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Influence of ITO deposition and post annealing on HIT solar cell structures

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Abstract

Heterojunction silicon with intrinsic thin layer (HIT) solar cells that combine advanced thin-film hydrogenated amorphous silicon (a-Si:H) and crystalline silicon (c-Si) technologies are promising because of the high performance at low cost. Due to the low conductivity of a-Si:H, indium tin oxide (ITO) needs to be used as a front contact layer on top of a-Si:H in order to collect photogenerated currents. The thin a-Si:H layer requires the ITO deposition to be soft so that the passivation is maintained after deposition. Otherwise, the passivation degradation resulting from ITO deposition should be recovered by some post processing. In this contribution, we investigate how the power density and the temperature during ITO deposition as well as post annealing influence the passivation quality of HIT solar cells as characterised by the open-circuit voltage (V_{oc}) and minority carrier lifetime. Firstly, ITO sputtering with lower power density can reduce the degradation of the passivation quality after ITO deposition. Secondly, we have investigated the simultaneous annealing during ITO deposition at elevated temperature. On one hand, simultaneous annealing can recover some of the degradation resulting from sputtering. On the other hand, there is a temperature threshold above which degradation of the passivation is observed, probably by hydrogen effusion. Thirdly, we observe that post annealing can fully recover the degradation resulting from ITO sputtering at room temperature (RT).

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Keywords: Heterojunction silicon solar cell; ITO; annealing.

1. Introduction

Heterojunction with intrinsic thin layer (HIT) solar cells first developed by SANYO Electric have attracted much attention due to the high performance and several industrial benefits resulting from low temperature processing [1, 2, 3]. In 2010, SANYO Electric reported a record efficiency of 23% on an area of 100 cm^2. Excellent passivation by hydrogenated amorphous silicon (a-Si:H) on silicon wafers leads to high V_{oc} (743 mV) in HIT solar cells [4]. Due to the high resistance of the a-Si:H, transparent conductive

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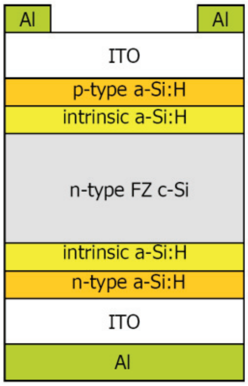
oxide (TCO) has to be used to collect the current. A fill factor (*FF)* as high as 80% can be achieved by reducing a-Si:H thickness and increasing the conductivity of TCO and doped a-Si:H. Optimization of optical properties of the HIT solar cell is very important to obtain high short-circuit current density (J_{sc}) (39.5 mA/cm^2) [3], e.g. by light trapping techniques and reduction of TCO and a-Si:H absorption.

In general HIT solar cells employ sputtered indium tin oxide (ITO) as the front contact layer for the current collection. Much research has been carried out to optimize the conductivity and transmittance of ITO and its antireflective property by investigating oxygen content, deposition temperatures, sputtering techniques and layer thicknesses [5, 6, 7, 8], which mainly influences *FF* and J_{sc} of these solar cells. However, it is also very important to investigate how ITO sputtering process itself influences the properties of the thin a-Si:H layer underneath, especially the passivation offered by a-Si:H. This passivation strongly affects V_{oc} of the HIT solar cell. In this contribution, we investigate how the ITO sputtering process parameters influence the passivation quality, in particular the power density and deposition temperature. Additionally, we demonstrate how post-annealing may recover some of the passivation quality.

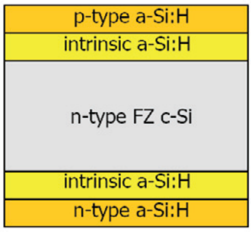
2. Experiments

To make HIT solar cells, flat float zone (FZ) silicon wafers are used. The resistivity of the 300 μm thick n-type wafers is 2~5 Ω·cm. Each wafer is chemically cleaned to remove the contaminants. Afterwards, the wafer is dipped in HF solution to remove the oxide on the wafer and to passivate the surface with hydrogen.

