Perovskite solar cells **Status: accepted, in press**

On top of commercial photovoltaics

Steve Albrecht and Bernd Rech*

*bernd.rech@helmholtz-berlin.de

Helmholtz-Zentrum Berlin für Materialien und Energie

The efficiency of single junction solar cells is intrinsically limited and high efficiency multijunctions are not cost effective yet. Now, semi-transparent perovskite solar cells suggest that low cost multijunctions could be within reach.

In recent years the power conversion efficiency of solar cells based on metal halide perovskite materials was tremendously enhanced to over 22%[1,2] due to the outstanding optoelectronic properties of these semiconductors such as methylammonium lead iodide. In addition, the ease of fabrication when utilizing perovskites paves the way towards very low production costs. Furthermore, the optical band-gap can be tuned by proper choice of composition[2], making this material highly interesting as a partner for $Cu(In,Ga)Se_2$ (CIGS) or crystalline silicon (c-Si) in multijunction solar cells, where each sub-cell absorbs a different portion of the solar spectrum. However, to make efficient multijunction solar cells, the top-cell should ideally leave the rest of the solar spectrum untouched (see Figure 1a). Now writing in *Nature Energy*, Fan Fu, Stephan Buecheler and colleagues[3], from Swiss Federal Labs for Materials Science and Technology (EMPA), report a highly infrared-transparent perovskite solar cell with an outstanding average transmission of over 80% between 800 and 1200 nm together with a remarkable power conversion efficiency of over 16%. This constitutes a crucial step forward to the realization of this fascinating tandem technology.

In the tandem configuration, the perovskite top cell uses the visible part of the sun light and converts it at a high voltage, while the infrared light is transmitted to the partner bottom cell, here CIGS or $CuInSe_2$ (CIS) (see Figure 1a,b). The high transmission in the IR regime is essential to allow high photocurrent generation in the bottom cell. Thus the efficiency potential of the tandem design surpasses the efficiency limit of single junction solar cells. Figure 2 presents the theoretical maximum efficiency of ~33% for single junction solar cells, based on thermodynamic considerations, called the Shockley-Queisser or radiative limit. It also presents an extension of the Shockley-Queisser limit to multijunction solar cells. However, tandem solar cells have a radiative limit of ~44%, triple junctions of ~50% and an infinite stack of junctions can achieve 65% in the limit.

Fabricating a highly transparent perovskite top-cell is challenging: it requires processing a transparent conducting contact (e.g. a transparent conductive oxide, TCO) without damaging the underlying sensitive perovskite or organic charge selective layers. The researchers from EMPA protected the perovskite layer stack with a thin layer of zinc oxide nanoparticles, avoiding direct exposure of the perovskite to harsh conditions during the sputter deposition of the top-contact TCO. Additionally, the researchers use hydrogen doped indium oxide (In_2O_3:H), an emerging TCO material that provides both a high optical transmission and a high electrical conductivity.[4] The successful combination of the semitransparent perovskite top cell with CIGS and CIS bottom cells yields record 4-terminal tandem efficiencies of 22.1% and 20.9% respectively. Remarkably, the efficiency of tandem cells surpasses that of the standalone CIGS or CIS cells by 2.9% and 4.8% respectively, in absolute value.

