Progress and trends in CIGS and perovskite/CIGS PV

S. Nishiwaki, T. Feurer, F. Fu, S. Pisoni, S. Buecheler, A. N. Tiwari, Laboratory for Thin Films and Photovolatics, Empa-Swiss Federal Laboratories for Materials Science and Technology, Duebendorf, Switzerland

ABSTRACT

Improvements in the efficiencies of CIGS thin-film solar modules and the industrial production status of a few select companies are briefly reviewed. Industrial sub-module efficiencies of 19.8% on 7 x 5cm², 19% on 30 x 30cm² and 17% record efficiency on large-area industrial size (0.940m²) as well as the production volume ramp-up show a strong progressive trend in the industrial manufacturing sector. Roll-to-roll manufacturing of solar modules on metal and polymer foils is gaining industrial maturity as the modules find attraction for numerous applications where lightness and flexibility in form factor offer distinctive advantages. Construction of Net Zero Energy Buildings, reduction of CO_2 footprint and the integration of PV in buildings and vehicles open new application opportunities. However, low cost installation and high efficiency are needed, and future research objectives address those topics of low cost and high performance. While lab-scale solar cell efficiencies of up to 22.6% on glass and 20.4% on flexible polymer are achieved, further research efforts are directed towards finding ways for 25% efficiency with single junction CIGS and 30% with tandem solar cells combining semitransparent perovskite with CIGS solar cells.

Introduction

Thin-film solar cells based on chalcopyrite semiconductor Cu(In,Ga)(S,Se)$_2$ compound (hereafter called CIGS or CIGSeS irrespective of the exact composition) have continuously drawn interest because of their progressively increasing high photovoltaic conversion efficiencies and the merits of long-term performance stability, high energy yield, low cost production potentials and other advantages for industrial manufacturing and application of solar modules [1]. Installation of solar modules on buildings and transport vehicles is gaining momentum in achieving CO_2 footprint reductions and for construction of new Nearly Zero Energy Buildings by 2020, according to the directives of the EU Commission. CIGS solar modules are especially attractive for such applications. Most of the CIGS companies have already demonstrated installations of aesthetically beautiful and energy efficient modules developed on glass as well as flexible foils.

The CIGS Whitepaper (http://cigs-pv.net/cigs-white-paper-initiative/) jointly prepared in 2015 by a large group of experts from academia and industries highlighted the report with caption of "The time to invest is now", giving all the good reasons which include the inherent advantages of large-area, scalable thin-film deposition technologies for production of low-cost solar modules and manufacturing on glass as well as flexible foils. Recent reports indeed show that investments in CIGS manufacturing technologies have started picking up. Amongst several announcements only a few are mentioned in this report. European equipment suppliers such as Singulus, FHR-Centrotherm and Midsummer have reported purchase orders for their deposition equipment in Asia. Singulus is providing a different type of thin-film coating equipment for large volume production plants to be built in China by CNBM Company using the CIGS technology developed by AVANCIS.

The CIGS solar cells can be grown with a variety of deposition methods but high-temperature co-evaporation of elements and sputtering metals or alloys followed by selenization and sulfurization in some cases are the two most commonly used methods for the growth of absorber layers for high-efficiency solar cells. Generally high-efficiency solar cells on glass and stainless steel substrates are developed with high temperature (>550°C) CIGS processing while low temperature (about 450°C) CIGS deposition is used for polymer films. The most commonly used back and front electrodes are Mo and transparent conducting ZnO:Al or ZnO:B, respectively. Chemical bath-deposited CdS is used for junction formation with CIGS absorber but alternatively layers and deposition methods are also used, albeit with somewhat compromised efficiency values.

Industrial production of solar modules can be divided into three categories depending on the choice of substrate: glass for rigid modules or metal or polymer foils for lightweight flexible solar modules with roll-to-roll manufacturing. While production of solar modules on glass has reached an adequate level of industrial maturity for large volume production, the roll-to-roll manufacturing of flexible solar modules is still in the phase of evolution – with most of the plants operating below 10-50MW production capacity. Below is a status summary of a few selected CIGS module production companies.

CIGS solar module production on glass substrates

Manz AG in Germany, provider of a CIGS turnkey production plant, stands on a successful track record of several years of development work at Stuttgart University, ZSW (Center for Solar Energy and Hydrogen Research Baden-Württemberg) and Würth Solar in Germany. At the CIGSfab of Manz, the CIGS absorber layers are grown by co-evaporation of elements and chemical bath deposition is used for CdS buffer layer coating. With module efficiencies of up to 16% from its CIGSfab plant Manz is expanding R&D and production operations in partnerships with Shenhua Group, Shanghai Electric and Beijing Future Science Park Development Group in China. ZSW, a pioneering institute with numerous contributions in the advancement of CIGS, is an exclusive R&D partner of Manz and has been leading the progress of CIGS solar cells on glass substrates with a current world record efficiency of 22.6%. The two are collaborating for further improvement of module efficiencies.

Solar Frontier in Japan is the largest manufacturer of CIGSeS PV modules with a current production capacity of about 1GW per year. Solar Frontier has been consistently improving the conversion efficiency of solar cells, submodules and large area production modules. In a three step process, high temperature selenization of sputtered metal precursor followed by sulfurization, is used for the coating of CIGSeS absorber layer. The conversion efficiencies of 22.3 and 22.0% on CdS-buffered and Cd-free cells were achieved in 2015-2016 [2,3], and by transferring these technologies into the submodule development, 19.2 and 19.8% efficiencies have been achieved on 30 × 30 and 7 × 5cm^2-sized Cd-free sub-modules and mini-modules, respectively [2–5]. The two devices are basically identical except for the alkali metal treatment only applied on the mini-module. Recently, Solar Frontier announced the launch of a new model (SFK series) whose module output is ranged from 180W (14.7%$_{TA}$) to 185W (15.1%$_{TA}$), which has an improvement of 10W from the previous model with the same size [6]. The upgrade of the module output was mainly brought about by transferring technologies developed in the previous sub-module research. Figure 1 shows the past pgoress and future projection for Solar Frontier's technology. Solar Frontier is currently targeting a 25% cell efficiency and 220W module output in 2020. Solar Frontier's research has been performed under Japanese national NEDO project, which is targeting levelized cost of electricity (LCOE) of 14 and 7 yen/kWh in 2020 and 2030, respectively. The former and latter targets are comparable to the business electricity price (grid parity) and conventional thermal power (generation parity) in Japan, respectively.

