Development of wide-bandgap $Cu(In,Ga)Se_2$ solar cells and modules on transparent back contacts

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SUMMARY OF THE ABSTRACT

$Cu(In,Ga)Se_2$ (CIGS) thin-film solar cell absorbers with bandgap energies (E_g) of around 1.5 eV or above are ideal stable, inorganic top cells in tandem devices, e.g. in combination with a Si bottom cell. Besides the high E_g, which is realized by increasing the [Ga]/([Ga]+[In]) (GGI) ratio above 0.7, a transparent back contact (TBC) such as indium-doped tin oxide (ITO) rather than the standard opaque Mo is needed to allow transmission of below-E_g light to the bottom cell.

In this study, we present our results for wide-bandgap (i.e., $E_g \geq 1.5$ eV) CIGS solar cells deposited with an industry-relevant 30 × 30 cm^2 multi-stage co-evaporation system on TBC-covered glass substrates. A state-of-the-art post-deposition treatment (PDT) with RbF is applied without breaking the vacuum to increase the open-circuit voltage (V_{OC}). Addition of some Ag (resulting in [Ag]/([Ag]+[Cu]) (AAC) ratios < 0.1) during the second stage of the co-evaporation process helps to increase fill factor (FF) values. So far, our cells based on CIGS with $E_g \approx 1.5$ eV on glass/ITO substrates achieve power conversion efficiencies (PCEs) above 10% with a CdS buffer, a (Zn,Mg)O high-resistive layer, and a ZnO:Al as front contact. One key element for this performance is the use of a ~10 nm thick sacrificial Mo layer deposited by sputtering on top of the ITO TBC. Cells without this thin Mo layer do not exhibit an appreciable PCE.

The combination of hard X-ray photoelectron spectroscopy (HAXPES) and scanning transmission electron microscopy (STEM) with energy-dispersive X-ray spectroscopy (EDX) analyses reveals that the thin Mo layer mostly reacts to $MoSe_x$ and MoO_x and that it reduces GaO_x formation at the ITO/CIGS interface.

The PCE gap to reference cells on opaque Mo back contact, however, remains quite significant with approx. 4% (absolute). The cells on ITO exhibit lower FF values around 63%, which is a well-known problem for CIGS cells on TBCs in general due to series resistance. Our best wide-bandgap CIGS cell (based on an absorber with $E_g \approx 1.5$ eV) on ITO shows a PCE of 10.3% (V_{OC} = 860 mV, FF = 63%, and short-circuit current density J_{SC}

= 20.6 mA/cm^2) compared to our best reference cell on opaque Mo back contact with a PCE of 14.1 (V_{OC} = 933 mV, FF = 73%, and J_{SC} = 22.7 mA/cm^2).

In the next step, we transferred the processes from cell level with 0.5 cm^2 total area to sub-module size (5 × 5 cm^2). We achieved a PCE of 7.1% for such a wide-bandgap sub-module on ITO with patterning steps P2 and P3 performed by mechanical and P1 by laser scribing. For an all-laser scribed sub-module on ITO we achieved a PCE of 7.4%. A reference module with opaque Mo back contact exhibits a PCE of 8.5%, while the reference cell with ITO back contact shows a PCE of 10.3%. Overall, the cell-to-module efficiency gap was reduced to 3% absolute.

APPLICABLE TOPIC AND SUB-TOPIC NUMBER

Topic 2 Thin Films and New Concepts; Sub-Topic 2.3 Compound and Organic Semiconductors

EXPLANATORY PAGES

AIM AND APPROACH

Establishment of an industry-relevant wide-bandgap CIGS absorber deposition on TBCs like ITO for the application as a top cell/module in a tandem device with a Si bottom cell.

SCIENTIFIC INNOVATION AND RELEVANCE

Wide-bandgap CIGS absorbers with GGI ratios > 0.75 and a corresponding E_g > 1.48 eV on TBCs are relevant for top cell applications in a tandem device with a Si bottom cell. An around 10 nm thick Mo on top of the ITO seems to be a key feature to fabricate our wide-bandgap devices (small-area cells and modules) with decent efficiencies. The thin Mo layer reduces formation of unwanted GaO_x at the ITO/CIGS interface to achieve working cells and enables the formation of $MoSe_x$. With such an ITO/thin Mo back contact an all-laser patterned 5 × 5 cm^2 CIGS wide-bandgap sub-module was fabricated.