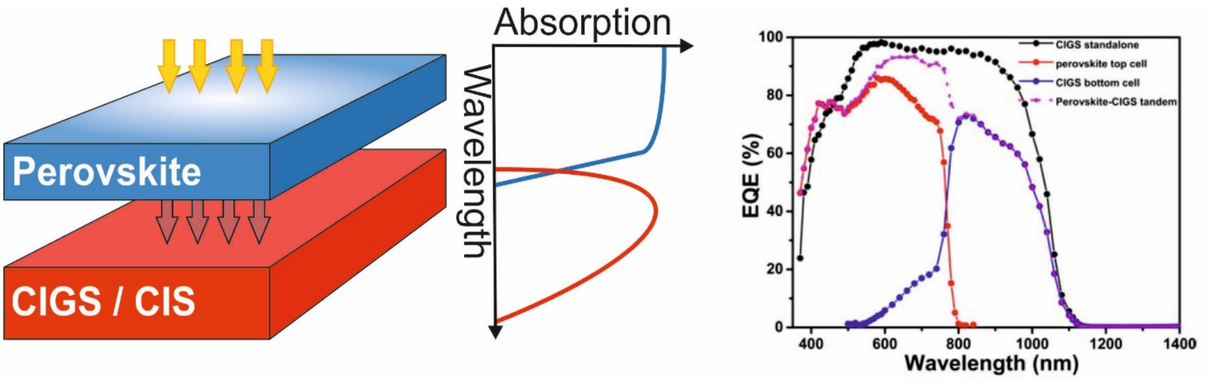

Figure 1: Perovskite/CIGS tandem devices. a) Schematic representation of the perovskite/CIGS tandem design with the perovskite top cell absorbing only the visible part of the incident sun-light leaving the near infrared for the CIGS/CIS bottom cell. b) Tandem cell external quantum efficiency (EQE). The EQEs of the individual sub-cells and the sum of both compared to a standalone CIS solar cell are shown. Panel b is adapted from ref. 3, NPG.

