the evaluation of the photovoltaic properties. The results suggest that good quality ITO films, with a sheet resistance less than 50 Ω and an absorption coefficient less than 10^3 cm^{-1}, can be deposited at elevated temperature (225-250 °C) and low pressure (~8 mTorr) with an RF power of 30-50 W for a 2" target. ITO targets with different In_2O_3 and SnO_2 compositions were studied. Higher quality ITO coatings were produced using a target with 90% In_2O_3 and 10% SnO_2 as suggested by our preliminary results. Using such an optimized ITO film as the top electrode, we obtained triple-junction a-Si solar cells with an initial efficiency of 8.8%.

Keywords: ITO - 1: a-Si - 2: sputtering - 3

1. INTRODUCTION

A stable 13% record efficiency has been recently achieved by United Solar for amorphous silicon (a-Si) based solar cells [1]. These high efficiency solar cells have a stainless steel substrate-type, triple-junction structure with a thin indium-tin-oxide film as the top electrode as well as an antireflective coating. The ITO layer in substrate-type a-Si based solar cells is conventionally deposited using a reactive evaporation process from a molten source of indium and tin mixture in an oxygen ambient. However, such an evaporation process suffers some difficulties in its reproducibility and consistency, particularly among different labs. One difficulty arises from the different vapor phase pressures of In and Sn at different temperatures, which consequently result in different evaporation rates of In and Sn from the source and a depletion of indium in the mixture after some evaporation runs.

The difficulty in the ITO film reproducibility and consistency could be avoided by depositing ITO films using a sputtering process. Sputter deposition of ITO films have been studied extensively for other types of solar cells, such as ITO/InP solar cells [2]. However, the requirement for the ITO deposition and performance are different for different types of solar cells or different device structures. For a-Si substrate-type solar cells, the device performance depends sensitively on the interface between the ITO film and the μc-Si window p-layer as well as the ITO film properties.

Recently, Hegedus *et al* studied the sputter deposition of ITO for n-i-p substrate-type solar cells [3]. They investigated various deposition conditions of ITO sputtering on top of n-i-p solar cells deposited at Energy Conversion Devices, Inc. (ECD) [4]. However, the performance of a-Si n-i-p/ITO solar cells was not encouragingly high, most likely due to the fact that the ITO sputter deposition in this work was carried out at room temperature, while higher quality ITO films are usually grown at elevated temperatures. To the best of our knowledge, no systematic study has been reported for ITO films sputter-deposited at elevated temperatures for a-Si solar cells. The objective of this study is to gain a deep understanding of the ITO sputter deposition and the interface between the ITO and μc-Si p-layer for a-Si based n-i-p solar cells. In this paper, we report our preliminary results for this study.

2. EXPERIMENTAL

We have studied ITO sputter deposition for use in a-Si n-i-p solar cells. The ITO films were deposited using RF sputtering from a 2" sputter gun in a vacuum chamber backed by a turbo molecular pump. The sputter sources used in this study were In_2O_3/SnO_2 targets having a In_2O_3 content of 95, 90 and 85%, respectively. In searching for the optimal ITO film properties, we have investigated a broad deposition parameter space including RF sputtering power, substrate temperature, and Ar pressure. The ITO films were deposited either on glass substrates for resistivity and transmission measurements, or on a-Si n-i-p solar cells for I-V and quantum efficiency measurements.

Single- and triple-junction a-Si based solar cells, used in this ITO study as substrates, were deposited in our laboratory using a plasma enhanced CVD process in a multi-chamber, ultra high vacuum deposition system made previously by GSI. The structure of the triple-junction solar cells is: SS/Ag/ZnO/a-Si-n^+/a-SiGe-i_1/μc-Si-p^+/a-Si-n^+/a-SiGe-i_2/μc-Si-p^+/a-Si-n^+/a-Si-i_3/μc-Si-p^+. The ITO layer is deposited on the μc-Si-p^+-layer, which is then followed by an evaporation of aluminum grids to complete the solar cell fabrication.

3. RESULTS

We have deposited a variety of ITO films on glass substrates to measure the sheet resistance and absorption loss of the ITO films. Table 1 lists the various sputter deposition conditions for a series of ITO films deposited in

Table I: Deposition conditions and quality for ITO films deposited under various sputtering conditions.