RESULTS (OR PRELIMINARY RESULTS) AND CONCLUSIONS

	Mo back contact	**ITO/thin Mo back contact**
PCE (%)	14.1	10.3
FF (%)	73.2	61.6
J_{SC} (mA/cm^2)	20.6	19.1
V_{OC} (mV)	933	860

Table 1: Solar cell parameters of wide-bandgap (Ag,Cu)(In,Ga)Se_2 (ACIGS) cells with opaque Mo (reference cells) and transparent ITO/thin Mo back contacts. The stacking sequence of the cells is glass/back contact/ACIGS/CdS/(Zn,MgO)/ZnO:Al without anti-reflective coating and the total area is 0.5 cm^2. The GGI is 0.73 (E_g ≈ 1.47 eV) for both cells and the AAC is 0.07 (Mo) and 0.09 (ITO/thin Mo), respectively. The ACIGS absorber

thickness is around 2.3 µm. The FF and V_{OC} values are reduced for the cell on ITO/thin Mo compared to the reference cell on Mo.

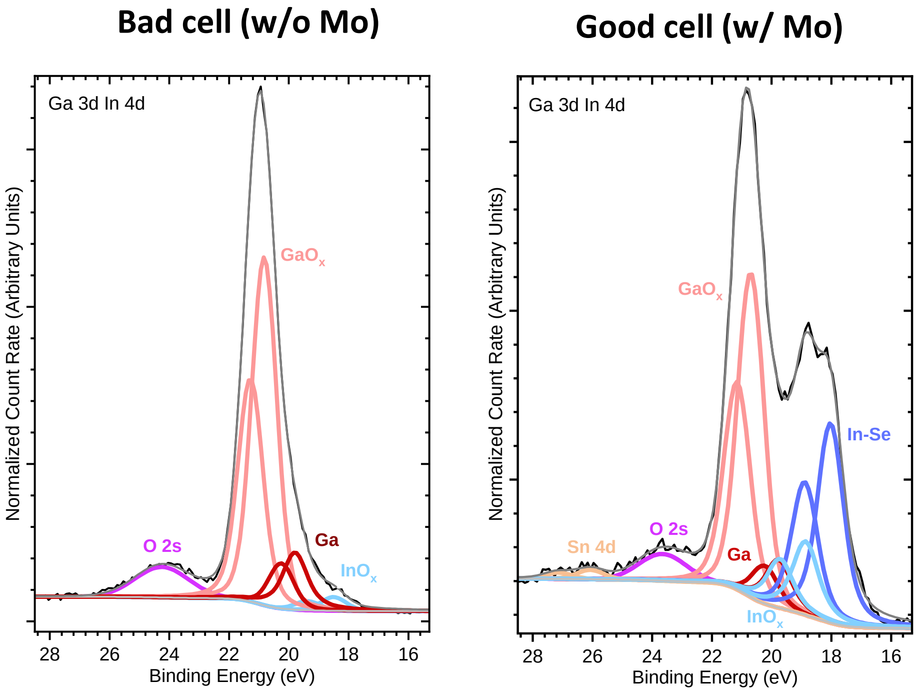


Figure 2: HAXPES measurements (Ga 3d In 4d) with 2 keV on the exposed ITO side after cleaving the ITO/ACIGS and ITO/thin Mo/ACIGS interfaces. Left: bad-performing cell (PCE = 0.6%) with ITO/ACIGS. Right: good-performing cell (PCE = 10.1%) with ITO/thin Mo/ACIGS.

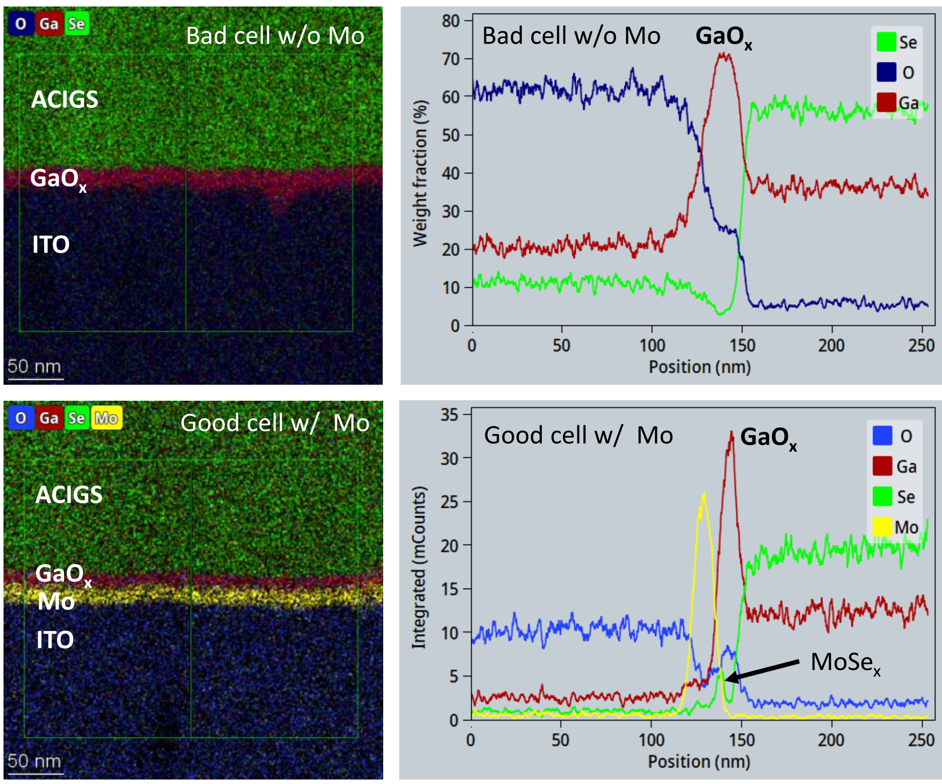
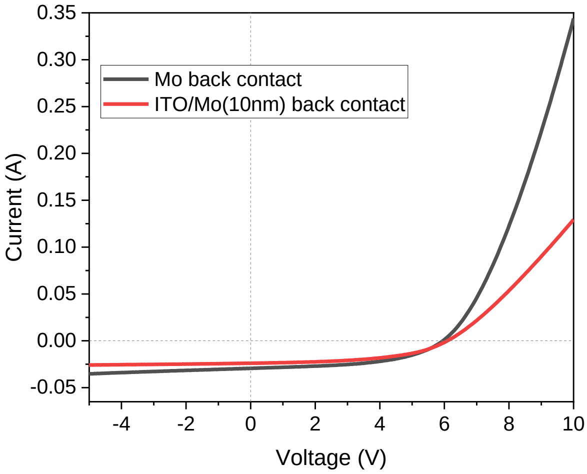


