Cu(In,Ga)Se$_2$ superstrate solar cells on transparent conducting zinc oxide layers

F.-J. Haug, M. Krejci, H. Zogg, A.N. Tiwari

Thin Films Physics Group, Institute of Quantum Electronics,
ETH (Swiss Federal Institute of Technology)
Technopark, ETH-Building, Technoparkstr.1, CH-8005 Zurich, Switzerland

ABSTRACT

For the development of superstrate solar cells Cu(In,Ga)$_x$Se$_y$ (CIGS) absorber layers have grown by vacuum evaporation on ZnO/ZnO:Al coated soda lime glass substrates. The resistivity of RF sputtered ZnO:Al depends on the deposition temperature and RF power. After the growth of CIGS layer the resistivity of ZnO:Al increases by a factor of 3. The grain size of CIGS depends on the growth procedure. Microstructural analysis of the interface indicated the formation of an interfacial layer but no-significant diffusion of elements across the interface.

1. Introduction

The Cu-chalcopyrite semiconductors have been successfully employed for the preparation of high efficiency and stable thin film solar cells. Usually the CIGS absorber layer is evaporated on Mo-coated glass substrates, on top of this a thin CdS buffer layer and a transparent ZnO front contact are deposited. Solar cells with conversion efficiencies of more than 17% have been obtained in this configuration [1-3].

Another configuration is the so called "superstrate" in which the p-type absorber is grown on glass covered with a wide band gap window layer and/or a transparent front contact. This structure offers the advantage of easier encapsulation and therefore lower costs. The application of conventionally used CdS buffer layer is unsuitable because of a strong cross-diffusion of elements during the deposition of absorber layer at a high temperature of about 500 °C. However, recently a conversion efficiency of 10% has been obtained with a ZnO window layer [4].

2. Experimental

Layers of ZnO and ZnO:Al were grown by RF magnetron sputtering from pure ZnO and composite (ZnO mixed with 2 wt% Al$_2$O$_3$) targets, respectively. First, ZnO:Al layers with a sheet resistances of below 8 $\Omega_\square$ and optical transmission of about 90% were grown on soda lime glass substrates. Then buffer layers of 100 to 200 nm thick undoped ZnO were subsequently deposited.

The absorber layers were grown by co-evaporation of Cu, In, Ga and Se elements from effusion cells. The substrate temperature was raised from 450°C in the initial stage to the desired growth temperature of 550 or 570 °C at a rate of 5°C per minute. The standard growth time was 90 minutes for 2 μm thick solar cell absorbers. After the growth the layers are cooled down under Se-flux.

3. Results

Thermal stability of ZnO

The resistivity of ZnO:Al is observed to change after the growth of absorber layers. In order to optimize the properties of the front contact ZnO:Al layers were deposited at various temperatures and RF-powers and the resistivity/sheet resistance was measured before and after the growth of the CIGS layers.

As shown in figure 1, the resistivity of the as-deposited ZnO:Al layers with low sputtering power 200 W increases with increasing substrate temperature. Layers sputtered with higher powers of 250 and 300 W are almost independent of the deposition temperatures. The resistivity of the layers increases by a factor of about 3 after the CIGS deposition, e.g. for a layer grown with 300 W it increases from 1x 10^{-3} to 3x 10^{-3} Ωcm (the corresponding change in the sheet resistance is from 3 to 8 $\Omega_\square$).
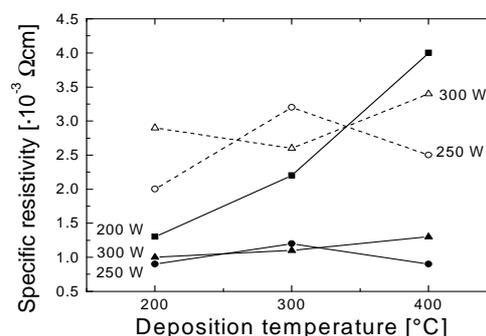

Fig. 1: The resistivity of ZnO changes during the growth of the absorber layer. Full symbols represent the as-deposited values at three different RF-powers. Open symbols correspond to measurements after the growth. The values of the 200 W deposition change to much higher values and are not shown on this scale.

The measurements indicate that a lower deposition temperature combined with a high RF-power seems more favorable for the growth of low resistivity (sheet resistance lower than 10 $\Omega_\square$) ZnO:Al layers.

