INVESTIGATION OF ANTI-REFLECTION-COATING STACKS FOR SILICON HETEROJUNCTION SOLAR CELLS

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ABSTRACT: High-efficiency silicon heterojunction solar cells, like the Panasonic HIT cell [1], use transparent conductive oxides (TCO) as anti-reflection layers. We investigated whether a single TCO layer or a two layers ARC stack is the better option for such a cell. Therefore we simulated the reflection and transmission properties of single indium tin oxide (ITO)-layers with various optical constants and layer systems with two different anti-reflection coatings (ARC). We also calculated the short-circuit current density (J_{sc}) for these systems. We found out that with a second anti-reflection layer the standard weighted reflectance (SWR) can be reduced by 5 % compared to single layers coatings. The best calculated J_{sc} for non-textured surfaces was 35.7 mA/cm^2. With a texture we consider an additional J_{sc} gain of approx. 3 mA/cm^2 approaching 39 mA/cm^2.

Keywords: Heterojunction, TCO, Optical Properties, Modelling, Antireflection Coating

1 INTRODUCTION

All solar cells need to minimize the reflection of the incoming light for a higher conversion efficiency [2, 3]. This is normally done by using an anti-reflection coating. The refractive index of the coating has to be well adapted to the used substrate and the extinction coefficient has to be as low as possible to avoid any absorption within the film.

High-efficiency silicon heterojunction solar cells use transparent conductive oxides as anti-reflection layers because the TCO layer has to ensure a good lateral conductivity between the grid fingers.

However high conductive layers show a higher absorption which makes the optimization of the TCO as an ARC and good conducting layer difficult [4–6].

One way to improve the reflection properties and thus to increase J_{sc} of the cell could be to use a suitable two layer ARC system.

For the comparison of the single and double layer ARC systems the standard weighted reflection SWR can be used. From the reflection data and using a known IQE the possible J_{sc} for a cell can be calculated.

2 EXPERIMENTAL

We sputtered one of the most used TCO, indium tin oxide (ITO), with different process parameter. The produced films have various optical and electrical parameters [7][8]. The ITO was sputtered on two different substrates, 1 Ωcm shiny etched n-type wafers and borofloat glass in order to determine the ITO properties like the reflection, the transmission, the specific resistance and the optical constants (see Table I and II).

Table I: Sputtering process parameters and properties for the different sputtered ITO films

sample	DC11	DC24	RF20	RF21
$O_2/(O_2+Ar)$	0.015	0.02	0	0
Temp. [°C]	150	RT	250	200
RF [W]	0	0	300	100
DC [W]	200	200	0	200
ρ [µΩcm]	62.3	73.6	16.5	32.2
$T_{400-1200}$ [%]	82	90	92	90

All manufactured ITO layers have a reflection minimum at 620 nm. Because of the different refraction indices the films have slightly different thicknesses.

The optical constants n and k were measured with spectroscopic ellipsometry (see figure 1 and table II).

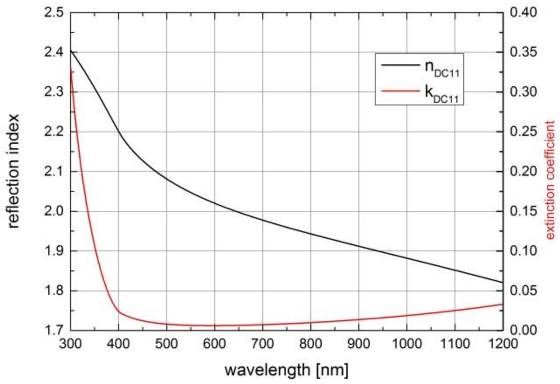

Figure 1: Optical constants for ITO film DC11 determined from spectroscopic ellipsometry measurement

Table II: Extracts of optical constants for two different wavelengths

	DC11	DC24	RF20	RF21
n @ 620 nm	2.011	1.993	1.843	1.977
k @ 350 nm	0.107	0.149	0.032	0.098

We used the program WVASE to simulate the optical properties (reflection (R) and transmission (T)) of single ITO layer and two layer ARC systems with TiO_2 or MgF_2 as second layer on top of an ITO layer.