Solibro is another leading CIGS module manufacturing company, with a 145MW production capacity plant in Thalheim, Germany, using co-evaporation technology for the growth of absorber layers. Solibro has a close partnership with Uppsala University, Sweden, where innovative R&D on CIGS solar cells has resulted in breakthroughs and advancements in the technology. In 2014 Solibro announced a 21.0% aperture area efficiency on 1cm^2 area cell and then

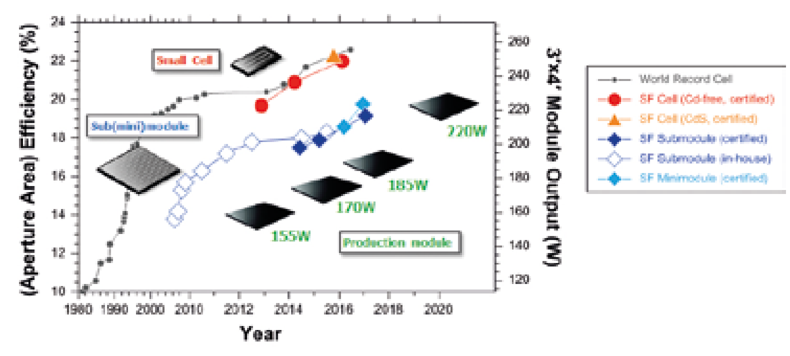

Figure 1: Progress and projection of Solar Frontier's technology in lab and on production scale. Figure supplied by Hiroki Sugimoto and Takuya Katou, Solar Frontier.

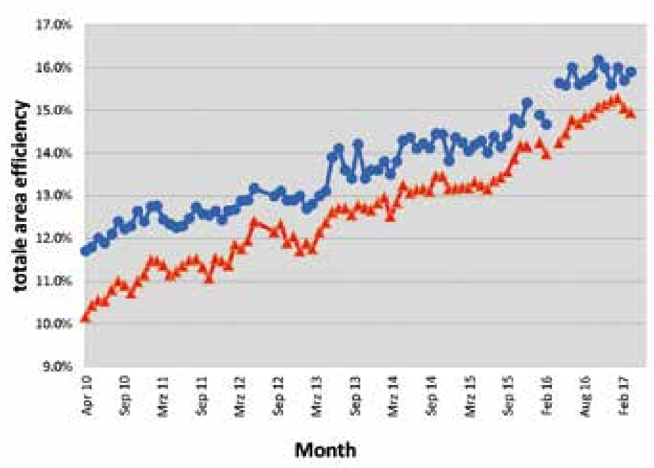

Figure 2. Production efficiency evolution at Solibro of champion modules (blue dots) and monthly average (red dots). Figure supplied by Lars Stolt, Solibro.

a 30 x 30cm^2 sub-module with 18.8% aperture area efficiency (internal measurement). The average efficiency of Solibro´s modules have progressed to about 15% (Figure 2).

Solibro has recently announced a new record efficiency of 17% on a 0.940m² module size with 159.6Wp power, independently measured by TÜV Rheinland, Germany; 17.9% is the measured aperture area efficiency of such a module. The module was manufactured at the Solibro production plant in Germany using standard production equipment and processes, which indicates the capability of the company to produce high-efficiency modules comparable to the best commercial polycrystalline silicon wafer modules. Solibro is also developing solar modules with aluminium grids and thinner TCO. The company has successfully applied metal grid on large size modules and reported a gain ≥ + 0.7 % in absolute total area efficiency with this approach.

AVANCIS in Germany develops and manufactures its CIGSeS modules using the AVANCIS 'SEL-RTP' process (stacked elemental layer – rapid thermal processing) in combination with a dry Cd-free PVD buffer process, namely the proprietary thermal evaporation of In_xS_y:Na. The efficiency development of the CIGSeS technology is driven in the Munich-based R&D pilot line based on medium-sized 30 x 30cm^2 CIGSeS modules. Figure 3 depicts the evolution of the externally certified champion efficiencies of AVANCIS' 30 x 30cm^2 modules over the past years. The graph shows the steady increase of the efficiencies without an indication for any saturation upto now.

The efficiency development on 30 x 30cm^2 modules resulted in parallel in a steady increase of the performance of the AVANCIS' PowerMax product family with power classes now reaching 150W or 15.7% aperture area efficiency. The production capacity of AVANCIS is 100MW/year each in Torgau, Germany, and in Ochang, South Korea, and now AVANCIS, a part of the CNBM Group, is expanding production capacity to 1.5GW/year in Bengbu, China, and 1GW/year in Meishan, China.

The CIGSeS modules of AVANCIS foster the company's premise of a thin-film technology to be used as a premium component for the building industry: in the construction of solar active facades for public, commercial and residential buildings. The flexibility in colour, transparency, size and shape which is required for the building industry is per se compatible with CIGSeS thin-film processing on glass substrates. For this purpose, AVANCIS has recently launched a new architects panel for solar facades with variable colours. Its PowerMax Skala is a first-of-a-kind product with frameless design and backrails, and has received the German building code approval (abZ).

