ZnO Layers Incorporated into µc-Si :H Solar Cells : Quantum Efficiency (QE) Results and Proposal for a Figure of Merit

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Abstract: Doped ZnO layers deposited by Low Pressure Chemical Vapour Deposition technique have been studied for their use as transparent contact layers for thin-film silicon solar cells. The effect of a variation in the doping level of the front LP-CVD ZnO on solar cell performance is investigated. Based on these experimental results, authors propose to evaluate the effect of the different ZnO layer properties on solar cell performance by the use of a wavelength-dependent figure of merit.

Key Words: LP-CVD ZnO, rough TCO, Figure of Merit, Thin-Film Silicon Solar Cell.

1 Introduction

Zinc Oxide (ZnO) deposited by Low Pressure Chemical Vapour Deposition (LP-CVD) has proven to be a good candidate as Transparent Conductive Oxide (TCO) for thin-film silicon solar cells. These ZnO layers are not only transparent and electrically conductive, but possess also a pronounced light scattering capability, which leads to an increase of the photo-generated current in the solar cell. This property is especially important in the case of amorphous and microcrystalline silicon (a-Si:H and µc-Si:H) thin-film solar cells, because of their relatively low values of absorption coefficient; it can be attributed to the as-grown surface texture of the LP-CVD ZnO layers[1, 2].

LP-CVD technology allows one to easily vary deposition parameters over a wide range of values and to obtain thereby ZnO layers having various values of surface roughness, sheet resistance and optical transparency [1]. This high flexibility of deposition conditions means, however, that ZnO layer design (i.e. variation of thickness and doping level) can become a time-consuming task, if one wants to optimize these layers for a-Si:H or µc-Si:H solar cells.

The effect of a variation in the thickness of front LP-CVD ZnO on µc-Si:H solar cell performance has already been presented in [2]: thicker ZnO layers, which are more conductive, possess also a rougher surface that considerably enhances the photo-generated current in the solar cell. The effect of a variation in the doping level of front LP-CVD ZnO has then been studied. The results of this study are presented in this paper. The authors will then introduce a new wavelength-dependent figure of merit, which allows one to theoretically evaluate the effect of the different ZnO layer properties on solar cell performance.

2 Experimental

LP-CVD ZnO layers have been deposited using diethylzinc (DEZ) and H_2O vapours as reactants, and diborane gas (B_2H_6) as dopant. The flow rate of B_2H_6 has been varied from 0 to 18 sccm, in order to enhance the doping ratio, i.e. the B_2H_6/DEZ ratio. The total pressure was kept at 0.5 mbar (~ 0.37 Torr), and the substrate was heated during the ZnO deposition at a temperature of 155°C. p-i-n µc-Si:H solar cells have been deposited on ZnO front contact layers (on glass) by the in-house VHF PE-CVD process.

Optical transmission, both total and diffuse (TT and DT, respectively), and total reflection (RT) have been measured using a spectrometer with an integrating sphere. To quantify the light-scattering capacity of the ZnO layers, the haze factor (H(λ)) has been defined as the DT/TT ratio measured at 600nm. Solar cells were analyzed by external quantum efficiency (EQE) measurements.

3 Results

A first doping series consisted of boron-doped 2.5 µm-thick LP-CVD ZnO layers deposited with various B_2H_6/DEZ ratios. Their haze factor and conductance are shown in Fig.1.

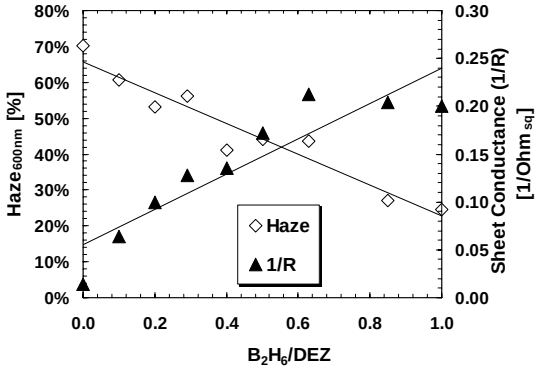

Fig. 1 Haze factor and conductance variation of the LP-CVD ZnO layers, in function of the doping ratio used during the ZnO deposition.

When the doping level is increased, the scattering capacity of the ZnO layer is reduced, whereas its conductance is improved. A compromise has therefore to be made, in order to give to the ZnO layer a sufficient light scattering capacity while keeping it conductive enough.

ZnO samples that were conductive enough have been incorporated as front TCO into µc-Si:H solar cells. As already seen in [2], QE curves are higher in the near-infrared range for rougher ZnO layers, which are the less doped layers. However, undoped and slightly doped ZnO layers, which are the roughest layers of this series, and therefore the layers with the highest light scattering capacity, could not be evaluated, as their sheet resistance (R_{sq}) was too high to act as electrical contacts for the solar cell.

A second doping series has then been deposited, for which R_{sq} was kept constant at 10 Ω_{sq}, and both doping ratio and ZnO layer thickness were varied, so as to ensure a constant sheet resistance value. This series and the performance of µc-Si:H solar cells deposited on it has been presented in detail in [3]. Here again, the best QE curves were obtained for undoped

ZnO layers, whereas the thickness of these layers is around 5µm. J_{sc} values over 21 mA/cm^2 for 2 µm thick µc-Si:H cells without any back reflector were thereby obtained. Furthermore, a linear trend between the front-ZnO roughness and the photo-generated current has also been established. However, low values of FF were obtained for solar cells deposited on the roughest ZnO layers. This could come from the growth of the silicon on very rough ZnO, which is indeed affected by the high surface roughness of the front ZnO layer. This aspect is studied in more detail in [4].

