



FLEXIBLE CIGS SOLAR CELLS AND MINI-MODULES (FLEXCIM)

Final Report

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Abstract

This project contributed significantly to further developments in the field of Cu(In,Ga)Se_2 thin film solar cells on flexible substrates such as plastic and metal foils. Process optimization at low temperature deposition conditions resulted in a new world record of the highest achieved solar conversion efficiency for any solar cell on plastic substrate. 14.1% efficient cells were obtained with a prospect for efficiencies beyond 15% by reduction of reflection losses. Preliminary tests of larger area solar cells connected with metal grids resulted in flexible solar cells of 8% efficiency on 16 cm^2 . Further, Improvements in efficiency of cells on alternative back contact materials such as transparent conducting oxides were made and 6.7% efficient solar cells on aluminium foils, an alternative low-cost substrate material, were shown. For up scaling the laboratory scale processes to industrial manufacturing an in-line deposition system was designed and installed. This equipment was used to investigate the co-evaporation of absorber layer deposition on substrate sizes of up to $30 \times 30\text{ cm}^2$. Improvement of the evaporation system is necessary to fulfil the requirements of homogeneous large area deposition.

1. Current Status

Polycrystalline thin film CIGS solar cells are important because of very high efficiency, long term stable performance, and their potential for low cost generation of solar electricity. The National Renewable Energy Laboratory, USA has reported a world record efficiency of 19.5% for the CIGS solar cells grown on glass substrates and several groups including ETHZ have achieved efficiencies exceeding 16% on glass substrates. Flexible and lightweight solar cells are interesting for a variety of terrestrial and space applications that require a very high specific power (kW/kg, defined as the ratio of output electrical power to the weight of solar module). Integration of such flexible CIGS solar modules in buildings (roofs and facades) is an emerging field with many attractive possibilities for the application of PV, and it offers an interesting commercial viability in future.

The processing of high efficiency solar cells requires deposition of a stack of polycrystalline layers of $\text{ZnO:Al/ZnO/CdS/Cu(In,Ga)Se}_2/\text{Mo}$ on a substrate (glass or metal or polyimide). A typical lightweight and flexible CIGS encapsulated solar module could be up to ten thousand times lighter than the module based on a 3 mm thick glass. In addition, the roll-to-roll manufacturing of flexible modules has certain other advantages leading to a significant cost reduction and expanding the applicability range of solar modules for diverse applications.

ETH group has been involved in the development of high efficiency flexible CIGS solar cells with low deposition temperature processes and incorporating controlled amount of Na in CIGS for efficiency enhancement. In this project the work is focused on the improvement of cell efficiency and process reproducibility on polyimide foils, and also to test the potential of the ETH invented process on steel and aluminium metal foils. We have been developing these solar cells on $5 \times 5\text{ cm}^2$ foils, but in this project proof of concepts are to be developed for scaling-up the deposition processes for larger area, up to $30 \times 30\text{ cm}^2$, size substrates. Strategies for large area solar cells and mini-modules are to be developed.

Mo is commonly used as a back electrical contact in CIGS solar cells. The damp heat tests of non-encapsulated or poorly-encapsulated modules quite often may show long term performance degradation because of contact corrosion. An important reason is the instability of Mo in moisture. Compared to some other possible contact materials Mo is an expensive material, and in case of flexible solar cells Mo layer can influence the stress and micro cracks in solar cell layers. Therefore, experiments are needed to investigate alternative strategies for ohmic back contact. First the role of MoSe₂ interface layer has to be understood for which CIGS solar cells need to be grown on metal or semi-metal like materials with a very thin “buffer layer” of MoSe₂.

2. Objectives

Flexible Cu(In,Ga)Se₂, called CIGS, solar cells are important for a variety of terrestrial applications, especially for integration in roofs and facades of buildings and as lightweight portable source of solar electricity. The overall project objective is to develop high efficiency solar cells and mini-module development strategies on commercial polyimide and metal foils with emphasis on improving the performance, process reproducibility and large area deposition capabilities. In addition, alternative electrical back contact to conventional Mo is to be evaluated based on application of a suitable buffer layer facilitating tunnelling of carriers across the CIGS-back contact interface.