After rinsing and the following drying processes, the wafer is transferred into the deposition chamber for a-Si:H deposition. The wafer is preheated for about 50 minutes at a temperature of 180°C before a-Si:H deposition. Subsequently 7-nm thick intrinsic (*i*) a-Si:H, 9-nm thick n-type (*n*) a-Si:H and 9-nm thick p-type (*p*) a-Si:H are deposited by radio frequency (rf) plasma enhanced chemical vapor deposition (PECVD) in separate chambers, followed by the deposition of 80-nm thick ITO on both sides of the silicon wafer with an rf-sputtering system. Finally, 500-nm thick aluminium contacts are deposited by electron beam evaporation. The resulting solar cell structure is illustrated in FIG. 1a. FIG. 1b indicates the structure before ITO deposition, which is used for the investigation of the influence of ITO deposition temperatures.



(a)



(b)

FIG. 1. Schematic structures of (a) the HIT solar cell and (b) the structure for the investigation of the influence of ITO deposition temperatures.

JV characteristics of the HIT solar cell are measured by using an Oriel Corporation solar simulator. The implied-V_{oc} and minority carrier lifetime for samples without contacts are measured by Sinton photoconductance lifetime tester WCT-120. Suns-V_{oc} and minority carrier lifetime for sample with contacts are measured by Sinton Suns-Voc setups. In our measurements we observe a difference in the V_{oc} measured by the solar simulator and Suns-Voc. We have found that this difference is due to the cell configuration and almost disappears when the solar cell is completely isolated from the rest of the silicon wafer. Annealing at low pressure with Ar is carried out in our ITO deposition setup in order to investigate the exact influence of ITO deposition temperature. The annealing time at each temperature is one hour.

3. Results and discussion

3.1. Influence of ITO sputtering power density on passivation

In the sputtering process, the substrate surface immersing in the plasma can be impinged by various energetic particles such as sputtered ITO species, neutralized ions reflected from the target and positive ions accelerated in the sheath [9]. High-energy particles striking the a-Si:H can affect the properties of the thin a-Si:H layer (16 nm) including both doped and intrinsic a-Si:H and therefore also the passivation quality as characterized by minority carrier lifetime and implied-V_{oc}, although investigation of this effect is barely reported. The energy of particles in the plasma is directly related to the power density. Therefore, in order to reduce the influence from high-energy particles we have decreased the power density. In FIG. 2 the V_{oc} and minority carrier lifetime of the HIT solar cells increase with decreasing power density, which we ascribe to the smaller particle-bombardment energy. However, at a power density of 0.1 W/cm^2 the lifetime drops again. At this power density the plasma is unstable and the deposition rate is reduced dramatically. The low deposition rate also implies that the sample is exposed to the elevated deposition temperature for a long time. The effect of the ITO deposition temperature is further discussed in the following sections.

3.2. Influence of ITO deposition temperatures

Generally ITO is deposited at elevated temperatures in order to achieve good optical and electrical properties [10]. However, using a high temperature during ITO deposition anneals the structure that is displayed in FIG. 1b. In order to investigate how the ITO deposition temperature influences the passivation, we anneal the structure as presented in FIG. 1b in the ITO deposition chamber with an Ar atmosphere at a pressure of 20 μbar. Our results show that minority carrier lifetime as well as implied-V_{oc} start to drop at a temperature of 150 ºC, which is below the deposition temperature for a-Si:H of 180 ºC (FIG. 3). This observation implies that there is a temperature threshold for ITO deposition. We speculate it is due to hydrogen effusion from thin a-Si:H at elevated temperatures, degrading the passivation quality. Passivation degradation caused by hydrogen effusion has been studied by De Wolf and Kondo [11]. They have observed passivation degradation at a temperature of 240 ºC after 30 min annealing. However, in our case, the degradation occurred at a lower temperature than in their experiments. Since the initiation temperature of hydrogen effusion is dependent on several layer properties like e.g. a-Si:H thickness, a-Si:H deposition conditions and Si-H bonding situation (dihydride or monohydride) [12, 13], hydrogen effusion is likely to be triggered at about 150 ºC. This issue needs further investigation. We believe the temperature threshold can decrease at longer annealing time due to kinetics of hydrogen effusion, which can explain the decrease of V_{oc} at 0.1 W/cm^2 in FIG. 2. In contrast, a sample with the same structure annealed in air shows a slightly enhanced passivation quality (FIG. 3). This indicates that this annealing effect is dependent on the environment e.g. pressure and atmospheric gas. Further investigation will be continued in order to confirm which component in air prevents the degradation process.