The PV module as a solar active building material embedded into the roof or facade imposes new demands for material research for the module itself and for its interaction with the other building materials. For example, aesthetic product attributes like homogeneity, gloss and angle dependency are becoming at least coequal to electrical specifications. In this emerging market, CIGS or CIGSeS modules can substantiate their unique aesthetic properties besides their electrical pros like high shading tolerance, good low light characteristics, low temperature coefficient and broad spectral response.

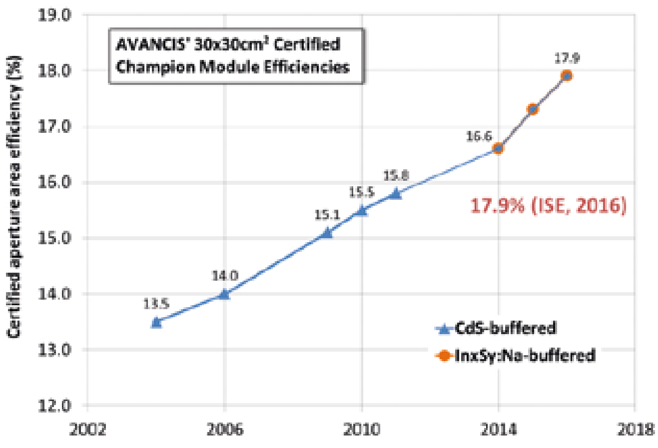

Figure 3. Externally certified champion efficiencies of AVANCIS' 30 x 30cm² CIGSSe modules. Blue triangles represent modules with CdS buffer layer, orange dots In_xS_y:Na-buffered modules. Figure supplied by Thomas Dalibor and Jörg Palm, AVANCIS.

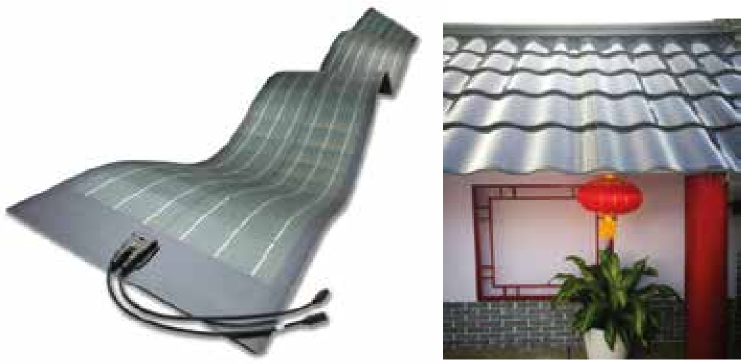

Figure 4. Flexible CIGS solar modules on steel foils (left picture from Urs Schoop, Global Solar Energy) and Miasole-Hanergy's solar tile (right picture from Atiye Bayman, MiaSolé).

Flexible CIGS modules with roll-to-roll manufacturing process

Flexible lightweight CIGS solar modules produced with roll-to-roll manufacturing offer numerous advantages for potentially low cost production of solar modules, and they enable new application possibilities, especially where much heavier rigid modules are not suited or when easy customization in terms of shape/size/power is desired. Such modules are specifically attractive for applications in buildings (BIPV, BAPV and rooftops), vehicles, airships, portable power, etc. Production of flexible solar modules with roll-to-roll processing is challenging because of the lack of appropriate quality equipment and processing knowhow, especially on the topics of CIGS growth, interconnect technology, low cost transparent moisture barrier films, and substrate foils. Realizing the great potential of flexible lightweight solar cells as a differentiated product for hugely untapped market solar cell development work started a few years back and now companies have started production on limited scale. Choice of flexible substrate- metal or polymer, CIGS absorber deposition method and interconnect technology for module making are the key differentiators for companies.

Global Solar Energy, USA, is the first company to commercially produce flexible CIGS solar cells on stainless steel foil with roll-to-roll manufacturing methods and open the market with applications where solar modules with lightweight and flexibility features are desired. CIGS layers are deposited by co-evaporation of elements in a roll-to-roll coating system. Large area solar cell strips are cut from the roll and they are subsequently stringed together with metal grid/wire to make large area modules (Figure 4). Production modules with aperture area efficiencies up to 16.3% are reported and its modules are fully certified to UL and IEC standards.

Global Solar Energy has commissioned two fully automated Integrated Cell Interconnect (ICI) manufacturing lines with combined capacity of 50MW/year in Tucson, Arizona, and the company is expanding capacity in China for volume manufacturing. In 2013 Global Solar Energy was acquired by Hanergy group. The company is currently improving the production technology