For the comparison of the different systems the standard weighted reflectance (SWR) has been used.

$$\text{SWR: } SWR_{\lambda1-\lambda2} = \frac{\int_{\lambda2}^{\lambda1} R(\lambda) \cdot SE(\lambda) d\lambda}{\int_{\lambda2}^{\lambda1} SE(\lambda) d\lambda}$$

R(λ) is the calculated reflection, SE(λ) is the AM1.5G sun spectrum (2008) for 350-1200 nm in 1nm steps on earth [9].

At last the possible J_{sc} of a non-textured solar cell is calculated with the reflection using

$$J_{sc} = \frac{e}{hc}\int_{0}^{\infty} \lambda \cdot \frac{IQE(\lambda)}{1-R(\lambda)} \cdot SE(\lambda)\, d\lambda$$

For the internal quantum efficiency IQE values have been used which are given in [10]. The backside reflection has been taken into account.

3 RESULTS

3.1 Optical Properties of single layer TCO films

A comparison of the simulated reflection, transmission and absorption for the different sputtered films is shown in the figures 2-4. Figure 2 shows that above 600 nm the reflection for the ITO_{RF20} film is up to 5% higher than the reflection of the other sputtered ITO films. The ITO_{DC11} and ITO_{DC24} films show the lowest reflection values.

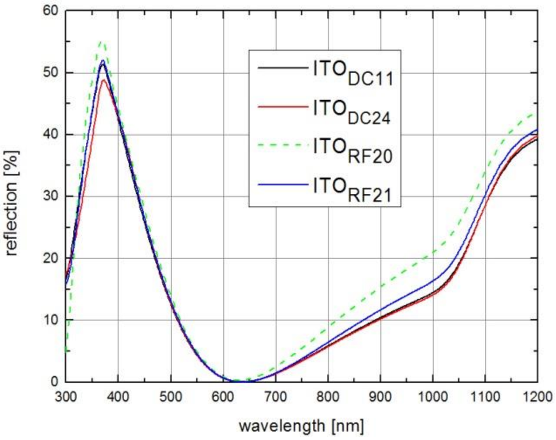

Figure 2: Reflection curves for different magnetron sputtered ITO films on silicon

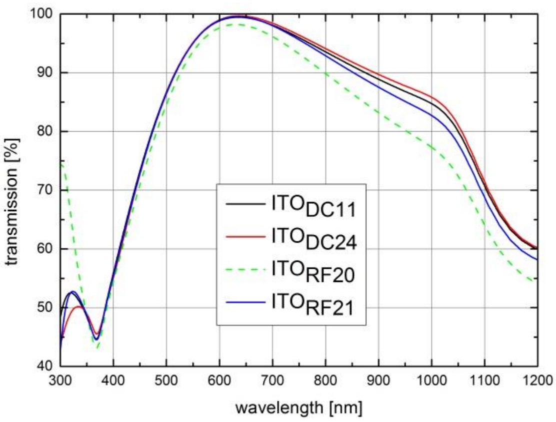

Figure 3: Transmission curves for different magnetron sputtered ITO films on glass

Figure 3 shows the transmission curves for the different layers on glass. The ITO_{RF20} film has a significantly lower transmission than the other transparent conducting oxides. Only in the small wavelength range of 300 - 350 nm it has the highest transmission of all.

In the wavelength range of 300 - 400 nm the ITO_{DC24} film has the lowest transmission value of all ITO films. In the higher range above 650 nm the ITO_{DC24} has the highest transmission of all. The ITO_{DC11} film has a slightly lower transmission than the ITO_{DC24} film.

The transmission of the ITO_{RF21} film is better than the transmission for the ITO_{RF20} film, but still lower than the transmissions of the two other DC sputtered films.

