FLEXIBLE AND LIGHTWEIGHT SOLAR MODULES FOR NEW CONCEPTS IN BUILDING INTEGRATED PHOTOVOLTAICS

S. Buecheler, A. Chirilă, J. Perrenoud, L. Kranz, C. Gretener, P. Blösch, F. Pianezzi, S. Seyrling, A.N. Tiwari

Laboratory for Thin Films and Photovoltaics, Empa – Swiss Federal Laboratories for Materials Science and Technology, Überlandstr. 129, 8600 Dübendorf, Switzerland

ABSTRACT

Most promising technology for cost-effective decentralized solar electricity production is based on thin film photovoltaics. Lowest production costs per output power are reached with thin film solar modules based on the inorganic compound semiconductors CdTe and $Cu(In,Ga)Se_2$ (CIGS). The high conversion efficiency potential of these two technologies has been demonstrated on laboratory scale solar cells reaching 16.5% and 20.3%, respectively, resulting in high power output per installed area. Substituting the commonly used rigid glass substrate by flexible and lightweight materials such as polyimide films or metal foils will further reduce production costs due to the possibility of fast roll-to-roll manufacturing and will also open new markets and enable advanced applications. In addition to mobile solar energy production in consumable electronics as well as in vehicles on land, on sea, in air, and in space, the flexibility and lightweight of this technology allows new concepts for solar electricity sources integrated in facades or roofs of sustainable buildings in future.

Latest results on the development of flexible thin film solar cells and monolithically interconnected modules based on CdTe and CIGS absorber materials are presented in this paper. The concept of coloured solar cells for architectural glazing or shading elements will also be presented. CdTe and CIGS devices are multilayer stacks of thin films and precise structuring on nanometre scale is essential to obtain high efficiencies. We focus on low-temperature deposition processes for both technologies which allow exact control of required nanostructure at the interfaces and grain boundaries of the polycrystalline layers. For CIGS we developed an innovative multi-stage deposition process yielding an optimized energy band gap profile across the absorber layer thickness in order to reduce recombination losses in the device. We present conversion efficiencies for flexible CdTe solar cells exceeding 13% and for flexible CIGS solar cells crossing 18%. We also demonstrate the feasibility of up-scaling of the processes and fully laser based monolithically interconnected mini-modules with conversion efficiency towards 10% for CdTe and 15% for CIGS.

INTRODUCTION

Inorganic thin film photovoltaics based on chalcogenide semiconductors such as $Cu(In,Ga)Se_2$ (CIGS) and CdTe proved high potential as the most cost-effective PV technology in the near future. This is due to the lower production costs compared to wafer based PV technologies and higher achievable conversion efficiencies compared to other thin film approaches like amorphous/micromorph silicon, dye sensitised, or organic solar cells. The latter two might, however, become even more cost-effective in remote future.

In this paper we present the latest achievements in the development of flexible and lightweight CIGS and CdTe solar cells and modules. We discuss the feasibility of up scaling of these technologies and the impact on sustainable building development.

METHOD

The CIGS and CdTe solar cells and modules presented in this paper are grown by low temperature processes on polyimide films.

For CIGS solar cells a Molybdenum based metal layer structure is deposited as back contact by dc-sputtering onto the flexible polyimide substrate. The p-type CIGS absorber layer is grown by a multi-stage co-evaporation process in high-vacuum. The maximum substrate temperature during the evaporation process is in the nominal range between 450-500°C as measured contactless with a k-type thermocouple behind the substrate. The n-type CdS buffer layer is grown by chemical bath deposition followed by a transparent i-ZnO/ZnO:Al bi-layer front contact. The solar cells are finished with Ni/Al/Ni fork-shaped grid fingers and separated by mechanical scribing to nominal 0.6 cm^2 device area. Details of the fabrication process can be found elsewhere [1,2].