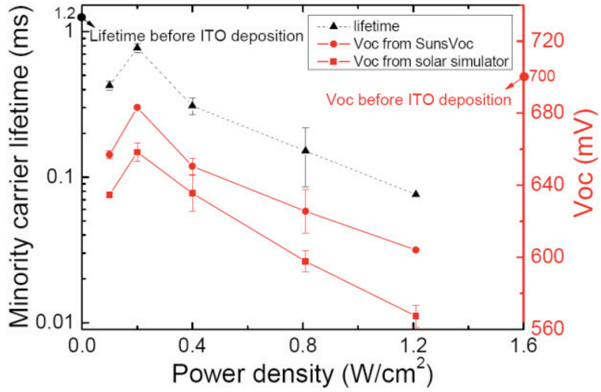


FiG. 2. V_{oc} and minority carrier lifetime at a carrier density of 10^{15} cm^{-3} as a function of power density used in the rf sputtering process. ITO deposition temperature is 110 ºC. The sample structure is illustrated in FIG. 1a.

Before ITO deposition, our a-Si:H passivated wafer has a carrier lifetime of about 1.2 ms as measured by the Sinton photoconductance lifetime tester. In table 1, the external parameters of HIT solar cells as well as the Suns-V_{oc} and minority carrier lifetime are presented for several ITO deposition temperatures. The HIT solar cell with ITO deposited at RT has a very low V_{oc} due to the passivation degradation probably resulting from particle bombardment of ITO sputtering. At higher deposition temperatures the V_{oc} is higher, suggesting recovery due to the simultaneous annealing during ITO deposition. That is, using high temperatures below the threshold temperature during ITO deposition can recover some of the degradation induced by ITO sputtering. The higher ITO deposition temperatures also increase the *FF* and J_{sc} as a result of increased conductivity and transparency of the ITO.

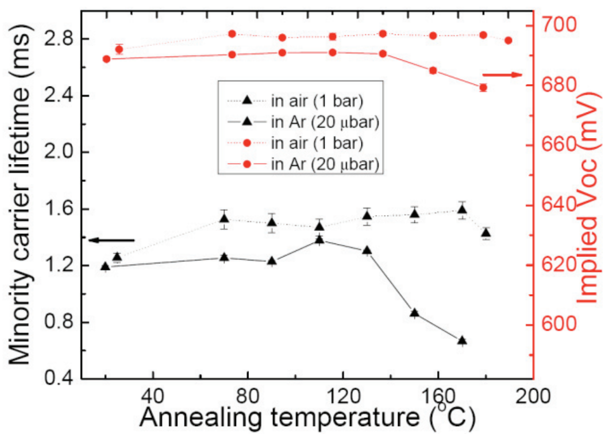


FiG. 3. Minority carrier lifetime at a carrier density of 10^{15} cm^{-3} and implied V_{oc} as a function of annealing temperature. The sample structure is illustrated in FIG. 1b.

Table 1. External parameters of the HIT solar cells as well as Suns-V_{oc} and minority carrier lifetime (τ) for different ITO deposition temperatures. The sample structure is illustrated in FIG. 1a.