4 Discussion

All the various studies concerning front TCO optimization for their integration into thin-film silicon solar cells have revealed several points for consideration:

- In all test series, roughest front ZnO layers lead to highest photo-generated currents in the cell.
- LP-CVD ZnO layers have a high transparency that allows one to use thick layers and, thus, obtain high surface roughness and conductance values.
- For each kind of front-TCO roughness, a particular and complex work of optimization of the on-deposited multi-layers solar cell has to be done. Each interface has to be reevaluated as well as the quality of each individual layer.

The latter point highlights the difficulty of the optimization work of thin-film silicon solar cells: **we need efficient prediction tools that can help us to choose the optimum TCO as a basis for the long and fastidious optimization of the silicon layers deposited on these TCO layers**. It is for this purpose that we propose a new wavelength-dependent Figure of Merit (FoM(λ)), as a new way to evaluate the efficiency of rough TCO for thin-film solar cells:

$$\mathbf{FoM(\lambda)= H(\lambda)*(TT(\lambda)+RT(\lambda))*R_{dev}} \quad (1),$$
$$\mathbf{R_{dev} = 1 \text{ if } R_{sq}<R_{ref};\ R_{dev} = R_{ref}/R_{sq} \text{ if } R_{sq}>R_{ref}}$$

where R_{ref} is the reference value of sheet resistance that is required by the connection scheme of the solar cell.

This FoM(λ) consists of successive multiplications of factors comprised between 0 and 1. The haze factor, the factors TT&RT, and the factor R_{dev}, are weighting coefficients for the light scattering capacity, the transparency, and the electrical properties, respectively. Absorbance and resistance factors, which are the physical parameters to which the solar cell is "directly connected", have been chosen here, rather than absorption coefficient and resistivity, which are the intrinsic material properties of the TCO layers.

FoM(λ) of ZnO layers from the first doping series (for which the thickness was kept at 2.5 µm) are shown in Fig.2, for $R_{ref} = 10\Omega_{sq}$ and $5\Omega_{sq}$.

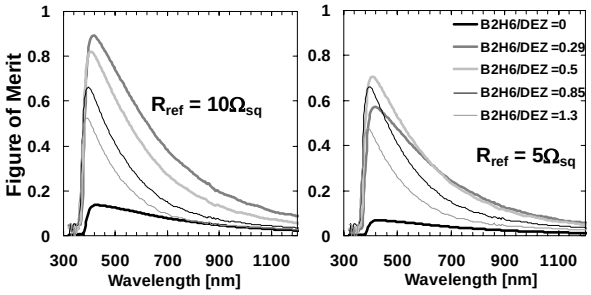

Fig.2 Wavelength-dependent Figure of Merit for 2.5µm-thick ZnO layers deposited with various doping gas ratios. The data are computed for two reference values of sheet resistance.

If the connection scheme of the solar cell allows one to have R_{sq} of TCO layer up to 10 Ω_{sq}, then the optimum TCO would be the one deposited with a B_2H_6/DEZ ratio of 0.3. On the other hand, if a R_{sq} value of only 5 Ω_{sq} is required, the optimum TCO would be the one deposited with a B_2H_6/DEZ ratio of 0.5.

FoM(λ) of ZnO layers from the second doping series (for which R_{sq} was kept at $10\Omega_{sq}$) are shown in Fig.3, for $R_{ref} = 10\Omega_{sq}$. The advantage of using thick undoped ZnO layers is thereby highlighted and confirms the conclusions that could be deduced from the experimental tests with entire solar cells [3].

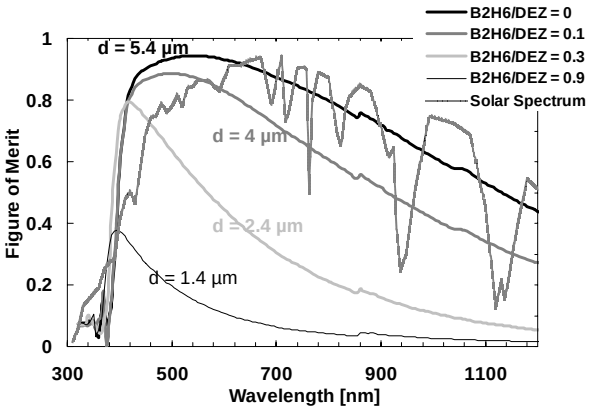

Fig.3 Figure of Merit for ZnO layers deposited with various doping gas ratios and thicknesses (d), and a similar value of sheet resistance equal to $10\Omega_{sq}$. The reference value of sheet resistance is $10\Omega_{sq}$.

The flexibility of this new FoM(λ) allows one to define the important criteria to choose the optimum TCO: for example, each factor can be set to 1 if it is not considered as being of influence in a certain range of values (as was shown here for R_{sq}). Furthermore, the wavelength dependency gives a clear and direct picture that can be correlated to the spectral sensitivity of the solar cell (which varies in function of the solar cell type). Note also that other factors could easily be added, like the angular distribution function of scattered light (ADF), to refine the choice of TCO.

4 Conclusions

In this paper, the optimization work of front-ZnO for pin µc-Si:H solar cells has been described and evaluated. Whereas it is clear that the roughest ZnO will induce the highest photo-generated current in the cell, attention has now to be paid on the growth of the cell on rough substrates, which is critical to get high FF and V_{oc} values.

A new figure of merit has also been proposed and evaluated, in order to facilitate the identification of optimum TCO for a particular thin-film silicon solar cell application.

5 References

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