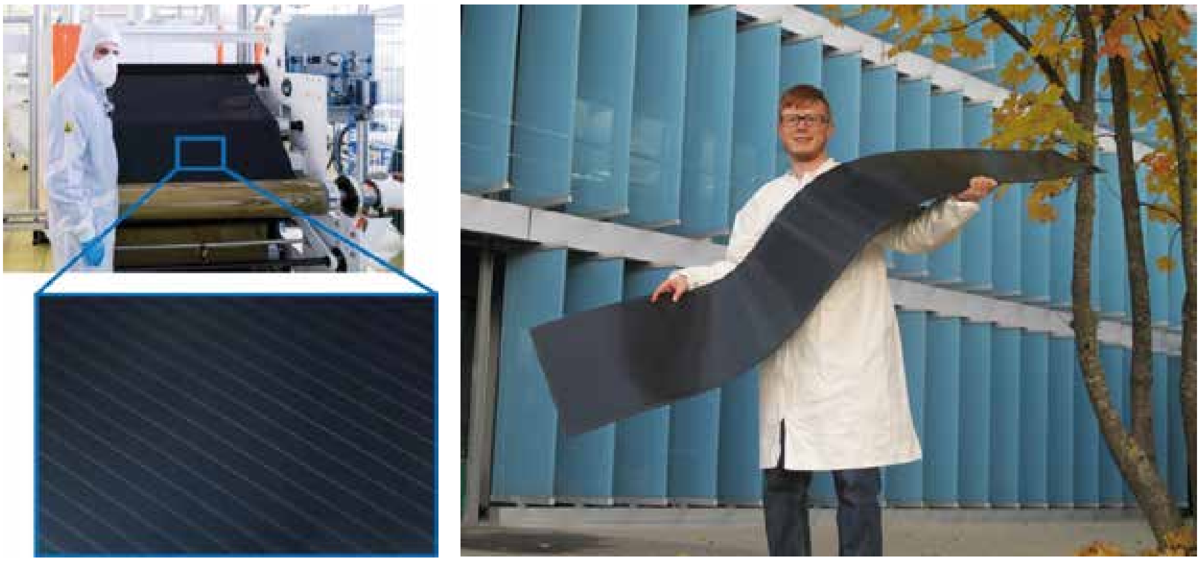

Figure 5. Flisom's laser patterning system for monolotithich interconnect of cells on 1 meter wide rolls (left) a large-area flxible solar module produced on polymer film (right).

for higher performance and lower cost and it aims to reach to the production cost below US$0.50/Wp in future.

MiaSolé, owned by Hanergy company, has a production plant in Sunnyvale, California, and has reported 19% efficiency CIGS cells (1sq cm area cell and measured by NREL) using a sputtering method and a corresponding 17.4% module 0.49sq m) efficiency measured by Fraunhofer ISE. The MiaSolé FLEX series modules are the solar industry's highest efficiency flexible CIGS thin-film modules on the market today with a production conversion efficiency of 16.5%.

All MiaSolé PV products use the flexible cells manufactured with MiaSolé's proprietary deposition equipment called the Roll Coater. Roll Coater is an integrated multi-chamber tool where all the films that comprise the solar device are deposited sequentially on a 50 micron thick stainless steel foil. Solar cells are finished with a low resistance collection grid that is applied by roll lamination. This basic cell technology has been used since 2009 when the first product was introduced to the market. MiaSolé provides both rigid glass and flexible lightweight products in a variety of form factors. In the last three years the company has focused on product development for applications in distributed power generation and off-grid applications.

MiaSolé has demonstrated steady increases of aperture area conversion efficiency in its products since 2009, from 11% to 16.5% today, and is planning to get to 17.5% in 2018. MiaSolé is also a provider of manufacturing equipment for PV factories that use MiaSolé technology and it is seeing strong business growth in China with a >2GW of backlog.

Flisom in Switzerland is a spin-out company of ETH Zurich and has close partnership with Empa-Swiss Federal Laboratories for Materials Science and Technology, which holds the 20.4% efficiency world record for flexible CIGS solar cells processed with a low temperature (~450°C) process. Flisom uses co-evaporation of elements and alkali post-deposition treatment (PDT) for deposition of CIGS absorber layers on polyimide films in roll-to-roll coating system for one meter width rolls. The company has developed its own proprietary roll-to-roll manufacturing equipment and processes for production of monolithically interconnected flexible solar modules on polymer film. Laser patterning not only enables high throughput production but also provides aesthetically nice looking uniform dark appearance (Figure 5).

Figure 6. Lightweight flexible solar modules of Flisom for BIPV applications in EU-PVSITES project. Source: PVSITES/Flisom.

Polymer films, in contrast to steel foils, do not require barrier coatings against detrimental metal impurities from the substrate and also provide an insulating surface as needed for monolithic interconnections. However a low temperature CIGS deposition process is needed for polyimide films. With low temperature grown absorbers in one meter wide roll-to-roll coating system solar cells of 16.8% efficiency (without anti-reflection coating) have been achieved. Laser patterned monolithic sub-modules and large area modules of 12% to 15%, depending on the module area, have been achieved. Flisom, while further improving the efficiency and ramping up production volume on 15MW plant, has started commercial supply of lightweight flexible solar modules for diverse applications including roofs and facades of buildings. Within the EU-PVSITES project Flisom is developing lightweight flexible solar modules for different types of BIPV applications including curved roofs (Figure 6). PVSITES consortium is working on an "industrial joint approach to provide robust BIPV technology solutions and the ultimate goal is to significantly enhance BIPV market deployment in the short and medium term". The objective of the PVSITES project is driven by the needs for Nearly Zero Energy Buildings according to the directives of the EU commission.

Ascent Solar in the USA and Sunplugged in Austria are the other companies involved in manufacturing of flexible CIGS solar cell on polymer films. Swedish company Midsummer is a supplier of equipment and offers DUO systems with a capacity of 5MW/year. Midsummer does not use a roll-to-roll manufacturing method, rather an all-sputtering process in which cells are developed on 15.6 x 15.6cm^2 stainless pieces resembling silicon wafers that are subsequently stringed together to make solar modules. Midsummer has reported a 16.4% total area efficiency on 6"cells. Besides them there are some other stealth mode or early stage companies developing technologies for industrial production of CIGS modules.

Solar cell efficiency improvements and Sharc25

Recent improvements in the efficiency of CIGS solar cells were triggered by a post deposition treatment (PDT) first invented by Empa where they applied KF PDT to achieve a breakthrough with 20.4% efficiency cells on polymer film with a low temperature process. The alkali PDT method was later adapted and applied by several research groups for efficiency improvements. Solibro and Solar Frontier have reported 21% and 22.3% efficiency cells, respectively, with the application of KF PDT on their absorber layers.