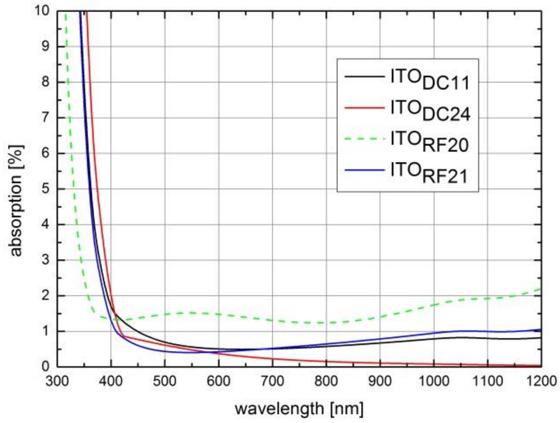

Figure 4: Absorption curves for different magnetron sputtered ITOs

In figure 4 the absorption for all four ITO films is shown. The ITO_{RF20} film shows the lowest absorption in the wavelength range from 300 to 400 nm but above 400 nm this film shows the highest absorption of all films (more than 1%)

The absorption for the ITO_{DC11} and the ITO_{RF21} films from 300 to 400 nm and above 600 nm is very similar.

The absorption for the ITO_{DC24} film is the highest for wavelengths between 300 and 400 nm, but for wavelengths above 600 nm the absorption is the lowest of all investigated films.

Taking all optical properties into account the DC-sputtered ITO films are better suited as ARC than the RF-sputtered films. So the ITO_{DC24} film has the best optical properties at all and the ITO_{RF21} film is the better RF-sputtered film.

3.2 Reflection of anti-reflection coating stacks

The reflection for an MgF_2/TiO_2 reference ARC stack on silicon is shown in figure 5. The layer thicknesses for all investigated ARC stacks are optimized to achieve a minimal SWR. This means for the MgF_2/TiO_2 stack that the stack consisting of a 90 nm thick MgF_2 and 65 nm thick TiO_2 film has the lowest SWR of 9.69 %.

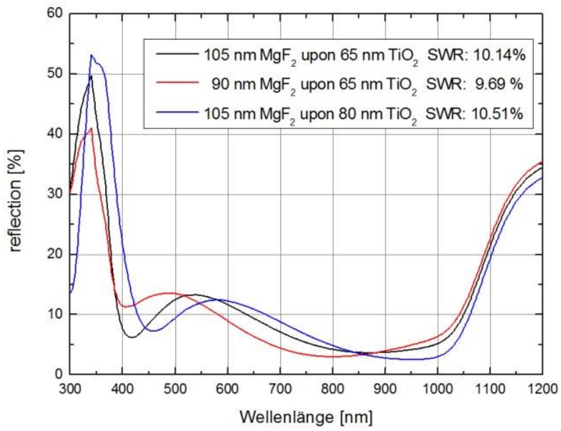

Figure 5: Reflection curves for MgF_2/TiO_2 stacks with different MgF_2 thicknesses

Figure 6 shows an example how a second anti-reflection layer can help to reduce the SWR even for an optically non optimal ITO layer (ITO_{DC11}). The ARC stack consists of an ITO_{DC11} film as the bottom layer and MgF_2 film as the top layer. The ITO_{DC11} film alone has a SWR of 12.12 %. With the MgF_2 the SWR is reduced by 4 % to 7.96 %.
Both single layers have a high reflection (50 %) at 400 nm, in the stack the reflection is halved to 25 %. While the reflection is higher in a small wavelength range of 550 - 700 nm than for the ITO_{DC11} alone for all other shown wavelengths the ARC stack has a lower reflection.

