TCO and Front Stack Optimization for CdTe solar cell improvements

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I. INTRODUCTION

In thin film CdTe solar cells, the electrical and optical properties of the transparent conducting oxide (TCO) and front stack layers have been widely investigated, to obtain an optimal front stack structure with a dedicated choice of material composition and thickness. It is well known that a high efficiency CdTe solar cell should have a high mobility, low absorption TCO and a wide gap buffer front stack layer offering minimal blue loss [1,2]. Therefore, proper engineering of the TCO and front stack is necessary in order to improve the Jsc, Voc, FF and efficiency.

In this report, we investigated the TCO and front stack layers in CdTe solar cells. To optimize the front stack and obtain better device performance, we presented various front stack combinations, including replacing the HRT layer with a wider bandgap MgZnO (ZMO) and Al doped ZMO; replacing SnO2 with a higher conductive Cadmium Stannate (CTO); and UV-ozone treatment on TCO surface.

II. NOVEL MATERIALS AND EXPERIMENTALS

We fabricated our CdTe solar cells based on the typical configuration of glass/TCO/HRT/CdTe. The TCO layer consisting of 350 nm of SnO_2:F was deposited on pre-cleaned and UV-Ozone treated glass first, followed by 40-100 nm of HRT layer, using Hollow Cathode sputtering and ZM targets. The CdTe layer of 4–5 micron was then grown by close-spaced sublimation (CSS) method, in an O_2-containing ambient. A 10-min vapor $CdCl_2$ treatment was performed at 400 ^oC in a separate CSS system. The back contact was thermally evaporated consisting of 3 nm of Cu followed by 300 nm of Au. The full-device stack was annealed in a furnace at 230 ^oC for 30 min with a He gas flow, in order to allow Cu diffusion. In our experiments, we employed ZMO and Al doped ZMO as HRT, and replaced the TCO with CTO. Therefore, the final device structure is
Glass/TCO(SnO_2:F or CTO) /HRT(ZMO or Al doped ZMO)/CdTe/Cu/Metal.

The J-V measurement was carried out under 1-sun illumination. Film thicknesses were determined using a Dektak IIA stylus profilometer. Optical properties were measured using a Filmetrics FI0-RT-UVX system. Resistivity and mobility were determined using an Ecopia 21 HMS-3000 Hall system in a square van der Pauw configuration formed by etching. The magnetic field (0.57 T) was measured using an Alpha Lab Hall magnetometer.

III. RESLUTS AND DISCUSSION

$Mg_xZn_{1-x}O$ (ZMO) was proved to reduce the electron affinity of HRT layers. For the TCO/ZMO/CdTe configuration, controlling electron affinity to optimize front contact band

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alignment is an important consideration. By increasing the Mg content, MgxZn1-xO has a higher band gap and lower electron affinity. However, the ZMO layers with even higher Mg exhibit a strong secondary barrier, and the "kink" of J-V curves also has been observed in the J-V curve with 100 nm or greater thickness [3,4]. So, finding a clear interaction between thickness and composition in determining Voc and barrier behavior is the very practical work that can be used to reach an optimum [5,6]. We deposited the ZMO layer of 50 to 350 nm, and found the charge carrier density falls into the range of 10^{18} cm^{-3} and resistivity varies from 10^4 to 10^{-1} Ω cm. The best performance was found as shown in Fig 1, where J_{sc} reaches $28.1 mA/cm^2$ based on TCO/ZMO/CdTe structure. This cell had a 60 nm ZMO layer which we believe allowed the higher V_{oc} (782 mV). Consistent with the higher V_{oc}, the dark J-V curve is pushed to higher voltages and the dark/light age, indicative of V_{bi}, is also higher.

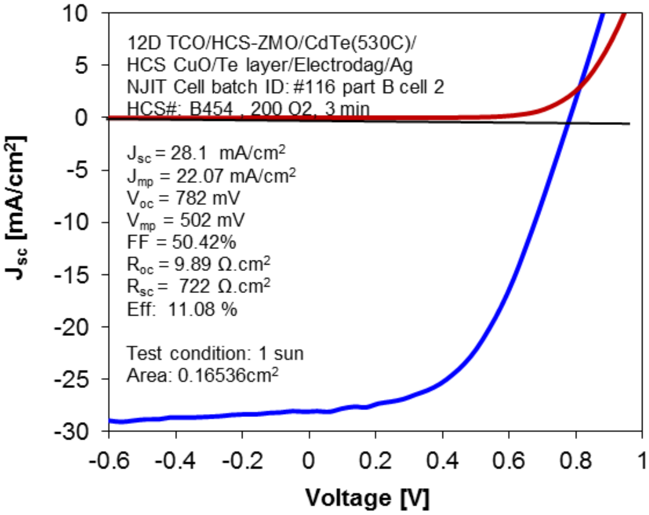


Fig 1. J-V curve for 11.1% efficiency ZMO/CdTe cell with 60nm ZMO

Table 1. Hall Measurements on thin Al-doped ZMO films

Run #	Al wire power W	Thickness (nm)	ne (cm^{-3})	μH (cm^2/Vs)	ρ (Ω cm)
B382	10	367	1.36E+20	33.04	1.39E-03
B477	10	112	2.21E+20	11.02	2.57E-03
B478	10	60	1.97E+20	7.94	4.00E-03
B479	10	54	1.15E+20	5.93	9.13E-03