In June 2016 an independently certified cell record efficiency of 22.6% with anti-reflective coating (ARC) was achieved by ZSW with a CIGS absorber, which underwent an in-situ RbF-PDT process and involved a solution-grown CdS buffer in combination with a (Zn,Mg)O high-resistive layer and a ZnO:Al as front contact. It should be noted that CIGS cell efficiencies above 20% with ARC could be achieved with KF-PDT, RbF-PDT, and even CsF-PDT of the CIGS absorber layer, whereas Na was supplied from the glass substrate [8]. In addition, many single cells were fabricated with high reproducibility at ZSW with an efficiency level around 22% (with ARC).

Even such high efficiencies achieved for CIGS thin-film solar cells reveal that there is still a prominent gap between experimental results and the theoretical Shockley-Queisser limit of 33% for single-junction solar cells. This was one of the reasons why the EU funded project "Sharc25" was initialized in 2015 with the goal to challenge the key limiting factors in state-of-the-art CIGS solar cells, namely non-radiative carrier recombination and light absorption losses in emitter layers.

Sharc25 is coordinated by the Center for Solar Energy and Hydrogen Research Baden-Württemberg (ZSW), focusing mainly on high-temperature CIGS deposition and device fabrication. The consortium consists of 11 research partners from eight European countries. The idea behind this EU-funded project is to pool these organizations' multidisciplinary skills in a bid to push the CIGS cell performance towards 25%.

ZSW's partners in this endeavor are scientific coordinator of the project, Empa-Swiss Federal Laboratories for Materials Science and Technology, with special expertise on low-temperature CIGS growth, and IMEC in Belgium, which contributes on the development of passivation layers for the CIGS absorber using skills borrowed its work in silicon PV. They could successfully adapt a standard technique for structuring to the comparably rough front side of the CIGS absorber to realize point contact openings in passivation layers grown by ALD.

In addition, partners with special and often unique expertise in materials and device characterization are on board: the HZB (Helmholtz-Zentrum Berlin für Materialien und Energie, D) with lab- and synchrotron-based x-ray and electron spectroscopies, and the International Iberian Nanotechnology Laboratory INL, with expertise in Kelvin probe force microscopy, both for CIGS surface and CIGS/buffer interface characterization. They could for instance reveal that there is a distinct difference in the first growth stages of CBD CdS and Zn(O,S) buffer layers on CIGS with RbF-PDT in terms of chemical composition at the interface and p-n junction formation. The University of Luxembourg, specialized in photoluminescence and admittance measurements, is also on board to analyze bulk absorber properties, and the University of Rouen, France, to perform highly spatially resolved atom probe tomography analyses on the CIGS absorber, revealing for example the distribution of alkali metals on a nanometer scale; thus, Rb intentionally introduced by RbF-PDT process accumulates at the CIGS grain boundaries and also at dislocations. These in-depth analyses were supported by ab-initio calculations with density functional theory (DFT) carried out by Aalto University from Finland, with a focus on intrinsic and extrinsic defects in CIGS and 2D/3D device simulations performed at the University of Parma, Italy. A main result from DFT is that Li and Na compared to Rb and Cs have distinct effects on the structure of the $CuInSe_2$ absorber whereas K lies in between [9]. The companies Flisom and Manz assess results in terms of exploitation, manufacturability and transferability to production.

Launched in May 2015, the project will run for 3.5 years with funding sourced from the EU research framework programme Horizon 2020 and the Swiss government.

Towards 30% efficiency tandem solar cells:

The power conversion efficiency of single junction solar cells is intrinsically limited by the trade-off between absorption losses where photons with energies lower than the bandgap are not absorbed, and thermalization losses where hot carriers excited by high-energy photons rapidly thermalize to the bandgap energy of the absorber, releasing the extra energy as heat. In 1961, Shockley and Queisser calculated the theoretic limit of power conversion efficiency for a p-n junction solar cell to be around 33% considering only radiative recombination as required by the principle of detailed balance [10].

A viable way to overcome the S-Q limit for a single junction device is stacking solar cells with different bandgaps in a tandem (the number of junction equals two) or multi-junction structure, where the thermalization loss is minimized. In a tandem configuration, a wide-bandgap solar cell is stacked on top of a narrow-bandgap solar cell, so that the wide-bandgap top cell absorbs the high energy photons with minimized thermalization loss and transmits low energy photons into the narrow-bandgap bottom cell. The tandem and multi-junction concept has been successfully realized on expensive single-crystal III-V materials, and attempts to develop cheap tandems based on polycrystalline thin-film solar cells has had limited success mainly due to the lack of suitable wide-bandgap top cells.

This situation has changed recently with the advent of emerging perovskite solar cells. Perovskite solar cells have several distinct advantages, such as wide bandgap, which is tunable over a broad energy range, and high efficiency, which make them an ideal candidate as top cells in tandem configuration with CIGS bottom cells to realize highly efficient and cost-effective thin-film photovoltaics. Tandem solar cells can be connected in a four-terminal configuration (Figure 7) or two-terminal configuration, each with their own advantages and disadvantages. In the four-terminal configuration tandem, the top and bottom cells are individually processed and mechanically stacked together, which means the top cell and bottom cell are electrically independent and optically coupled. This type of tandem is easy to make and has less restriction in design as no tunnel junction or recombination layer is needed, and no current matching is required. However, more electrical components, including maximum power point trackers and converters,