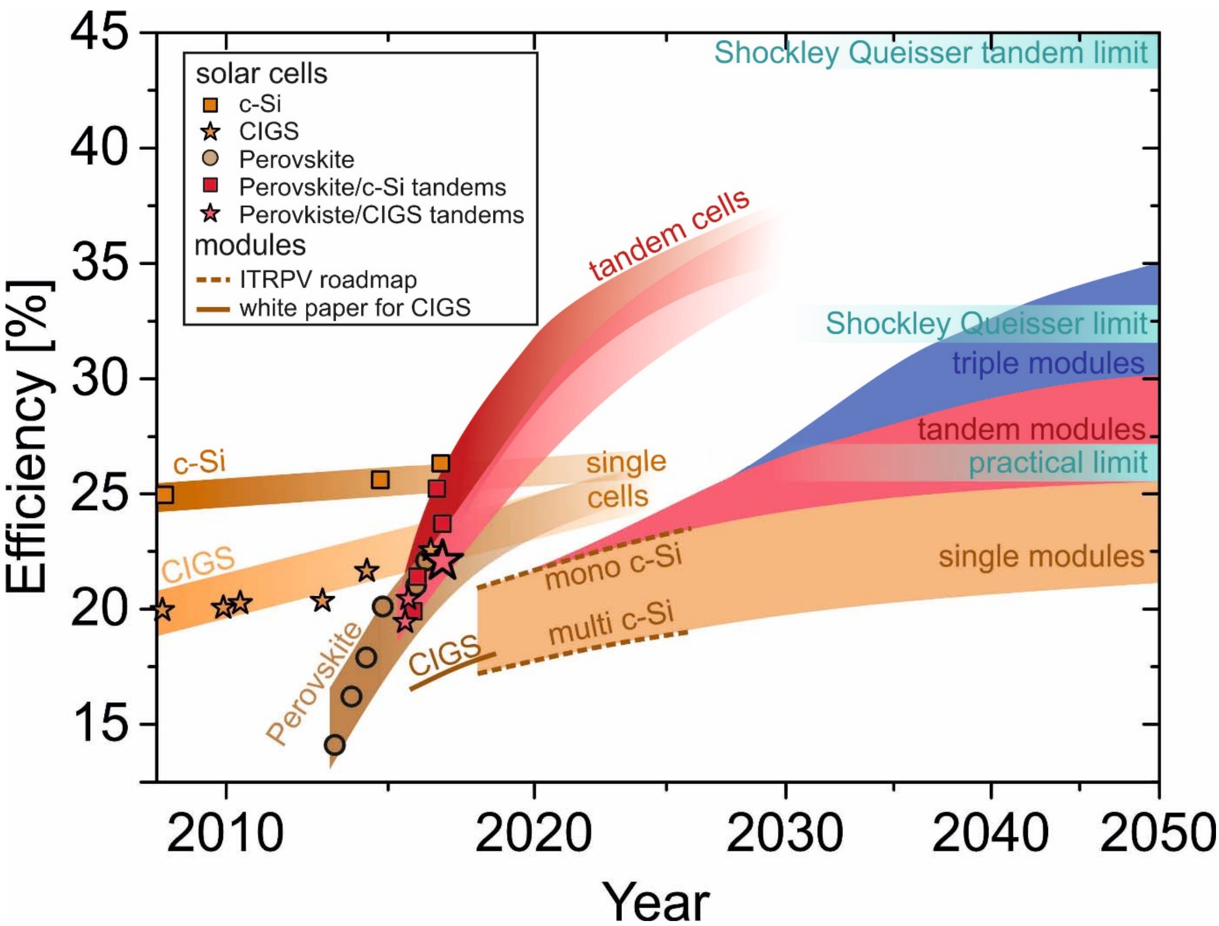

Figure 2: Achieved and predicted efficiency evolution for single and multijunction solar cells. Also shown are the predicted evolutions for single-, tandem- and triple junction modules. Brown symbols indicate the efficiency of lab-based champion solar cells for c-Si (squares), CIGS (stars) and perovskite (circles) single junctions, taken from NREL[1], together with recent records for c-Si[5] and CIGS[6]. Red symbols for perovskite/c-Si[7-11] (squares) and perovskite/CIGS[3,12,13] (stars) are based on recent publications. Predictions for the efficiency range of single junctions modules are represented by the brown colored area based on the ITRPV[14] roadmap for c-Si mono- and multicrystalline modules (dashed brown lines) and the white paper for CIGS[15] roadmap (solid brown line). The different module

technologies, in red and blue colored areas, merge the values extracted from the Agora[16] study for the year 2050.

Fu, Buecheler and colleagues' reported progress on semitransparent perovskite solar cells sets a benchmark for the future development of low cost, highly efficient multijunction modules, which we predict will overcome single junction technologies in the next decades, see Figure 2. The high potential of tandem modules was recently shown by achieving 17.8% power conversion efficiency for a perovskite/CIGS mini module[17]. In 2015 more than 90 % of the global PV world market was dominated by solar modules based on crystalline silicon wafers showing efficiencies between 15 % and 20 % on the module level (typically 1.6 m^2)[14]. According to most established roadmaps,[14] this dominance will be maintained while production cost will continuously decrease and module efficiencies will increase. However, the efficiency of solely silicon-based PV is fundamentally limited by the Shockley-Queisser limit to 32-33 %, and is limited in practice to slightly below 30 % due to Auger recombinations[18]. The efficiency of fully encapsulated solar modules is a few percent lower than that of individual cells due to spacings between the individual cells for cell interconnects and an isolated boundary area at the outer edges required for encapsulation and thus long term stability. Note that all single-junction solar cell and modules are capped by similar limits. However, higher module efficiencies could disproportionally reduce the costs of PV electricity generation by two means: First, module costs are largely determined by non-semiconductor related materials costs like cover glass, encapsulation, framing, and junction boxes; second, on the system level, higher module efficiencies reduce installation and transport costs as well as area use.

Tandem and triple-junction solar cells are the most viable and proven approach to overcome the limitations of single junction technologies as already demonstrated by III-V semiconductor combinations. However, current III-V semiconductor technology is still far away from being cost effective for large-scale, flat-panel PV applications. Fu, Buecheler and colleagues show that perovskite solar cells can be implemented as a drop-in technology on top of Si and/or CIGS solar cells and could speed up the development of PV to become the cheapest and most ubiquitously applied energy source. The race for record efficiencies has only started very recently with the first perovskite/silicon and perovskite/CIGS tandem cells published in 2015[13]. In future developments, this race has to overcome the obstacles of large scale processing, long term stability[2] under environmental conditions and compatibility with system requirements such as high system voltages – and life cycle assessments have to prove feasibility for the whole production, application and disposal circle.