Sample No.	RF (W)	Temp (C)	P (mT)	d (nm)	Rsh (Ohm)	T (%)	R* (Ohm)	A* (%)
ITO-37	30	225	8	454	1.5E+01	83.3	1.1E+02	0.47
ITO-25	40	225	8	620	5.9E+00	80.2	5.7E+01	0.75
ITO-34	50	225	8	779	5.0E+00	80.2	5.9E+01	0.60
ITO-50	10	150	6	171	1.9E+02	80.0	5.1E+02	2.77
ITO-49	20	150	6	327	4.2E+01	81.9	2.1E+02	1.00
ITO-47	30	150	6	449	2.4E+01	81.0	1.7E+02	0.89
ITO-48	40	150	6	601	1.5E+01	79.6	1.4E+02	0.85
ITO-55	50	150	6	771	1.1E+01	79.7	1.3E+02	0.65
ITO-66	60	150	6	916	2.4E+01	79.2	3.4E+02	0.60
ITO-51	10	175	6	176	2.2E+02	80.0	6.1E+02	2.70
ITO-53	30	175	6	460	1.8E+01	80.8	1.2E+02	0.90
ITO-67	50	175	6	785	2.3E+01	76.6	2.8E+02	0.97
ITO-68	30	200	6	452	3.1E+01	79.9	2.2E+02	1.08
ITO-69	40	200	6	589	1.3E+01	81.1	1.2E+02	0.66
ITO-71	50	200	6	761	1.1E+01	80.1	1.3E+02	0.62
ITO-72	30	225	6	459	1.8E+01	81.0	1.3E+02	0.87
ITO-73	40	225	6	547	8.8E+00	80.5	7.4E+01	0.80
ITO-65	20	250	6	288	2.1E+01	80.8	9.5E+01	1.44
ITO-75	30	250	6	378	8.7E+00	82.8	5.1E+01	0.67
ITO-78	40	250	6	586	1.1E+01	80.2	9.8E+01	0.79
ITO-79	50	250	6	760	9.6E+00	79.4	1.1E+02	0.70
ITO-16	30	200	18	387	1.4E+03	84.0	8.1E+03	0.41
ITO-20	20	225	18	266	1.4E+04	83.9	5.7E+04	0.63
ITO-24	30	225	18	386	7.0E+03	85.1	4.1E+04	0.19
ITO-19	40	225	18	606	1.3E+02	83.8	1.2E+03	0.29
ITO-23	50	225	18	741	1.0E+02	82.8	1.2E+03	0.34
ITO-14	30	250	18	940	8.9E+02	85.0	1.3E+04	0.09
ITO-15	30	250	18	320	1.5E+03	85.0	1.1E+04	0.26

30 min. In this table, the film thickness, d, was calculated from the interference fringes in the optical transmission. R_{sh} is the sheet resistance of the film, measured using a four point probe. T is the transmission around 550 nm, calculated using $T=(T_{max} \bullet T_{min})^{1/2}$, where T_{max} and T_{min} are the transmission maximum and minimum in the UV/Visible transmission spectroscopy. Since the desirable ITO thickness in an a-Si solar cell is around 65 nm to achieve antireflection, we calculated an *effective* sheet resistance (R*) for a film which would have been 65 nm thick using

$$R^* = R_{sh} \cdot \frac{d}{65nm} \qquad (1)$$

In addition, we calculate the absorption coefficient, α, of ITO films using

$$T = \frac{(1-R_1)(1-R_2)\exp(-\alpha \cdot d)}{1-R_1 R_2 \exp(-2\alpha \cdot d)} \qquad (2)$$

where R_1 and R_2 are the reflectances at the interfaces with air and glass substrates with $R=\{(n_1-n_2)/(n_1+n_2)\}^2$.

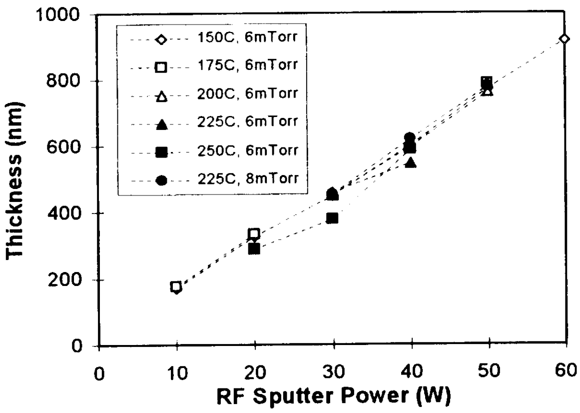

Figure 1: ITO thickness as a function of RF power for 30 min deposition under various temperatures and pressures.