Figure 3: STEM-EDX mappings performed on cross-sections at back contact/absorber interfaces (left column) and corresponding line scans across the ITO/ACIGS (upper right) and ITO/thin Mo/ACIGS (lower right) interface. The formation of GaO_x and $MoSe_x$ is indicated.



	Module with Mo back contact	Module with ITO/Mo(10nm) back contact	reference cell ITO/Mo(10nm)
PCE (%)	8.5	7.1	10.3
FF (%)	50.5	50.2	62.6
V_{OC} (mV)	5952	6092	
V_{OC} per cell (mV)	850	870	860
I_{SC} (mA)	29.3	23.9	

Figure 4: Top: *I-V* curves of 5 × 5 cm^2 wide-bandgap ACIGS modules on ITO/thin Mo (red) and on Mo (black) back contacts. The P1 patterning was performed by laser whereas P2 and P3 was realized by mechanical scribing. Bottom: Corresponding *I-V* data of modules on Mo, on ITO/thin Mo, and data of a reference cell with an ITO/thin Mo back contact from the same ACIGS deposition campaign. The cell-to-module efficiency gap on glass/ITO/thin Mo substrates is around 3% absolute.

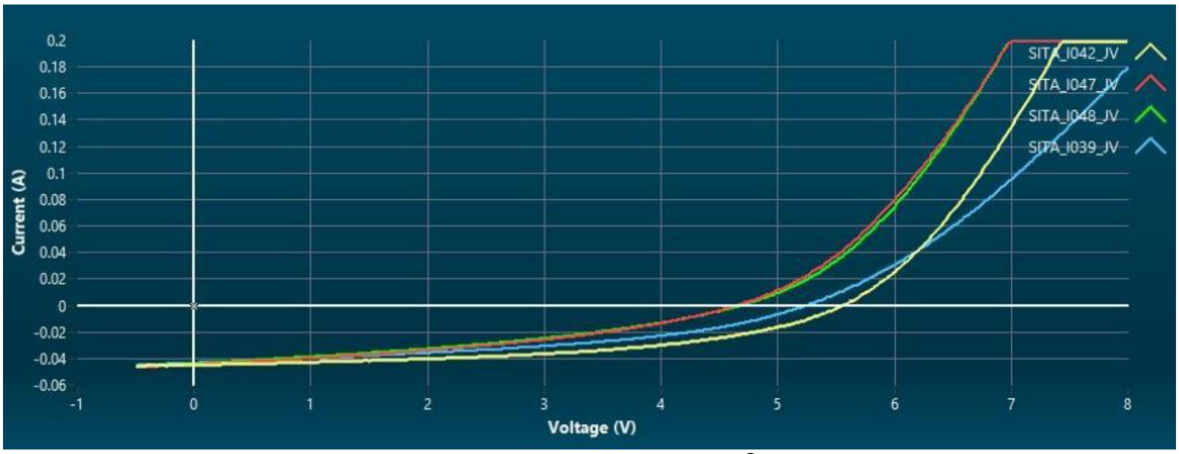


Figure 5: *I-V* curves of four all-laser patterned 5 × 5 cm^2 wide-bandgap ACIGS modules with ITO/thin Mo back contacts. The best performing module (yellow line; ID: SITA_IO42_JV) shows a PCE = 7.4 %, FF = 48.1%, V_{OC} = 5557 mV, and I_{SC} = 44.8 mA.