3. Results

Our group has successfully developed flexible solar cells on polymer and metal foils of 5 x 5 cm² size by using vacuum evaporated CIGS layers and applying a patented process for controlled and reliable incorporation of Na in CIGS layers. This low temperature CIGS deposition and Na doping process offers several advantages for development of high efficiency solar cells on different substrates.

We have developed 14.1% efficiency ($V_{oc} = 649$ mV, $J_{sc} = 31.5$ mA/cm², FF= 69.1%, total area = 0.595 cm², no antireflection coating) flexible solar cell on polyimide foil (**figure 1**) [1]. This efficiency measured under AM1.5 illumination at ISE-Fhg, Freiburg, Germany is the highest efficiency world record for any kind of solar cell grown on polymer foil. Quantum efficiency and reflection measurements (**figure 2**) performed on such samples suggest that efficiencies exceeding 15% can be achieved by applying antireflection coating to reduce the reflection losses. This value of 14.1% efficiency, achieved in December 2004, still remains the highest efficiency record for any kind of solar cell grown on polymer foil. Historical progress of efficiency of flexible CIGS cells of leading groups in the world is shown in **figure 3**.

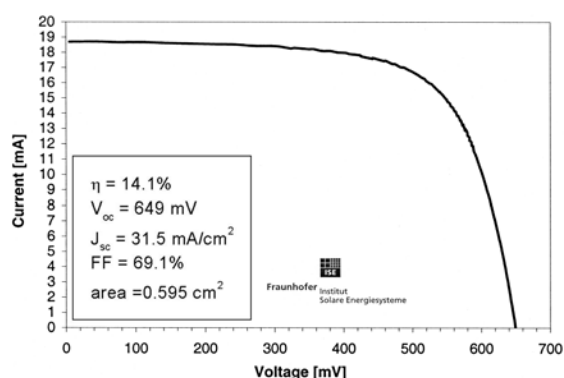


Figure 1: Flexible CIGS solar cells on a 5 x 5 cm² polyimide foil (left) and current-voltage characteristic of the 14.1% efficiency cell measured under simulated AM1.5 standard test conditions at ISE-Fhg Freiburg, Germany (right). This value still remains the highest efficiency record for any kind of solar cell grown on polymer foil.

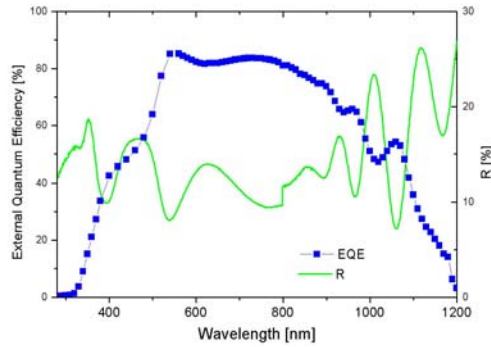


Figure 2: Quantum efficiency and reflection curves of 14.1% efficiency cell suggest that application of anti-reflection coating to reduce 13% reflection loss can further enhance the efficiency.

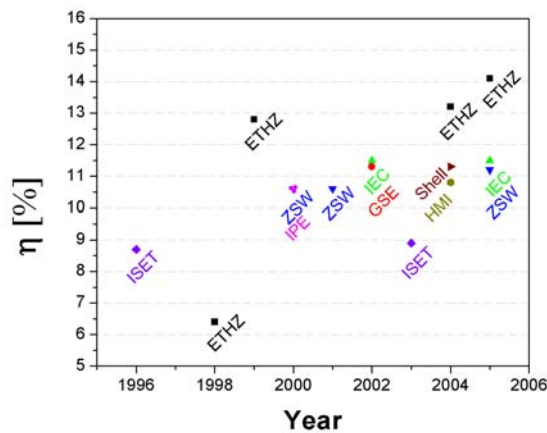


Figure 3: Progress in efficiency of flexible CIGS solar cells on polymer foils.