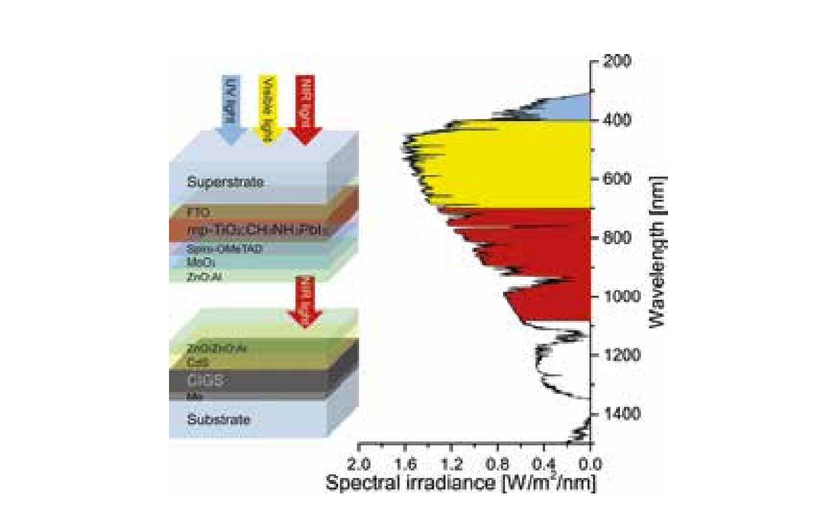

Figure 7. Schematic illustration of four-terminal perovskite-CIGS tandem solar cells. Reproduced with permission from [11].

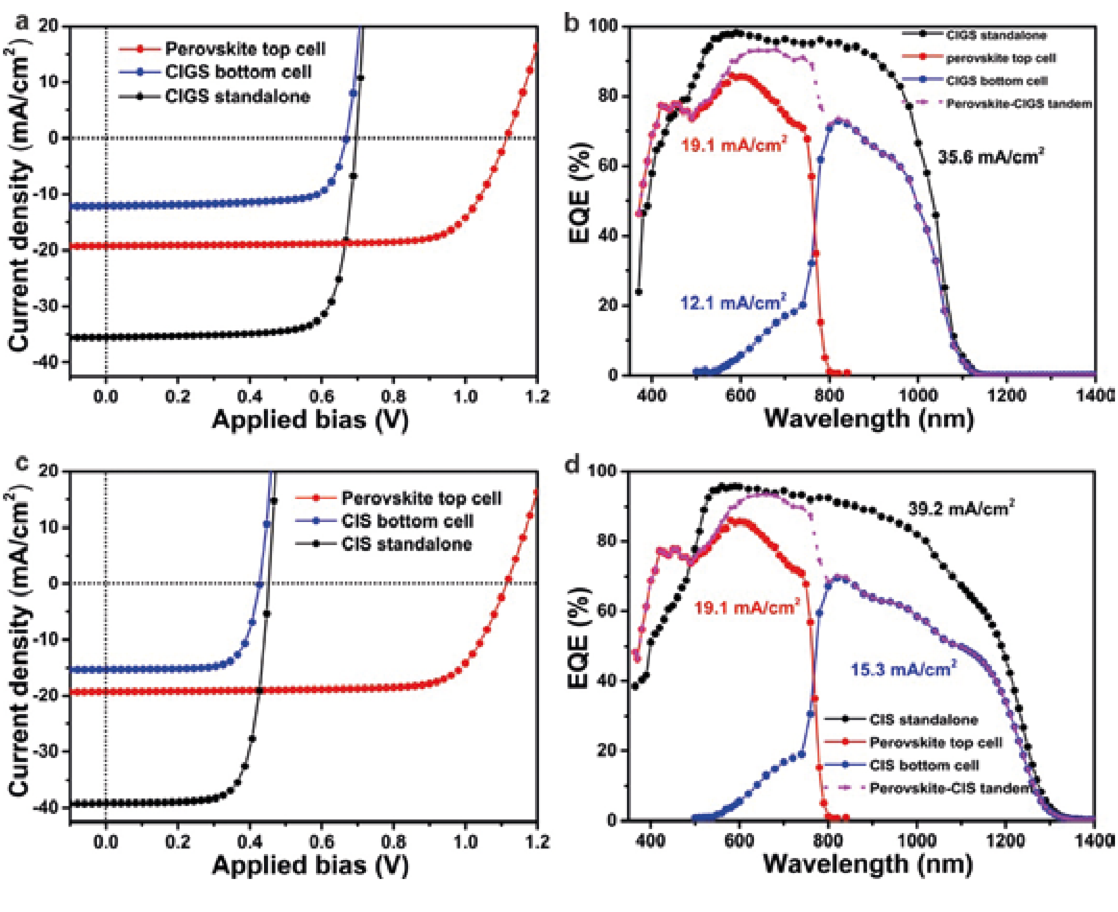

Figure 8. Current density-voltage curves (a) and EQE spectra (b) of the perovskite-CIGS in four-terminal tandem configuration; current density-voltage curves (c) and EQE spectra (d) of the perovskite-CIS in four-terminal tandem configuration. Reproduced with permission from [12].

Solar cell	V_{OC} (V)	J_{SC} (EQE) (mA/cm^2)	*FF* (%)	*Eff* (%)	MPP (%)	Cell area (cm^2)
Perovskite top cell	1.116	19.1	75.4	16.1	16.1	0.286
CIGS (standalone)	0.696	35.6	77.3	19.2	19.2	0.213
CIGS bottom cell	0.669	12.1	73.6	6.0	6.0	0.213
Perovskite-CIGS four-terminal tandem					**22.1**	
CIS (standalone)	0.453	39.2	73.1	13.0	13.0	0.213
CIS bottom cell	0.428	15.3	73.1	4.8	4.8	0.213
Perovskite-CIS four-terminal tandem					**20.9**	

Table 1. Photovoltaic parameters of perovskite-CI(G)S four-terminal tandem solar cells.

