Investigation of the In-Depth Gallium Profile in Co-Evaporated $Cu(In,Ga)Se_2$ Thin Films and its Influence on Photovoltaic Applications

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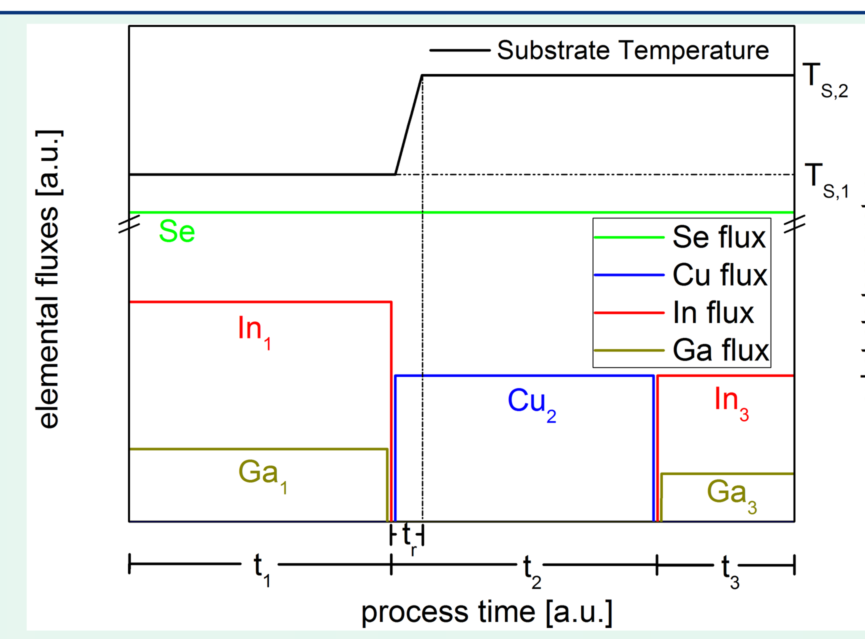
Introduction

We deposit Cu(In,Ga)Se2 thin films on Mo-coated soda-lime glass substrates using a co-evaporation process often referred to as 3-stage process. Different Ga profiles are obtained by varying the deposition rates of In and Ga in either the first or the third stage. The absorber material is characterized by x-ray diffraction (XRD). Grazing incidence XRD is used to access in-depth variations of the lattice parameter and thus the fraction Ga/(Ga+In) of the material concentrations for Ga and In. Photovoltaic devices are completed with a CdS by CBD, i-ZnO and ZnO:Al front contact by sputtering. The opto-electronic properties are investigated by current-voltage and spectral quantum efficiency measurements.

Absorber Deposition

- **Co-evaporation of Cu, In, Ga, Se on Mo coated glass substrates in 3 stages.**
- **Deposition rate ratio in the 1st stage fixed to $GGI_1 = 0.4$.**
- **Variation of Ga and In deposition rates in 3rd stage. Deposition rate ratios Ga/(Ga+In) (GGI_3) between 0 and 0.375**



Absorber Characterization

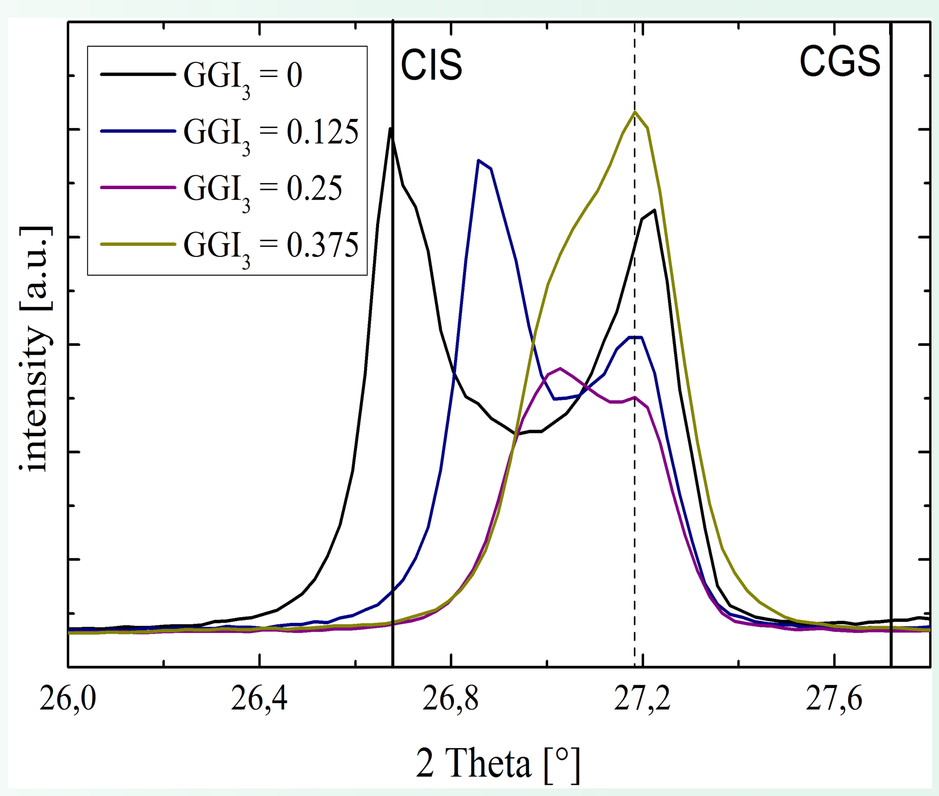


Figure 2: XRD measurement of the $Cu(In_{1-x},Ga_x)Se_2$ (112) plane. Peak position shifts with Ga content x.