(1) http://www.nrel.gov/ncpv/images/efficiency_chart.jpg, accessed November 16, 2016.
(2) Saliba, M.; Matsui, T.; Domanski, K.; Seo, J.-Y.; Ummadisingu, A.; Zakeeruddin, S. M.; Correa-Baena, J.-P.; Tress, W. R.; Abate, A.; Hagfeldt, A.; Grätzel, M. *Science* **354**, 206-209 (2016).
(3) Fu, F. *Nature Energy*, *xx*, xx (2016).
(4) Takashi, K.; Hiroyuki, F.; Michio, K. *Japanese Journal of Applied Physics* **46**, L685 (2007).
(5) http://www.kaneka.co.jp/kaneka-e/images/topics/1473811995/1473811995_101.pdf, accessed November 21, 2016.
(6) https://www.zsw-bw.de/fileadmin/user_upload/PDFs/Pressemitteilungen/2016/pr09-2016-ZSW-WorldRecordCIGS.pdf, accessed November 21, 2016.
(7) Albrecht, S.; Saliba, M.; Baena, J. P. C.; Lang, F.; Kegelmann, L.; Mews, M.; Steier, L.; Abate, A.; Rappich, J.; Korte, L. *Energy & Environmental Science*, **9**, 81-88 (2016).
(8) Chen, B.; Bai, Y.; Yu, Z.; Li, T.; Zheng, X.; Dong, Q.; Shen, L.; Boccard, M.; Gruverman, A.; Holman, Z.; Huang, J. *Advanced Energy Materials* **6**, 1601128 (2016).
(9) Werner, J.; Barraud, L.; Walter, A.; Bräuninger, M.; Sahli, F.; Sacchetto, D.; Tétreault, N.; Paviet-Salomon, B.; Moon, S.-J.; Allebé, C.; Despeisse, M.; Nicolay, S.; De Wolf, S.; Niesen, B.; Ballif, C. *ACS Energy Letters* **1**, 474-480 (2016).

(10) Werner, J.; Weng, C. H.; Walter, A.; Fesquet, L.; Seif, J. P.; De Wolf, S.; Niesen, B.; Ballif, C. *J Phys Chem Lett*, *7*, 161-166 (2016).
(11) http://web.stanford.edu/group/mcgehee/research.html accessed November 16, 2016.
(12) Fu, F.; Feurer, T.; Jager, T.; Avancini, E.; Bissig, B.; Yoon, S.; Buecheler, S.; Tiwari, A. N. *Nat Commun*, *6*, 8932 (2015).
(13) Kranz, L.; Abate, A.; Feurer, T.; Fu, F.; Avancini, E.; Löckinger, J.; Reinhard, P.; Zakeeruddin, S. M.; Grätzel, M.; Buecheler, S.; Tiwari, A. N. *The Journal of Physical Chemistry Letters*, *6*, 2676-2681 (2015).
(14) http://www.itrpv.net/Reports/Downloads/, accessed November 16, 2016.
(15) http://cigs-pv.net/download/, accessed November 16, 2016.
(16)http://www.acatech.de/fileadmin/user_upload/Baumstruktur_nach_Website/Acatech/root/de/Publikationen/Materialien/ESYS_Technologiesteckbrief_Photovoltaik.pdf, accessed November 16, 2016.
(17) http://www.kit.edu/kit/english/pi_2016_133_record-for-perovskite-cigs-tandem-solar-module.php, accessed November 21, 2016.
(18) Swanson, R. M. In *Photovoltaic Specialists Conference, 2005. Conference Record of the Thirty-first IEEE* 2005, p 889