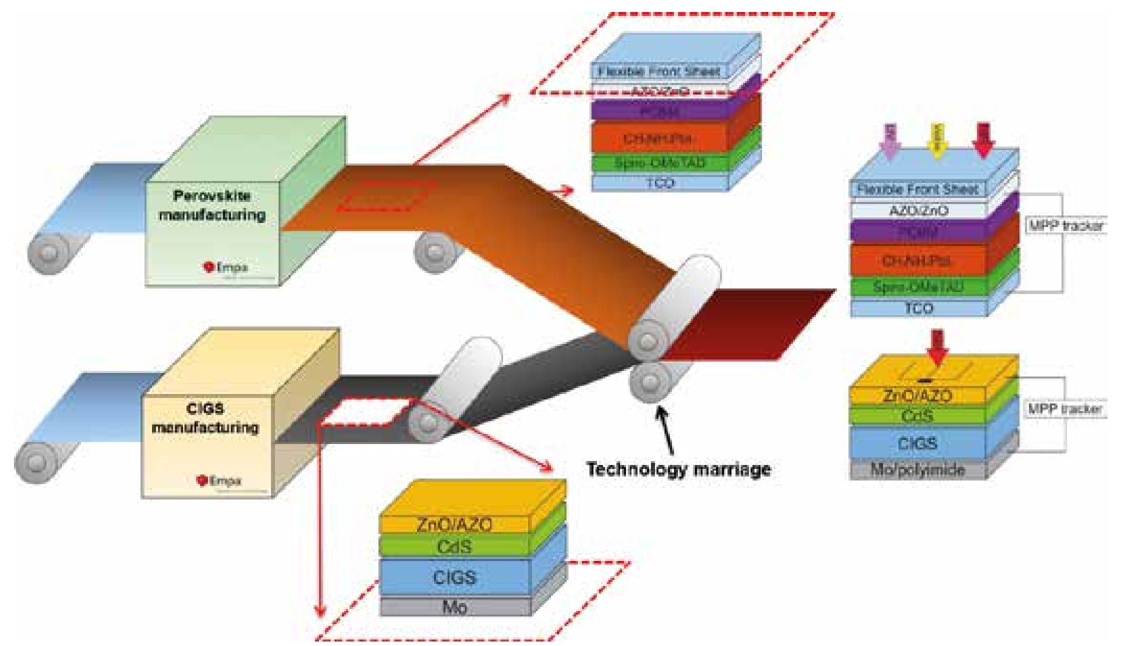

Figure 9. Schematic illustration of future roll-to-roll manufacturing of flexible Perovskite-CIGS polycrystalline thin-film tandem solar cells. The perovskite top cell and CIGS bottom cell could be fabricated individually on flexible substrates and then laminated together to make tandem device.

are needed, which will add additional cost. Moreover, the use of three TCOs (transparent conducting oxides) in four-terminal tandems will also introduce strong parasitic absorption. In the two-terminal configuration (monolithic tandem), the top and bottom cells are deposited sequentially on top of each other. There is only one electric circuit in the tandem device and only one TCO is needed, therefore reducing the cost and optical loss. This architecture requires a tunnel junction or recombination layer deposited between each junction to allow the current flow, and the current is dictated by the sub-cell that yields the lowest current as required by current-matching conditions. As the functional layers are sequentially deposited on top of each other, this imposes severe constraints on processing conditions and affects the yield.

The tandem solar cells work best when the solar spectrum is optimally utilized by both top and bottom absorbers. Under the standard AM1.5G one-sun illumination, the theoretical maximum efficiency in both two- and four-terminal configurations is around 45%, which is higher than 33% predicted in the SQ limit for single junction device. Besides the coherent merits of thin-film technology, another advantage of CIGS over c-Si is that the bandgap of CIGS can be easily tuned by varying the [Ga]/([Ga]+[In]) ratio in the absorber to realize current matching.

Here, we demonstrate the feasibility of adjusting the current of the bottom cell by comparing two different absorbers – namely, the state-of-the-art CIGS composition and Ga-free $CuInSe_2$ (CIS), with bandgaps of 1.15 eV and 1 eV, respectively. The J–V curves and EQE spectra of the perovskite top cell and CIGS bottom cell are shown in Figure 8 and the corresponding photovoltaic parameters are summarized in Table 1. The efficiencies of the CIGS and CIS used are 19.2% and 13%, respectively. Combined with the 16.1% perovskite top cell, efficiencies of 22.1% and 20.9% are measured in four-terminal tandem configuration. Absolute efficiency gains of 2.9% (CIGS bottom cell) and 4.8% (CIS bottom cell) are achieved compared to the highest-efficiency sub-cell. Further improved collection in the near-infrared region of the CIS cells will enable current-matching monolithic tandem devices to be built without sacrificing the high-energy photons in the top cell. Due to the low-temperature processing of the substrate configuration inverted perovskite solar cells, direct monolithic growth on the CI(G)S bottom cells is feasible. In the future, thin-film perovskite-CIGS tandem solar cells can be processed by high throughput roll-to-roll manufacturing processes to further reduce the production cost as shown in Figure 9.

Conclusion

The progress in efficiency and production of CIGS solar cells and modules show excellent trends for further successful deployment of the technology as companies ramp-up production volumes with new and enhanced production capacities. Already achieved results indicate the possibility of industrial production of modules with higher efficiencies -17%-19% with new production plants in future. Lightweight and flexible solar modules will find more and more market opportunities for their application in buildings, transport, space and portable power generation, and the huge market potential will drive the enhanced efforts in roll-to-roll manufacturing on a larger scale. Innovative research in labs is expected to develop device concepts and processing methods for greater efficiencies – 25% for single junction and 30% for all thin-film tandem devices in future. These targets may seem ambitious but a retrospective look to historical developments suggests the viability of success with innovation.

Acknowledgements

The authors thank the contributions from Wolfram Witte, ZSW; Lars Stolt, Solibro; Hiroki Sugimoto and Takuya Katou, Solar Frontier; Thomas Dalibor and Jörg Palm, AVANCIS; Urs Schoop and Jeff Britt, Global Solar Energy; Atiye Bayman, MiaSolé; Stephan Stutterheim, Flisom. Some of the mentioned results are from projects: EU-Sharc25, EU-PVSITES, Swiss National Science Foundation (SNF)-NRP70, PV2050, SNF-NanoTera and Swiss Federal Office of Energy (SYNERGY and CIGS projects).