It is also found that the extrinsic doping of ZMO using specific doping elements can improve the charge carrier concentration and conductivity. We summarized our work on Al-doped ZMO as shown in **Table 1**. The Al doped-ZMO experiments were conducted using Zn-Mg targets having 12 at.%Mg. For these Al-doped films the carrier concentration was in the range of 10^{20} cm^{-3} for all thicknesses, even the thinnest at 54 nm. These results suggest that extrinsic doping could be used, if necessary, to maintain adequate n_e in ZMO for solar cell applications. It also shows that the resistivity of Al-doped ZMO is largely reduced compared with undoped, which may be employed for future CdTe devices (Fig 2.).

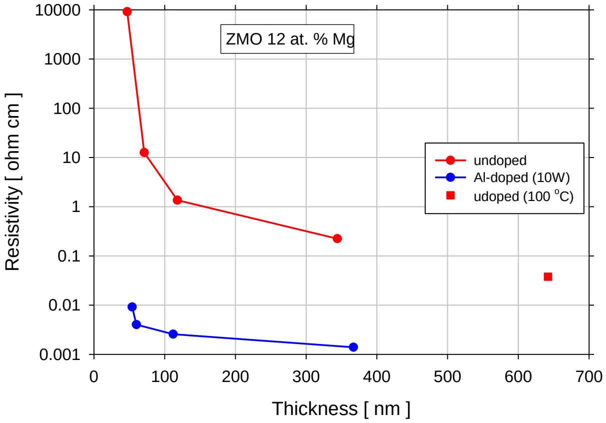


Fig. 2 Dependence of ZMO film resistivity on film thickness for doped and undoped ZMO films

The second alternative for front stack is replacing SnO_2 with CTO, due to its 6 times lower resistivity and better optical properties than that of SnO2 films [7,8]. Fig. 3 shows the transmittance and absorbance of the Cd_2SnO_4 and SnO_2 films with similar sheet resistivities (~10 Ω/sq). It is observed that the CTO film has higher transmittance and lower absorbance than the SnO2 film [9], indicating a less optical loss in the front structure. It is worth noting that this feature can be maintained in the longer-wavelength region, showing the potential for applications in polycrystalline thin film multi junction devices. [10]

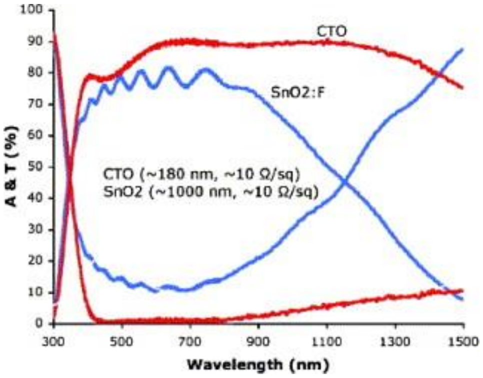
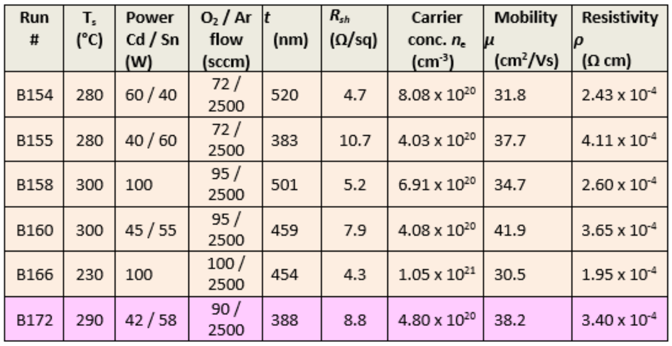


Fig. 3. Transmittance and absorbance of CTO and SnO_2:F films with similar sheet resistivity of ~10 Ω/sq.

As shown in Table 2, we included the experimental deposition parameters and resulting electrical properties of prepared CTO films. The R_{sh} of CTO films made averaged about 7 Ω/sq. Film B160 of 459nm in thickness, with resistivity $\rho=3.65 \times 10^{-4} \Omega$ cm, had an excellent mobility $\mu=41.9$ cm^2/Vs, and a sheet resistance of 7.9 Ω/sq. We note that film with high carrier concentrations (e.g. B166, with n_e=1.05×10^{21}cm^{-3}) tend to have lower mobility which can be explained increased ionized impurity scattering [11].

