HL 34: Focus Session: Perspectives in Cu(In,Ga)Se 2

Time: Thursday 15:00–18:00 Location: H33

Invited Talk HL 34.1 Thu 15:00 H33

Super-high efficiency CIGS devices: current status and pathways forward — •Romain Carron — Laboratory for Thin Films and Photovoltaics, Empa, Duebendorf, Switzerland

In this contribution, we discuss the limitations to the photovoltaic performance of Cu(In,Ga)Se2 (CIGS) devices, and possible pathways to boost cell efficiencies towards 25% and beyond. Starting from a comparison of record CIGS cells to other photovoltaic technologies, we evaluate the potential for improvement of each of the individual parameters Voc, Jsc, and FF towards the Shockley-Queisser limit. Then we walk through the main causes for losses for each of the individual parameters, connect them to the last decade's progress, and suggest pathways for future improvements. The open-circuit voltage is discussed in particular depth, including the prediction of its value, the role of impurities and alkali elements in high-efficiency devices, the impact of other absorber modifications, and of advanced optical management. Finally, we discuss how the layer sequence of a CIGS solar cell differs from its functional structure. On this basis, we describe potentially advantageous modifications to the device architecture and the related challenges.

Invited Talk HL 34.2 Thu 15:30 H33

Highlights from the development of the world record Cd-free CIGSSe 30x30cm2 solar module — •Anastasia Zelenina — AVANCIS GmbH, Otto-Hahn-Ring 6, 81739 Munich, Germany

In this contribution, the R&D process of 30x30 cm2 CIGSSe solar modules will be discussed [1]. One of the main advantages of the process is the application of an environmentally friendly dry Zn(O,S) buffer, which is applied as an alternative to the widely used CdS chemical bath deposition (CBD) process. Over the past few years, our development of the 30x30 cm2 CIGSSe modules has been focused on the optimization of the absorber properties. An increased absorber thickness has been applied, with the aim to increase absorption and increase the short circuit current density (JSC). The Jsc-improvement was combined with enhancing the absorber quality through the optimization of the elemental absorber depth profile. The enhanced absorber quality lead to better diode parameters and higher JSC*VOC product values. Furthermore, the absorber surface homogeneity was improved for this increased absorber thickness leading to an enhancement of the Fill Factor (FF) values. The improved absorber homogeneity results mostly from tuning the rapid thermal annealing (RTP) process. The combination of these development steps lead to the achievement of a world record efficiency of 19.8% [2]. This new process developments on 30x30cm2 sized modules will also be the basis for the power development on production-sized modules and will be used for further production upgrades.

[1] "Absorber optimization in CIGSSe modules with a sputtered Zn(O,S) buffer layer at 19% Efficiency", M. Stölzel et al., Proceedings of 36th EU PVSEC, Marseille (2019), p. 590-596, DOI: 10.4229/EUPVSEC20192019-3AO.7.1

[2] NREL Champion Photovoltaic Module Efficiency Chart https://www.nrel.gov/pv/module-efficiency.html

HL 34.3 Thu 16:00 H33

Overcoming current limitations of Cu(In,Ga)Se2 photovoltaic devices — •Daniel Abou-Ras — Helmholtz-Zentrum Berlin für Materialien und Energie GmbH, Hahn-Meitner-Platz 1, 14109 Berlin, Germany

Recently, a review paper entitled "CIGS photovoltaics: reviewing an evolving paradigm" (Stanbery et al 2022 J. Phys. D: Appl. Phys. 55 173001, doi: 10.1088/1361-6463/ac4363) has provided an overview of various issues to be improved in Cu(In,Ga)Se2 (CIGS) thin-film solar cells to reach power-conversion efficiencies of 25% and beyond. The authors of this contribution highlight the necessity of implementing device concepts already in use for the established Si and GaAs photovoltaic technologies also for CIGS devices. Possible ways of enhancing the collection and reducing nonradiative recombination in CIGS solar cells are described. I intend to give a brief insight into the main aspects of this review paper in the planned Focus Session.

HL 34.4 Thu 16:15 H33

Identification of nonradiative recombination centers in CuInSe2 and CuGaSe2 — •Baoying Dou[1], Stefano Falletta[2], Christoph Freysoldt[1], and Jörg Neugebauer[1] — [1]Max-Planck-Institut für Eisenforschung GmbH — [2]Ecole Polytechnique Fédérale de Lausanne

Cu(In,Ga)Se2 is a promising solar absorber for thin-film solar cell applications. Nonradiative carrier recombination is one of the key processes that limits the device efficiency. To achieve high performance, it is crucial to identify the critical defects and quantify their induced non-radiative recombination rates. Prior first-principle calculations proposed that the antisites InCu and GaCu, are donors with a transition levels in the band gap, so they may act as nonradiative recombination centers. However, the existence of transition levels in the band gap does not necessarily trigger nonradiative recombination. Using first-principles methods, we quantitatively show that internal conversion in the neutral charge state to the distorted DX center configuration plays a crucial role in carrier recombination by opening an efficient hole capture pathway. The positive charge state returns to the anti-site configuration without barrier to complete the entire recombination cycle. However, our calculations show that the DX center is only stable in CuGaSe2, not in CuInSe2. We discuss the consequences of these findings for defect engineering in CuInSe2, CuGaSe2, and its alloys.