CdTe solar cells are fabricated in the superstrate configuration where the choice of substrates is limited to transparent materials since the light enters the solar cell through the substrate. In the superstrate configuration a transparent conductive oxide (TCO) front contact ZnO:Al layer and a highly transparent and resistive i-ZnO layer are grown by rf-magnetron sputtering on the polyimide substrate. The n-type CdS and p-type CdTe layer stack is deposited by high vacuum thermal evaporation from the compounds and subsequently annealed at 420°C in a chlorine and oxygen containing ambient. The solar cells are finished by evaporation of a Cu/Au bilayer onto Te enriched CdTe surface. The solar cell area of 0.15 cm^2 is defined by the back contact geometry. More details of the process can be found elsewhere [3].

The photovoltaic properties of the flexible solar cells are measured by current-voltage characteristics at standard test conditions under simulated AM1.5G illumination at 1000 W/m^2 irradiation intensity and 25°C device temperature following the international standard IEC 60904-1 Ed.2.

RESULTS AND DISCUSSION

The chalcopyrite thin film solar cells are multilayer devices which can be grown on large area substrates. Figure 1 illustrates schematically the built-up of the layers of the two devices discussed in this paper. In both technologies the core of the device is a pn-junction formed between the p-type absorber layer CIGS or CdTe, respectively, and the n-type CdS layer. In this system the incoming light is absorbed and free charge carriers are generated which are then separated by the built-in electrical field in the pn-junction. The charge carriers are extracted by two electrical contacts, a transparent conductor at the front which is commonly made of a transparent conductive oxide (TCO) and a metallic structure at the back.

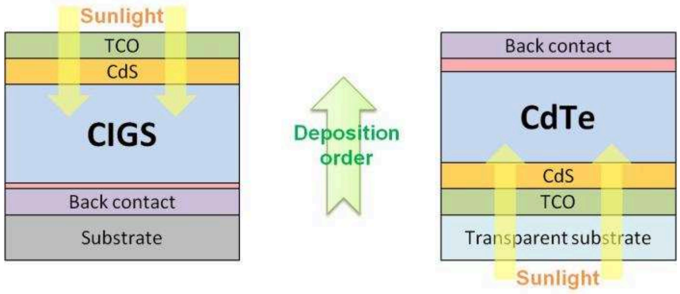


Figure 1: Schematic built-up of the CIGS and CdTe thin film solar cells. CIGS devices are commonly grown in the illustrated substrate configuration while highly efficient CdTe devices are achieved in the superstrate configuration. In the superstrate configuration the choice of substrates is limited to transparent materials because the light enters the solar cell through the substrate.

Conversion efficiencies of 20.3% for CIGS and 16.5% for CdTe are reported for solar cells on glass substrate fabricated with high temperature deposition methods (>600°C) [4-6].

Low temperature deposition processes for both the CIGS (<500°C) and CdTe (<450°C) technology were developed in our laboratory. These processes allow the utilization of a larger variety of substrate materials. This includes polyimide films, stainless steel and mild steel foils as well as aluminium foils for the CIGS process and transparent materials such as soda lime glass and polyimide film for the CdTe process.

Figure 2 shows the conversion efficiency values achieved for flexible CIGS and CdTe solar cells within the last decade. The photovoltaic performance continually increased due to improved understanding of material synthesis and interface engineering. For CIGS technology the most recent advancement was achieved by optimization of the CIGS composition grading, the sodium doping and the microstructure. This led to reduced recombination losses in the device and to a solar energy conversion efficiency of 18.7% for a flexible CIGS solar cell. This is the highest reported efficiency for any flexible and lightweight technology [7]. In case of CdTe the most recent improvement was achieved by reducing the parasitic light absorption in the substrate material. With a clear polyimide film the conversion efficiency was increased to 13.8% [8].