- **Fix peak (dashed line) attributed to phase at back side whose Ga content depends only on deposition rates in 1st stage**
- **Ga poor phase close to front side; Ga concentration increases with GGI_3 until $GGI_3 \approx GGI_1$**

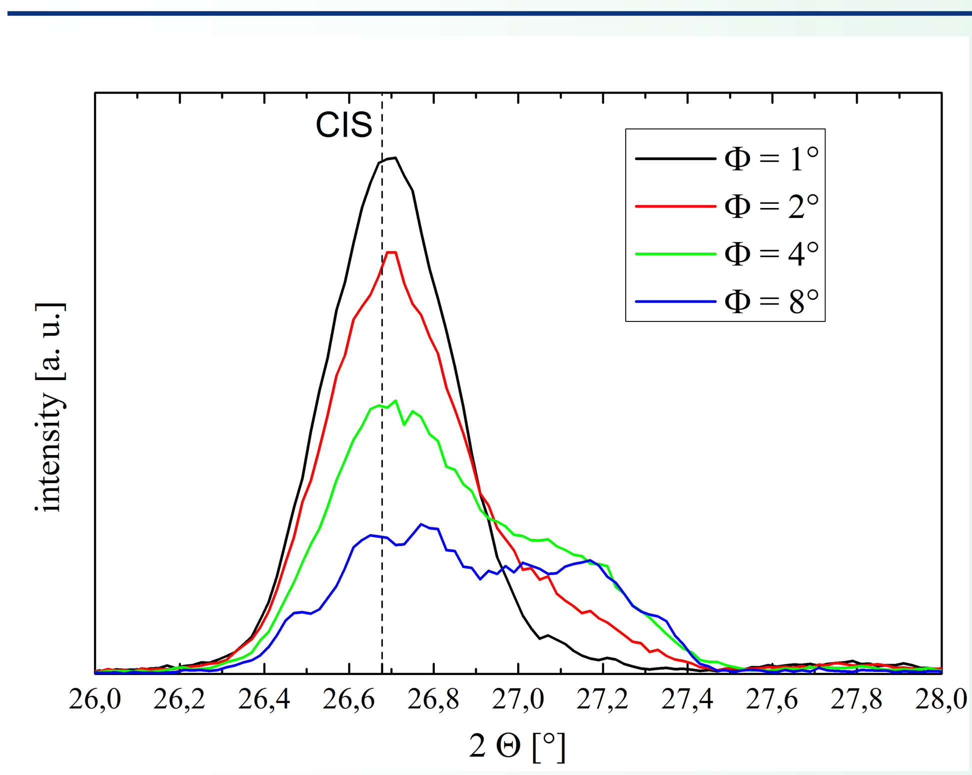


Figure 3: GI-XRD measurement of the $Cu(In_{1-x},Ga_x)Se_2$ (112) plane for different incident angles Φ. Information depth increases with Φ.

- **Confirmation of a Ga poor phase close to the front and a Ga rich phase deep in the absorber.**