30 min. break

Invited Talk HL 34.5 Thu 17:00 H33

Digital Twins - a simulation model for Cu(In,Ga)Se2 solar cells of high and moderate efficiency — •Matthias Maiberg[1], Chang-Yun Song[1], Marcin Morawski[1], Felix Neduck[1], Joshua Damm[1], Heiko Kempa[1], Dimitrios Harisko[2], Wolfram Witte[2], and Roland Scheer[1] — [1]Institute of Physics, Martin-Luther-University Halle-Wittenberg, von-Danckelmann-Platz 3, 06120 Halle (Saale), Germany — [2]Zentrum für Sonnenenergie- und Wasserstoff-forschung Baden-Württemberg, Meitnerstraße 1, 70563 Stuttgart, Germany

To overcome the current record efficiency of Cu(In,Ga)Se2 (CIGSe) solar cells, loss mechanisms need to be identified through comprehensive device models. The development of such models, however, is hampered by the complex film microstructure of CIGSe as well as its multi-component device structure. In the first part of our talk, we present one-dimensional models for CIGSe solar cells with high efficiency at around 19 % and moderate efficiency at around 16 %. These models have been obtained by a fitting routine for a set of experimental data which calls the simulation tool Synopsys TCAD as the subprogram. As an outcome, we obtain material parameters of CIGSe. The minority carrier lifetime, for example, exhibits values of >15 ns in the highly efficient cells while it is only 3 ns in the moderately efficient device. In the second part of our talk, we use such digital twin in order to identify loss mechanisms in the solar cells. Here, we address the non-radiative recombination as origin of electronic losses as well as the band gap grading and the window layers as origins for optical losses.

HL 34.6 Thu 17:30 H33

Analysis of the diode factor in CIGSe solar cells — •Valentina Serrano Escalante and Thomas Paul Weiss — University of Luxembourg

In previous work [1] we suggest there is a link between metastable defects and the diode factor. Changes in doping density after light soaking are observed when measuring CV profiles. Those changes are caused by metastable transitions, accounted by the shift of the majority fermi level upon illumination, which in turn increases the diode factor. There are several methods to determine this parameter, namely, from an analysis of the current-voltage curves (JV) [2], using the diode equation or from the slope of the Voc dependence with illumination intensity: Jsc-Voc [3]. Within this work, those methods are tested in a set of CIGSe, Cu poor samples, grown with the three-stage process, with good efficiencies (without any post-deposition treatment) in the range from 15% to 17%. For the analysis of the JV curves under dark, the two-diode model [4] is implemented. Using a 1-diode fit always results in a high value (>1.5), indicating dominant recombination in the space charge region. We use a 2-diode fit to obtain information on the diode factor originating from recombination in the quasi-neutral zone, which is affected by the metastable effects. In the case of JV under illumination, the extraction of the diode factor seems to be hampered by the cross-over between light and dark JV characteristics, which in CIGSe cells might be due to a change in an energetic barrier under light [5]. Therefore, the diode factor under illumination is determined more reliably from Jsc-Voc measurements.

HL 34.7 Thu 17:45 H33

Exact determination of Quasi-Fermi Level splitting from absolute photoluminescence and absorptance spectra — •Sevan Gharabeiki, Taowen Wang, Ajay Singh, Alex Redinger, and Susanne Siebentritt — Department of Physics and Materials Science, University of Luxembourg, 4422 Belvaux, Luxembourg

Photoluminescence (PL) is a powerful tool to investigate the Quasi-Fermi level splitting (QFLS) in absorbers and hence the upper limit of the open-circuit voltage (Voc) in a solar cell. Planck's generalized law and external radiative (ERE) method are the two most common ways to determine the QFLS. Planck's generalized law uses a high energy slope of the PL spectrum and assumes the absorptance (A) to be unity for the photons with energy sufficiently higher than the absorber bandgap. However, in CIGSe solar cells, which employ a graded bandgap, and poly-crystalline perovskite solar cells, the assumption A=1 is no more valid. On the other hand, the ERE method makes use of the radiative bandgap. Many studies consider the PL emission peak position to be the radiative bandgap which is not accurate. Herein, we present a combination of PL and absorptance measurements to accurately determine the QFLS in the CIGSe and methylammonium tin-triiodide Perovskite (MASI) absorbers. Then, we compare our QFLS values from the Plancks generalized law and the ERE method. We emphasize that the radiative bandgap and PL maximum are not the same, and using the PL maximum as a radiative bandgap can result in errors in QFLS extraction.