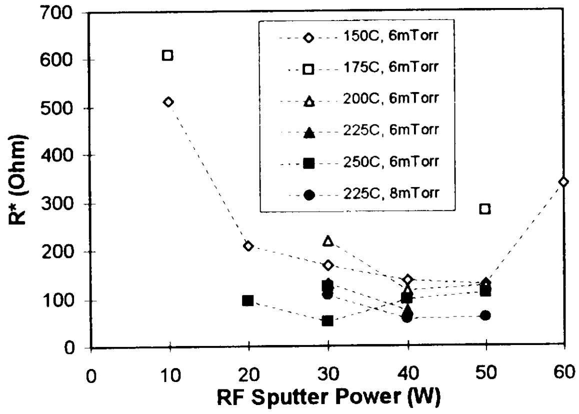

Figure 2: Effective sheet resistance of a 65 nm thick ITO film as a function of RF power.

Refractive indexes of 1 and 1.5 are used for air and the glass substrates. Since the refractive index for ITO varies with wavelength near 550 nm, we used 2.1 as the ITO refractive index in our calculation of R_1 and R_2. From Eq.2, we obtained the absorption coefficient and then used it to calculate an *effective* absorption loss (A*) for an ITO film that would have been 65 nm thick using

$$A^* = 1 - \exp(-\alpha \cdot 65nm) \qquad (3)$$

The values of R* and A* therefore reflect the film performance of the ITO layers.

Figure 1 shows the dependence of the film thickness on RF power. The film thickness increases linearly with the increased RF power, independent of temperature and pressure within the selected ranges. Figure 2 shows R* as a function of RF power at various temperatures and chamber pressures. To maintain the ITO electrical loss to be less than 1% at the maximum power point of a triple-junction a-Si solar cell, we need to have an ITO sheet resistance to be less than ~80 Ω/□, or the resistivity (ρ) to be lower than ~5×10^{-4} Ω•cm for a 65 nm thick ITO film.

From Figure 2, we observe that only those ITO films deposited at or above 225 °C and with RF power around 30-50 W could meet $\rho \leq 5\times10^{-4}$ Ω•cm requirements. At temperatures lower than 200 °C, the resistivity is higher.

Figure 3 shows the effective absorption A* for different RF power under various temperatures and pressure conditions. Again, to have the absorption loss lower than 1%, we will need to have a minimum sputtering power of around 30 W.

Among all the deposited ITO films, those made under conditions of RF power within 30-50W, temperature within 225-250 °C and pressure around 6-8 mTorr demonstrate the optimal film properties: R*=50 Ω and A*<1%. This range of conditions was then used as a starting point for the study of ITO films on substrate-type a-Si solar cells in which an ITO film intimately contacts a µc-Si p-layer.

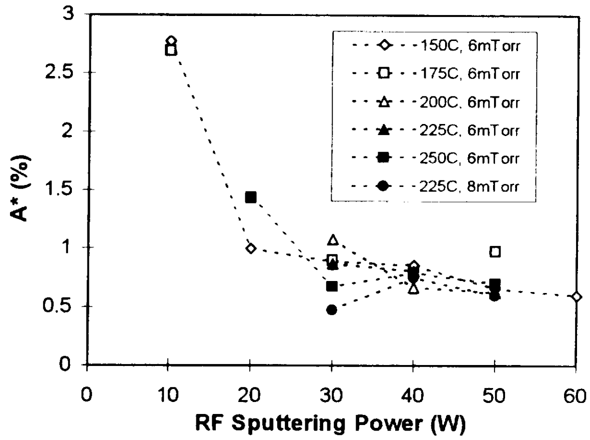

Figure 3: Effective absorption loss of a 65 nm thick ITO film as a function of RF power.