Cell Characterization

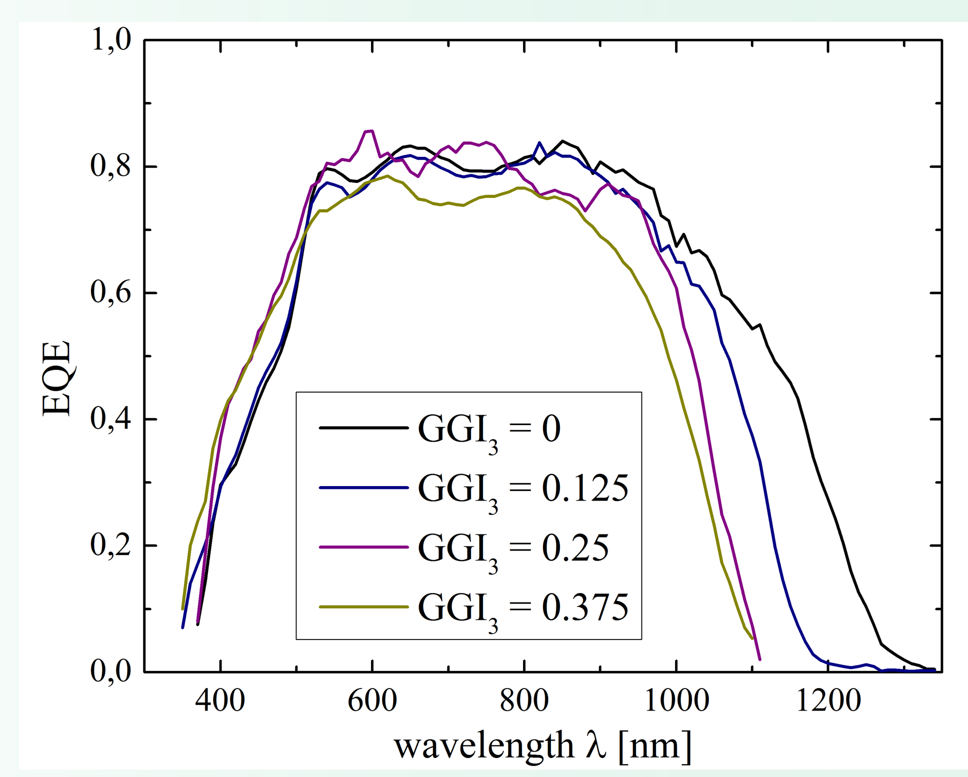


Figure 4: External quantum efficiency measurements for solar cells based on the 4 absorbers wiht different GGI_3.

- **E_{gap} increases with GGI_3 for $GGI_3 \leq 0.25$ (like the Ga content in the low Ga phase, see Figure 2.**
- **Lower Ga content close to front ($GGI_3 = 0.25$ vs. $GGI_3 = 0.375$) leads to higher QE at ≈ 950 nm and increase in FF.**

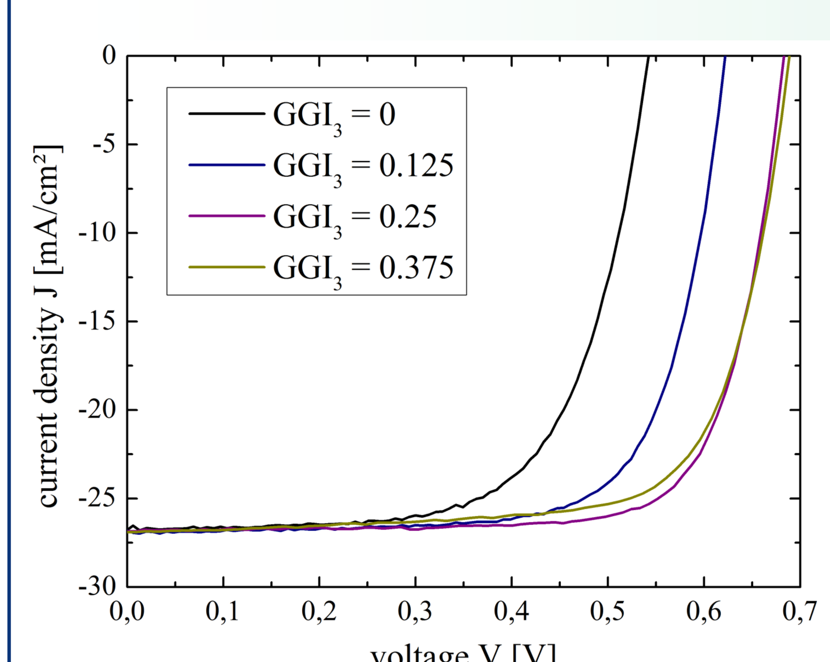


Figure 5: STC current voltage characteristics for the best cell of each absorber type. J_{sc} might be distorted by slightly different cell sizes.

Tab 1: Mean cell parameters for different absorber types extracted from STC IV and EQE (E_{gap}) measurements.

GGI_3	0	0.125	0.250	0.375
E_{gap} [eV]	1.00	1.08	1.16	1.17
V_{oc} [mV]	547	615	679	687
J_{sc} [mA/cm²]	28.7	28.6	28.1	28.3
FF [%]	65	70.8	75.4	71.8
η [%]	10.2	12.4	14.4	13.9

Conclusion

We controlled the extrinsic Ga gradient in the front part of our absorber layers by varying the In and Ga deposition rates in the 3rd part of a 3-stage co-evaporation process. XRD investigations showed the appearance of two phases with different relative Ga concentrations $c_{Ga}/(c_{Ga}+c_{In})$. The variation of GGI_3 had an influence on the Ga content of only one of these phases. By GI-XRD measurements, we were able to identify this phase to be located near the front surface of the absorber. The optical band gap is correlated to the Ga content of the low Ga phase. While J_{sc} is not influenced by GGI_3, V_{oc} follows the band gap. If the gallium content in the front is not sufficiently lower than the Ga content in the back, the fill factor and the quantum efficiency in the region at around 950 nm are reduced leading to an overall cell performance degradation. This is believed to be caused by an electron barrier near the front surface.

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