References

[1] T. Feurer et al. Progress in thin film CIGS photovoltaics – Research and development, manufacturing, and applications, Progress in Photovoltiacs: Research and Applications (2016), DOI: 10.1002/pip.2811.

[2] T. Kato, "Cu(In,Ga)(Se,S)2 solar cell research in Solar Frontier: Progress and current status", *Jpn. J. Appl. Phys.* 56, 04CA02 (2017).

[3] M. A. Green et al., "Solar cell efficiency tables (version 49)", Prog. Photovolt: Res. Appl. 25, 3 (2017).

[4] Solar Frontier press release (Feb. 27, 2017). "Solar Frontier's CIS thin-film submodule achieves highest efficiency world record of 19.2%." Available: http://www.solar-frontier.com/eng/news/2017/0227_press.html

[5] T. Kato et al., "Enhanced efficiency of Cd-free Cu(In,Ga)(Se,S)2 minimodule via (Zn,Mg)O second buffer layer and alkali metal post treatment", 44th IEEE Photovolt. Spec. Conf., June 25-30, 2017, Washington D.C., USA.

[6] Solar Frontier press release (Jun. 21, 2017). Available: http://www.solar-frontier.com/jpn/news/2017/0621_press.html [in Japanese].

[7] A. Chirilă et al., "Potassium-induced surface modification of Cu(In,Ga)Se_2 thin films for high-efficiency solar cells." *Nature Materials*, 2013. 12: p. 1107 - 1111.

[8] P. Jackson et al., "Effects of heavy alkali elements in Cu(In,Ga)Se_2 solar cells with efficiencies up to 22.6%", *Phys. Stat. Sol.* (RRL) 10 (2016) 583.

[9] M. Malitckaya et al., "Effect of Alkali Metal Atom Doping on the $CuInSe_2$-Based Solar Cell Absorber", *J. Phys. Chem.* C 121 (2017) 15516.

[10] W. Shockley and H. J. Queisser. "Detailed Balance Limit of Efficiency of p-n Junction Solar Cells", J. Appl. Phys. 32, 510 (1961).

[11] L. Kranz et al., "High-Efficiency Polycrystalline Thin Film Tandem Solar Cells", J. Phys. Chem. Lett. 6, 2676 (2015).

[12] F. Fu et al., "High-efficiency inverted semi-transparent planar perovskite solar cells in substrate configuration", Nature Energy 2, 16190 (2016).

About the Authors

Dr. Shiro Nishiwaki received his Ph.D degree in engineering in 1996 from the Hokkaido University, Sapporo, Japan. Prior to joining the Laboratory for Thin Films and Photovoltaics at Empa in 2008 he worked at Matsushita Electric Co. Ltd., Advanced Technology Research Laboratories, Kyoto, Japan (1997 - 2000), Optoelectronics Division of Electrotechnical Laboratory (present name: National Institute of Advanced Industrial Science and Technology (AIST), Ibaraki, Japan (2000), Hahn-Meitner-Institute, Abt SE2, Berlin, Germany (2000 - 2004), Institute of Energy Conversion, Newark, USA (2004 – Dec. 31, 2007). His research and development work is focused on processing of high-efficiency CIGS solar cells on different substrates.

Thomas Feurer received his master degree in physics from the Swiss Federal Institute of Technology (ETH) Zurich in 2014. He started his Ph.D at the Laboratory for Thin Films and Photovoltaics at Empa subsequently. His current research is focused on low bandgap CIGS solar cells and tandem devices with perovskite top cells.

Fan Fu received his master degree in materials science from Wuhan University of Technology (China) in 2013. He started his Ph.D at the Laboratory for Thin Films and Photovoltaics at Empa in 2014. His current research is focused on the design, synthesis and characterization of organic-inorganic hybrid perovskite solar cells and exploring their potential in thin-film tandem applications with CIGS solar cells.

Stefano Pisoni received his master degree in 2015 from the Polytechnic of Milan with master thesis project at University of Oxford. He is working at the Laboratory for Thin Films and Photovoltaics for his doctoral thesis. His current research activities are perovskite solar cells on different substrates including flexible foils, mini-module development and tandem solar cells.

Dr. Stephan Buecheler studied physics at ETH Zurich and received his diploma in 2007. After receiving his Ph.D. from ETH Zurich in 2010 he took the position of group leader in the Laboratory for Thin Films and Photovoltaics at Empa, where his research group is currently working on highly efficient CIGS, CdTe and perovskite solar cells, advanced concepts for tandem solar cells, topics of industrial interests to improve efficiencies and the use of material and device characterization techniques. His other research activity includes thin film solid state batteries.

Prof. Dr. Ayodhya N. Tiwari received his M.Sc. from the University of Roorkee, India in 1981, and his Ph.D. from the Indian Institute of Technology (IIT) Delhi in 1986. He joined ETH (Swiss Federal Institute of Technology) Zürich in 1989 and established a research group on compound semiconductor thin-film solar cells. In 2008, he joined Empa-Swiss Federal Laboratories for Materials Science and Technology as the head of the Laboratory for Thin Films and Photovoltaics. His lab at Empa is working on different types of thin-film solar cells covering fundamental and applied research topics for improving efficiencies, simplifying processing of devices, advance device structures, as well as on applied topics of industrial interests. His lab holds efficiency world records for flexible solar cells. He is an adjunct professor at ETH Zürich. He is a founder and chairman of Flisom AG, a Swiss company involved in the production of monolithically interconnected flexible and lightweight CIGS solar modules.