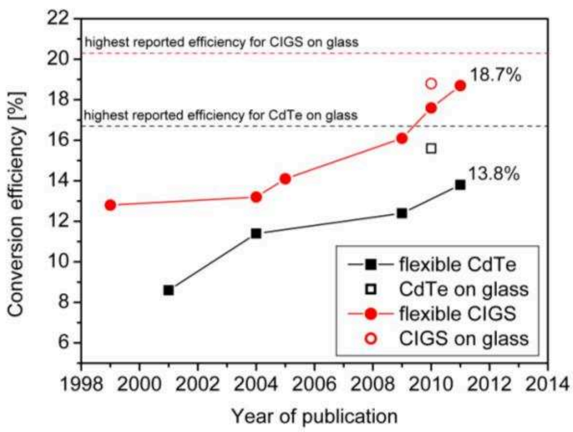
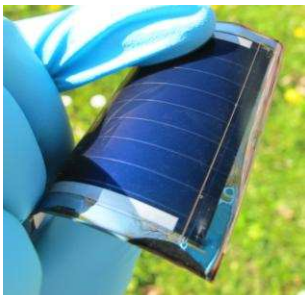


Figure 2: Conversion efficiencies of flexible CdTe and CIGS solar cells fabricated by low temperature processes. Also shown is the in-house reference on glass and the highest reported efficiency for each technology.

Photographs of flexible CIGS and CdTe solar cells on polyimide substrate are shown in figure 3. The solar devices have a critical radius of curvature below 1 cm and a power density without lamination of >2.3 kWp/kg and >1.7 kWp/kg for CIGS and CdTe, respectively.

Figure 3: Photographs of flexible CIGS (left) and CdTe (right) solar cells on polyimide substrates.

In operating conditions (maximum power point) CIGS and CdTe solar cells have a typical voltage of about 0.6 V and 0.7 V, respectively. This voltage is too small for most applications and also would result in major resistive losses in the cabling. The device voltage is increased by serial interconnection of the solar cells to solar modules. A key advantage of thin film photovoltaics is the possibility for monolithical interconnection. The flexible solar modules presented in this paper are monolithically interconnected using laser scribing technique for all patterning steps [9].



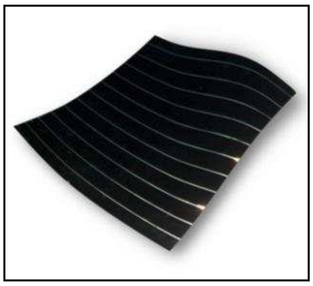


Figure 4: Flexible and lightweight CIGS (left) and CdTe (right) solar modules.

Figure 4 shows photographs of flexible CIGS and CdTe solar modules where all patterning steps are performed with laser scribing. For the CIGS solar module with an aperture area of 13 cm^2 eight cells are connected in series yielding a device voltage of 5.22 V and an active area efficiency of 14.7%. For the first time we proofed the concept of flexible CdTe solar modules. Eleven cells are connected to a module with an aperture area of 32 cm^2 yielding a voltage of 8.35 V and an active area efficiency of 9.4% [9].

The flexibility and lightweight of the highly efficient CIGS and CdTe solar devices allow building integration (and also building application) in structures which can not take the additional load of heavy and rigid glass laminated solar modules. Flexible photovoltaics can be integrated in light constructions in order to reduce the overall footprint. The flexible solar modules can be laminated to building elements such as flat roof membranes, tiles or metallic covers without adding weight and thus, the installation costs can be reduced significantly. Furthermore, the flexibility and lightweight allows for new concepts in design oriented PV application.

For optimized light absorption an additional optical coating is applied in order to match the refractive index at the interface and reduce reflection losses over a broad wavelength spectrum. Furthermore, the additional optical coating can be used to engineer constructive and destructive interference effects. By changing the thickness of the optical coating the narrow wavelength region for constructive reflection can be tuned, i.e. the colour of the thin film PV devices can be selected (fig. 5).