ITO deposition temperature	Suns-V_{oc} (mV)	τ (µs)	V_{oc} (mV)	J_{sc} (mA)	FF (%)	η (%)
RT	551	14	525	26.1	62.3	8.7
110 °C	655	350	622	31.8	73.6	14.6
130 °C	670	557	646	32.9	74.3	15.8

3.3. Investigation of post-annealing in air

In the previous sections, the power density and ITO deposition temperature have been investigated to retain the passivation quality although we find that degradation cannot be completely eliminated. However, we observe that post-annealing in air for the HIT solar cell is able to fully recover the decrease in minority carrier lifetime that is caused by ITO sputtering at RT. As illustrated in FIG. 4, the implied-V_{oc} and minority carrier lifetime before ITO deposition are 690 mV and 1.2 ms respectively. After ITO deposition at RT, the Suns-V_{oc} is only 550 mV and minority carrier lifetime is too low to be measured at a carrier density of 10^{15} cm^{-3}. When the post-annealing temperature is increased step by step the passivation quality is recovered. Eventually, at 180 °C the minority carrier lifetime is increased back to 1.2 ms and the Suns-V_{oc} increases up to about 710 mV.

In the case of the HIT solar cell with ITO deposited at an elevated temperature, post-annealing does not have any effect as can be seen in FIG. 5. This observation implies that simultaneous annealing during ITO deposition, which might induce hydrogen effusion, can cause irreversible passivation degradation, which in turn cannot be recovered by post-annealing. However, in the case of the HIT solar cell with ITO deposited at RT, there is no simultaneous annealing during ITO deposition. Although the passivation degrades significantly right after the ITO deposition at RT, the degradation can still be fully recovered as showed in FIG. 4.

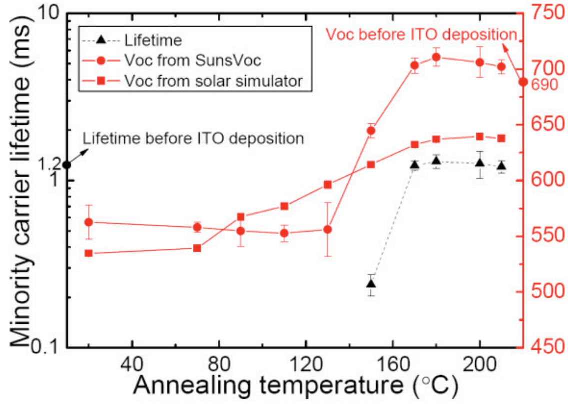


FiG. 4. V_{oc} and minority carrier lifetime at a carrier density of 10^{15} cm^{-3} as a function of post-annealing temperature. The ITO of this HIT solar cell is deposited at RT. The sample structure is illustrated in FIG. 1a.

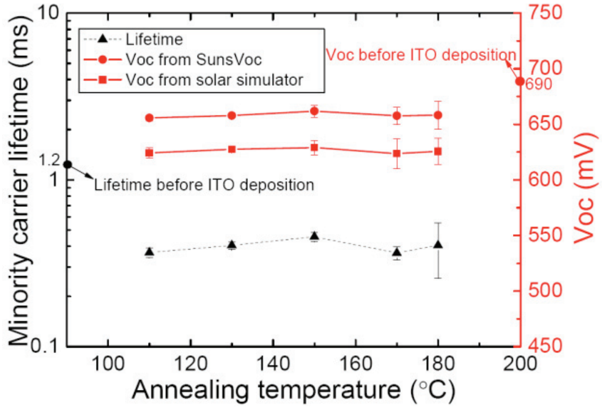


FiG. 5. V_{oc} and minority carrier lifetime at a carrier density of 10^{15} cm^{-3} as a function of post-annealing temperatures. ITO of this HIT solar cell is deposited at 110 ºC. The sample structure is illustrated in FIG. 1a.