Morphology of CIGS layers

The morphology of the CIGS layers was investigated with a scanning electron microscope (SEM) and the composition was determined with energy dispersive x-ray analysis (EDX). Figure 2 compares the morphology of layers of similar composition but grown with different methods. The layer of the upper image was grown at constant beam fluxes, while

the growth of the second layer was started Cu-rich and finished with low Cu-flux in order to adjust the composition. The influence on the grain size is clearly seen. Layers grown with a one-stage process usually show a grain size in the range of 1 μm whereas in the two stage process the grain size is increased up to 2 to 3 μm.
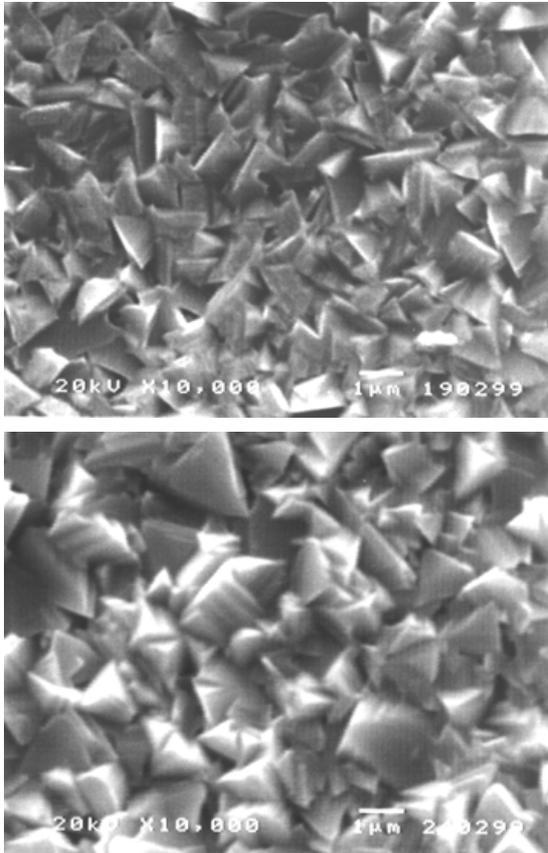

Fig. 2: Morphologies of CIGS/ZnO layers grown with a one-stage (upper) and a two-stage (lower) process.

Photovoltaic properties

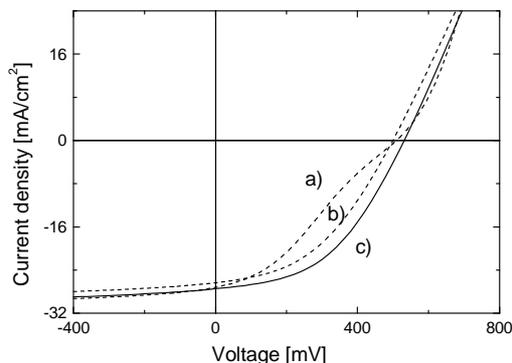For the solar cell efficiency measurements vacuum evapo-

Fig. 3: I-V characteristics of the CIGS/ZnO superstrate solar cells. The dashed curves show the influence of light soaking: a) has been taken before, b) after light soaking under 1 sun. The solid curve c) corresponds to a solar cell with an efficiency of 6.7%.

rated Au was used as a back contact on CIGS layer. Figure 3 shows the I-V characteristics of solar cells with a slightly group III-rich absorber. The as-deposited cells show a distinct double diode behavior. Light soaking under one sun generally improves the I-V diode characteristics. The improvement due to light soaking is attributed to the saturation of recombination centers near the junction and traps in the ZnO layer. The conditions for the light soaking have not been optimized. The highest efficiency solar cell has $V_{oc} = 531$ mV, $I_{sc} = 27.4$ mA/cm^2, FF = 46%, and $\eta = 6.7\%$.
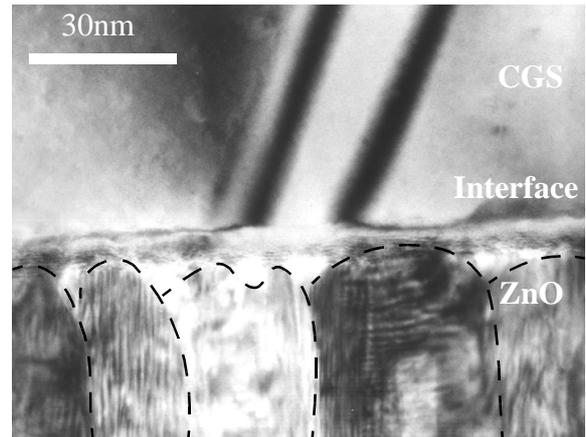

Fig. 4: Cross-section image of the interface between CGS and ZnO with an interfacial layer and inclusions.

Microstructure and interface properties

The microstructural properties of the interface between the absorber layer and ZnO were studied with transmission electron microscopy (TEM). Figure 4 shows a cross-section image of the interface between pure $CuGa_xSe_y$ and ZnO. Between the layers an interfacial layer about 5 nm is observed. It is suspected that interface layers like this might interfere with the formation of the p-n junction between the materials. With micro-probe EDX and SIMS measurements no-significant diffusion of elements across the interface was measured.

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