



# Rough ZnO layers by LP-CVD process and their effect in improving performances of amorphous and microcrystalline silicon solar cells

S. Fay<sup>\*</sup>, L. Feitknecht, R. Schlüchter, U. Kroll,  
E. Vallat-Sauvain, A. Shah

*Institut de Microtechnique (IMT), Rue A.-L. Breguet 2, 2000 Neuchâtel, Switzerland*

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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.

Surface roughness of these ZnO layers is related to their light-scattering capability; this is shown to be of prime importance to enhance the current generation in thin-film silicon solar cells. Surface roughness has been tuned over a large range of values, by varying thickness and/or doping concentration of the ZnO layers.

A method is proposed to optimize the light-scattering capacity of ZnO layers, and the incorporation of these layers as front transparent conductive oxides for p–i–n thin-film microcrystalline silicon solar cells is studied.

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## 1. Introduction

Transparent conductive oxides (TCOs) are an essential part of thin-film solar cells, both cost-wise and performance-wise. Amongst these TCOs, doped zinc oxide (ZnO) is a very promising candidate for future thin-film solar cell technology, especially because of its low cost and because of the wide availability of its constituent raw materials.

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<sup>\*</sup>Corresponding author. Tel.: +41 32 718 33 31; fax: +41 32 718 32 01.

*E-mail address:* [sylvie.fay@unine.ch](mailto:sylvie.fay@unine.ch) (S. Fay).

Doped thin-film ZnO layers deposited by the low pressure chemical vapour deposition (LP-CVD) technique are not only transparent and electrically conductive, but possess also a pronounced light-scattering capacity. The light-scattering capacity increases the path of the light within the solar cell, and, hence, enhances also its probability to be absorbed in the cell. This aspect is especially important in the case of amorphous and microcrystalline silicon (a-Si:H and  $\mu\text{c-Si:H}$ ) thin-film solar cells, because of their relatively low optical absorption coefficient in the red and near infra-red (NIR) spectral range. Moreover, thicker a-Si:H ( $>0.4\ \mu\text{m}$ ) and  $\mu\text{c-Si:H}$  ( $>3\ \mu\text{m}$ ) intrinsic (i)-layers cannot be used within the corresponding solar cells, because (a) the light-induced degradation effect (Staebler–Wronski effect) in a-Si:H p–i–n solar cells becomes more pronounced as the thickness of the a-Si:H i-layer is increased and because (b) the deposition times needed for thicker silicon layers become so long that cell manufacturing becomes economically prohibitive (especially in the case of  $\mu\text{c-Si:H}$  solar cells). The light-scattering property is linked to the surface roughness of the TCO layer used in the cell. Indeed, a rough surface allows one to scatter efficiently the light that enters into the solar cells through the TCO layer.

In the present study, ZnO layers have been deposited by LP-CVD, in a pressure range inferior to 1 Torr, well below the usual process-pressure range applied for deposition of ZnO layers [1,2]. Under our deposition conditions, a ZnO with surface roughness well suited for light-scattering in thin film solar cells has been obtained [3]. Our goal has thereby been to incorporate such layers as front TCO layers in microcrystalline/amorphous or ‘micromorph’ tandem [4] thin-film silicon solar cells [5–7].

This paper is a study of the impact of thickness and doping variation of the LP-CVD ZnO layers on their surface roughness and therefore on their light-scattering capacity. Moreover, the variation in the performance of p–i–n  $\mu\text{c-Si:H}$  solar cells, when the light-scattering capacity of the front ZnO layer is varied, has also been studied.

## 2. Experimental

ZnO layers have been deposited by LP-CVD. Diethyl zinc (DEZ) and water ( $\text{H}_2\text{O}$ ) vapours have been used as precursors, and directly evaporated in the system. In this case, the vapours were not diluted in a carrier gas. DEZ and  $\text{H}_2\text{O}$  flows have been set to 13.5 and 16.5 sccm, respectively. Diborane ( $\text{B}_2\text{H}_6$ ) has been used as doping gas, 2% diluted in helium. The flow rate of  $\text{B}_2\text{H}_6$  has been varied from 0 to 18 sccm, in order to enhance the doping ratio, i.e., the  $\text{B}_2\text{H}_6/\text{DEZ}$  ratio. The total pressure was kept at 0.5 mbar ( $\sim 0.37$  Torr), and the substrate was heated during the ZnO deposition at a temperature of  $155\ ^\circ\text{C}$ . The thickness of the ZnO samples has been varied from 400 to  $3\ \mu\text{m}$ . p–i–n  $\mu\text{c-Si:H}$  solar cells have been deposited on ZnO front electrode by the in-house very-high-frequency plasma-enhanced-chemical vapour deposition technique (VHF PE-CVD) [8,9].

Thickness ( $d$ ) has been measured using a profilometer, and sheet resistance ( $R_{\text{sq}}$ ) has been measured by the four-probe method. Resistivity values have been deduced from both  $d$  and  $R_{\text{sq}}$  measurements. Optical transmission, both total and diffuse (TT and TD, respectively), have been measured using a spectrometer with an integrating sphere, in the visible and NIR wavelength range. The haze factor has been defined as the TD/TT ratio measured at 600 nm. This factor quantifies the light-scattering capacity of the ZnO layers.

X-ray diffraction (XRD) measurements and transmission electron microscopy (TEM) cross-sections have been performed to characterize the crystallographic orientation and the microstructure of the ZnO layers. Finally, surface topography images have been taken by

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