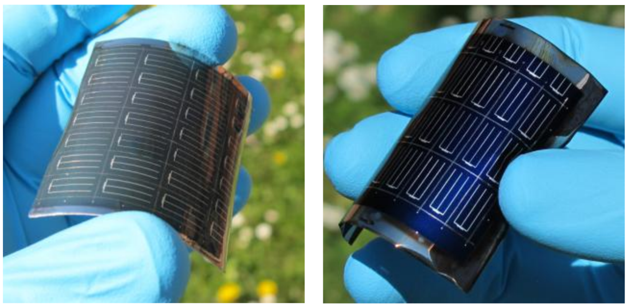


Figure 5: Illustration of the effect of constructive interference for colour selection. Choosing the colour of the PV devices for architectural glazing is possible.

Beside the advantages of flexibility and lightweight of the finished product the rollable substrate material enables the use of cost-efficient and fast roll-to-roll production methods which proofed very high throughput in applications like food packing or newspaper printing. With the roll-to-roll technology not only a higher throughput but also lower investment costs for the equipment are expected. Currently several companies such as Global Solar (USA), Ascent Solar (USA), Odersun (Ger), Solarion (Ger) or Flisom (CH) are developing or ramping up production facilities using roll-to-roll based manufacturing.

The high efficiency, flexibility, and lightweight of the presented thin film PV technologies have significant advantages and allow new concepts in PV application:

- Smaller surface area for same output power
- Lower balance of system costs
- Application on windows, roofs, and facades possible also in light constructions and curved surfaces
- Customizable for design oriented PV applications

These results show that conversion efficiencies of flexible and lightweight inorganic thin film photovoltaics are approaching the values achieved on rigid glass substrate yet with additional advantages not only of the product but also during manufacturing. The flexibility and the lightweight of the CIGS and CdTe thin film devices as well as the projected low production costs make the application in new concepts for building integrated photovoltaics possible.

ACKNOWLEDGEMENTS

This work was supported by the Swiss National Science Foundation, the Swiss Federal Office of Energy, the Commission for Technology and Innovation and the European FP7 Project hipo-CIGS. The Authors would like to thank Flisom AG, Switzerland for performing laser scribing and helping in mini-module development.

References

1. Chirilă, A., et al.: Optimization of composition grading in CIGS for flexible solar cells and modules, Proc. of the 35th IEEE Photovoltaic Specialist Conference Honolulu, 2010.
2. Chirilă, A., et al.: Cu(In,Ga)Se2 solar cells grown on flexible polymer substrate with efficiencies exceeding 17%.
3. Perrenoud, J., et al.: Flexible CdTe solar cells and modules: challenges and prospects, Proc. of SPIE, Vol 7409, pp. 74090L-1–74090L-5, 2009.
4. Jackson, P., et al.: High Quality Baseline for High Efficiency Cu(In1-x,Gax)Se2 Solar Cells, Prog. Photovolt. Res. Appl., Vol 15, pp 507-519, 2007.
5. Jackson, P., et al.: New world record efficiency for Cu(In,Ga)Se2 thin film solar cells beyond 20%, Prog. Photovolt. Res. Appl., DOI: 10.1002/pip.1078, 2011.
6. Wu, X.: High efficiency polycrystalline CdTe thin film solar cells, Solar Energy, Vol 77, pp 803-814, 2004.
7. Empa: Record efficiency of 18.7% for flexible CIGS solar cells on plastics, Empa Press Release, http://www.empa.ch/plugin/template/empa/1256/107447/---/l=1, Duebendorf, St. Gall, Thun, 19 May 2011.
8. Empa: Efficiency record for flexible CdTe solar cell due to novel polyimide film, Empa Press Release, http://www.empa.ch/plugin/template/empa/1256/108288/---/l=1, Duebendorf, St. Gall, Thun, 9 June 2011.
9. Perrenoud, J., et al.: Fabrication of flexible CdTe solar modules with monolithic cell interconnection, Solar Energy Materials & Solar Cells, Vol 95, pp 8-12, 2011.