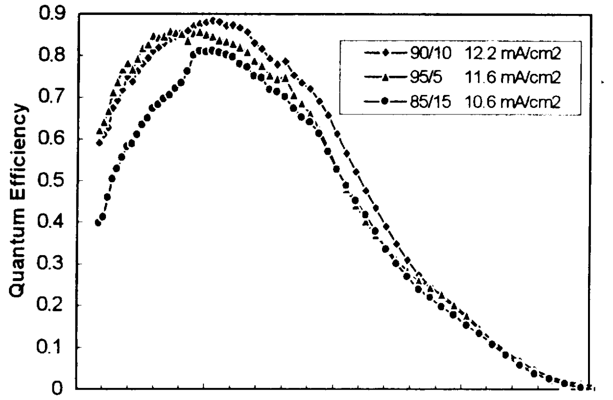

Figure 4: Quantum efficiency curves of a-SiGe solar cells with ITO layers deposited using In_2O_3/SnO_2 targets having different compositions.

We deposited approximately 65-75 nm thick ITO films on a-SiGe solar cells prepared on bare stainless steel without the use of a back-reflector. Three different sputtering targets having different In_2O_3 and SnO_2 concentrations were used. Figure 4 shows the quantum efficiency curves for a-SiGe solar cells having ITO layers sputter deposited using different targets. The numbers in the legend are the target compositions and the integrated short circuit current J_{ph} calculated using quantum efficiency curves. From Figure 4 we find that the target with 90% In_2O_3 and 10% SnO_2 (90/10) provides the highest current among the three due to a lower absorption loss.

In Table II, we list the device data for three a-SiGe solar cells with their ITO layers deposited using different targets. Again, the 90/10 target provides the highest FF and J_{sc} among the three samples, suggesting that the 90%/10% In_2O_3/SnO_2 target might be more desirable for use in a-Si based substrate-type solar cells. We would like to point out that these preliminary results were obtained from limited samples. Further study is needed to draw a general conclusion.

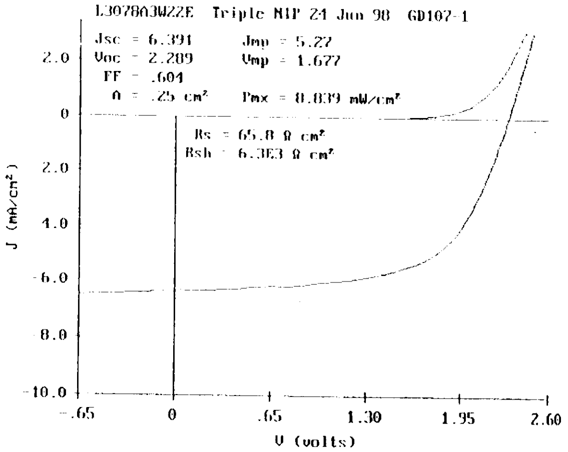

Figure 5: I-V curve of a triple-junction a-Si/a-SiGe/a-SiGe nip/nip/nip solar cell with sputter-deposited ITO film as the top electrode and antireflective coating.

We used 90/10 ITO target and deposited ITO layers on top of triple-junction a-Si/a-SiGe/a-SiGe solar cells prepared in our laboratory. Figure 5 is an I-V curve of such a triple cell, showing an 8.8% initial efficiency.

4. SUMMARY

Good quality ITO films were sputter-deposited for use as the top electrodes of substrate-type a-Si based solar cells. The ITO films, deposited at elevated temperature (225-250 °C) and low pressure (~8 mTorr) with an RF power of 30-50 W in a 2" sputter gun, exhibit an effective sheet resistivity of approximately 50 Ω and absorption loss of less than 1%. In our preliminary study, ITO films deposited using 90%/10% In_2O_3/SnO_2 target show higher performance than 95/5 and 85/15 ITO targets when being used in a-Si alloy solar cells. Triple junction solar cells, with an initial efficiency of 8.8%, were obtained using such a sputter-deposited ITO layer.

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Table II: I-V data of solar cells with ITO deposited from In_2O_3/SnO_2 targets having different compositions.

Sputter Target In_2O_3%/SnO_2%	V_{oc} (V)	J_{sc} (mA/cm^2)	FF	R_s (Ω•cm^2)	P_{max} (mW/cm^2)	J_{ph} from QE (mA/cm^2)
95/5	0.71	11.8	0.46	28	3.9	11.6
90/10	0.69	13.5	0.55	22	4.3	12.2
85/15	0.65	10.5	0.41	35	2.8	10.6