4. Conclusion

In this contribution, we have shown that lowering the power density in the ITO sputtering process reduces the minority carrier lifetime degradation. However, using a very low power density leads to low deposition rates and plasma instability. The use of elevated temperatures during ITO deposition results in simultaneous annealing and needs to be well controlled: on one hand, it can recover the drop in minority carrier lifetime induced by ITO sputtering itself; on the other hand, elevated temperatures used in ITO deposition can cause passivation degradation when the temperature is over a threshold. Post-annealing turns out to be very effective in recovering the passivation degradation resulting from ITO deposition at RT. However, degradation caused by long time simultaneous annealing during ITO deposition cannot be recovered by post-annealing probably due to irreversible hydrogen effusion. From the Sinton Suns-Voc measurement we conclude that the V_{oc} at one sun illumination can reach about 710 mV by post-annealing in air.

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References

[1] Tanaka M, Taguchi M, Matsuyama T, Sawada T, Tsuda S, Nakano S, Hanafusa H, Kuwano Y. Development of new a-Si/c-Si heterojunction solar cells: ACJ-HIT (artificially constructed junction-heterojunction with intrinsic thin-layer). *Jpn J Appl Phys* 1992; **31**:3518.

[2] Maruyama E, Terakawa A, Taguchi M, Yoshimine Y, Ide D, Baba T, Shima M, Sakata H, Tanaka M. Sanyo's challenges to the development of high-efficiency HIT solar cells and the expansion of HIT business. in *Proceedings of the 4th World Conference on Photovoltaic Energy Conversion* 2006; **2**: 1455.

[3] Mishima T, Taguchi M, Sakata H, Maruyama E. Development status of high-efficiency HIT solar cells. *Sol Energ Mat Sol* 2010;

95: 18.

[4] Fujishima D, Inoue H, Tsunomura Y, Asaumi T, Taira S, Kinoshita T, Taguchi M, Sakata H, Maruyama E. High-performance HIT solar cells for thinner silicon wafers. in *Proceedings of the 35th IEEE Photovoltaic Specialists Conference* 2010; 003137.

[5] Lien S. Characterization and optimization of ITO thin films for application in heterojunction silicon solar cells. *Thin Solid Films* 2010; **518**: S10.

[6] Plá J, Tamasi M, Rizzoli R, Losurdo M, Centurioni E, Summonte C, Rubinelli F. Optimization of ITO layers for applications in a-Si/c-Si heterojunction solar cells. *Thin Solid Films* 2003; **425**:185.

[7] Muñoz D, Favier A, Ozanne AS, Denis C, Ribeyron PJ. Analysis of O_2 content in front ITO layers for a-Si:H/c-Si heterojunction solar cells," in *Proceedings of the 25th European Photovoltaic Solar Energy Conference and Exhibition* 2010; 2255.

[8] Heimke B, Nyderle R, Junghähnel M, Hartung U, Kopte T, Junghähnel M. ITO thin films prepared by synchronal pulsed rf-DC sputtering," in *Proceedings of the 25th European Photovoltaic Solar Energy Conference and Exhibition* 2010; 3099.

[9] Ohring M. *Materials science of thin films: deposition and structure*. 2nd ed. San Diego: Academic Press; 2002.

[10] Lee J. Effects of substrate temperature on electrical and optical properties ITO films deposited by r.f. magnetron sputtering. *J Electroceram* 2009; **23**: 554.

[11] Wolf SD, Kondo M. Boron-doped a-Si:H/c-Si interface passivation: degradation mechanism. *Appl Phys Lett* 2007; **91**:112109.

[12] Matysik KJ, Mogab CJ, Bagley BG. Hydrogen evolution from plasma-deposited amorphous silicon films. *J Vac Sci Technol* 1978; **15**:302.

[13] Beyer W. Hydrogen effusion: a probe for surface desorption and diffusion. *Physica B: Condensed Matter* 1991; **170**: 105.

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