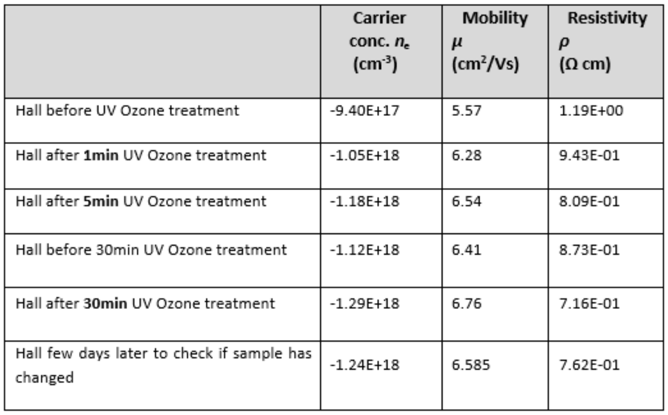
Table 2 Deposition parameters and electrical properties of CTO films



Run #	T_s (°C)	Power Cd / Sn (W)	O_2 / Ar flow (sccm)	*t* (nm)	R_{sh} (Ω/sq)	Carrier conc. n_e (cm^{-3})	Mobility *μ* (cm^2/Vs)	Resistivity *ρ* (Ω cm)
B154	280	60 / 40	72 / 2500	520	4.7	8.08 x 10^{20}	31.8	2.43 x 10^{-4}
B155	280	40 / 60	72 / 2500	383	10.7	4.03 x 10^{20}	37.7	4.11 x 10^{-4}
B158	300	100	95 / 2500	501	5.2	6.91 x 10^{20}	34.7	2.60 x 10^{-4}
B160	300	45 / 55	95 / 2500	459	7.9	4.08 x 10^{20}	41.9	3.65 x 10^{-4}
B166	230	100	100 / 2500	454	4.3	1.05 x 10^{21}	30.5	1.95 x 10^{-4}
B172	290	42 / 58	90 / 2500	388	8.8	4.80 x 10^{20}	38.2	3.40 x 10^{-4}

For the improvement of TCO surface, as mentioned earlier in the fabrication part, we employed the UV-Ozone cleaning experiment on 2XFTOs_ TEC15 and TEC15D for 5 min. It is found that white light transmission for TEC 15 is increased by 0.32% while that for TEC15D remains unchanged. Meanwhile, we observed from Hall experiment that the treatment can increase the mobility in ZMO by approximately 12.7%, which can be attributed to the factors: UV-OZone treatment cleans off the excess moisture, oil or any kind of dirt before further processing, as summarized in Table 3.

Table 3 The comparison of Hall measurements to study the effect of UVO treatment on ZMO sample



	Carrier conc. n_e (cm^{-3})	Mobility *μ* (cm^2/Vs)	Resistivity *ρ* (Ω cm)
Hall before UV Ozone treatment	-9.40E+17	5.57	1.19E+00
Hall after **1min** UV Ozone treatment	-1.05E+18	6.28	9.43E-01
Hall after **5min** UV Ozone treatment	-1.18E+18	6.54	8.09E-01
Hall before 30min UV Ozone treatment	-1.12E+18	6.41	8.73E-01
Hall after **30min** UV Ozone treatment	-1.29E+18	6.76	7.16E-01
Hall few days later to check if sample has changed	-1.24E+18	6.585	7.62E-01

IV. CONCLUSION

The work presented in this paper focused on the optimization of TCO and front stack of a CdTe solar cell, which is one of the most controversial (and interesting) areas of research of this technology. We employed various front stack combinations, including replacing the high resistance layer (HRT) with a wider bandgap ZnMgO (ZMO) and Al-doped ZMO; replacing SnO2:F with a higher conductivity Cadmium Stannate (CTO), and UV-ozone treatment on TCO surface. The high quality ZMO, Al doped ZMO, and CTO layers were fabricated by hollow cathode sputtering and were characterized by J-V, optical and Hall effect measurements. CTO layers with electron mobilities up to 41.9 cm2/Vs were demonstrated. Carrier concentrations in Al doped ZMO could be obtained over 10^{20} cm^{-3}. High Jsc up to 28.1 mA/cm^2 demonstrate that ZMO provides a means to obtain competitive CdTe solar cells. Our results suggested that with optimized TCO and front stack layers, the overall performance of thin film CdTe solar cells was improved due to better charge carrier mobility, higher layer transparency and less device optical loss.

V. ACKNOWLEDGMENT

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