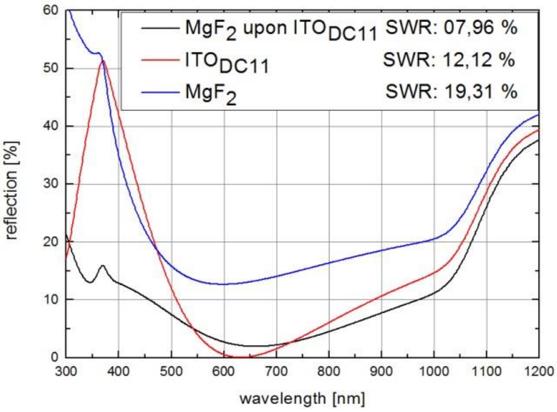

Figure 6: Reflection curve for an MgF_2/ITO_{DC11} stack in comparison to the corresponding single layers

In figure 7 an example is given in which a second layer does not reduce the SWR but enhances it. The three reflections curves for the ITO_{DC11} film, the TiO_2 film and a stack of these two materials are very similar with the reflection minimum at nearly the same wavelength, with the ITO film causing a slightly smaller reflection in the range of 300-400 nm. The SWR is lower for a silicon wafer with the ITO_{DC11} film alone, an additional TiO_2 film leads to a slightly increase of the total reflection.

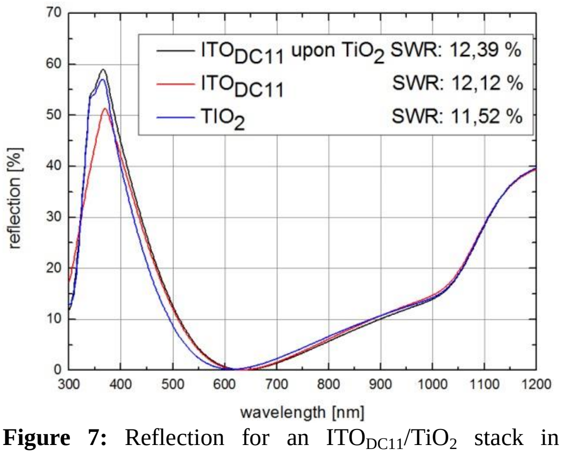

Figure 7: Reflection for an ITO_{DC11}/TiO_2 stack in comparison to the corresponding single layers

3.3 Calculation of short-circuit current

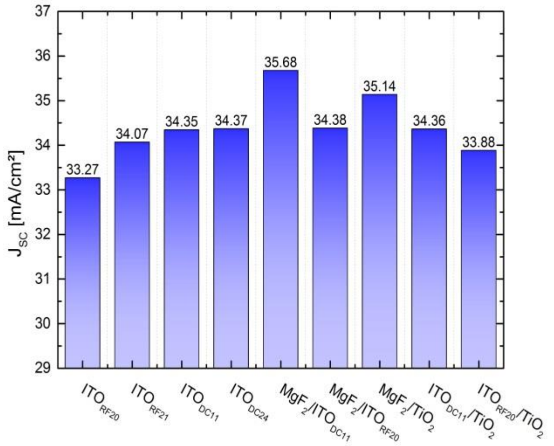

Figure 8: Calculated J_{sc} for different simulated ARCs

The calculated J_{sc} values are shown in figure 8. The bars show the different J_{sc} values for single layer ITO anti-reflection coatings and for ARC stacks. The two highest values for J_{sc} are obtained for the MgF_2/ITO_{DC11} and MgF_2/TiO_2 ARC stacks, the lowest values are obtained for the single layer ITO anti-reflection films, which were sputtered using an RF-plasma.
The difference between the highest J_{sc} of the single layer and the highest J_{sc} of the ARC stacks is 1.3 mA/cm². J_{sc} can be further increased by approximately 3 mA/cm^2 if textured substrates are used.

4 SUMMARY

Although the RF magnetron sputtering process delivers films with the better electrical properties the DC sputtered films have the better optical properties.
The lowest SWR of 7.96 % is obtained for a DC magnetron sputtered ITO film with an MgF_2 layer on top. The corresponding J_{sc} is 35.7 mA/cm^2. This is an increase of the short-current density by 3.8% compared to single layer anti-reflection coatings. However one has to take into account that with encapsulation the improvement of the current density might be lower.

5 ACKNOWLEDMENT

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