We have applied “our low temperature CIGS deposition and Na doping process” to develop solar cells directly on steel and Ti foil substrates, and during this project we continued the R&D work on Al (coated and un-coated) foils. Aluminum is an interesting substrate material because of low cost and light weight, and it is used in several applications, especially in buildings. Development of CIGS cells on Al has remained a big challenge because of mismatch in thermo-physical properties. However, we have now developed for the first time CIGS solar cells on Al-foil. We have grown CIGS layers at different substrate temperatures and investigated the properties of evaporated CIGS layers by different methods (SEM, SIMS, EDX).

One of the biggest challenges in depositing CIGS absorber on Al-foil is the large mismatch between the thermal expansion coefficient (CTE) of CIGS and Al. The mismatch causes stress between the different layers, which can create cracks in the absorber, and consequently shunt the cell. In the worst case this could even result in the complete delamination of the CIGS. The tension between the layers of course depends on the growth temperature. The higher the temperature the more tension is created during cooling down, therefore lower temperature results in better adhesion. On the other hand a minimal growth temperature is needed to obtain “device quality” CIGS layers and working solar cells.

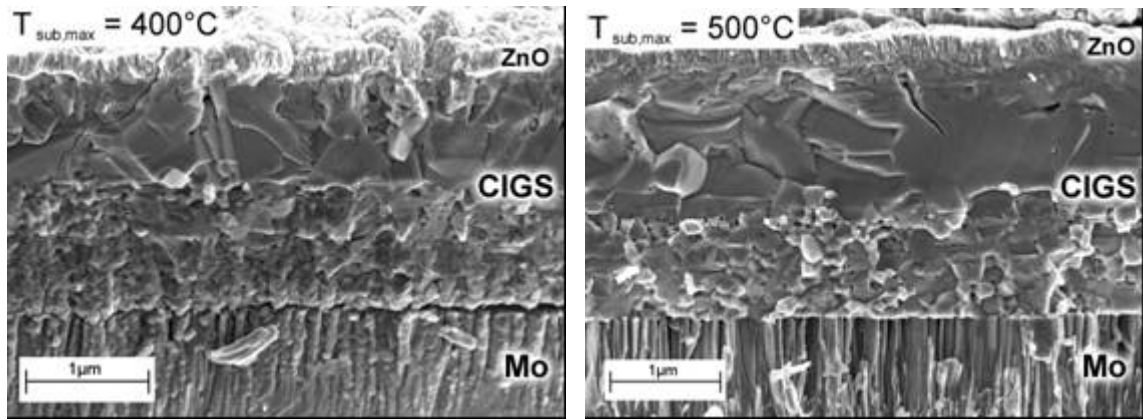


Figure 4: SEM cross-section images of solar cells on Al foils where CIGS layers were grown at a 400 °C (left) and 500 °C (right), the mentioned temperature is a reference value and not the exact substrate temperature.

The growth temperature has the most important impact on the structure and the quality of the absorber (**figure 4**). Solar cells grown at $T_{\text{sub,max}} = 400^\circ\text{C}$ don't show photovoltaic conversion efficiency at all. It is important to note that we mention a reference temperature while the actual substrate may be quite different. As it can be seen in figure 4, the temperature was not high enough to permit the inter-diffusion of the elements and it is inadequate for CIGS phase formation. One can distinctly see three different phase in the CIGS layer due to the 3stage process and the insufficient temperature for a proper Cu-In-Ga diffusion. The top part shows "classical" CIGS with relatively small grains, whereas the bottom of the absorber has the typical structure of Cu-poor CIGS. A micro crack in the left upper part of CIGS and the separation between Mo and CIGS is due to the sample preparation for SEM measurement.

The photovoltaic properties of small area solar cells were characterized with I-V and quantum efficiency measurements (**figure 5**). An efficiency of 6.6%, measured under AM1.5 standard test conditions, was achieved with Na free CIGS absorber layers ($V_{\text{oc}} = 434 \text{ mV}$, $J_{\text{sc}} = 30.7 \text{ mA/cm}^2$, $\text{FF} = 49.3 \%$, total area; no AR coating) [2]. While the short circuit current is reasonable, the open current voltage and the fill factor need to be improved. It is important to mention that Na was not added into the CIGS absorber layer, but it is known that addition of Na can significantly increase the efficiency by additionally up to 70% of the Na free value.

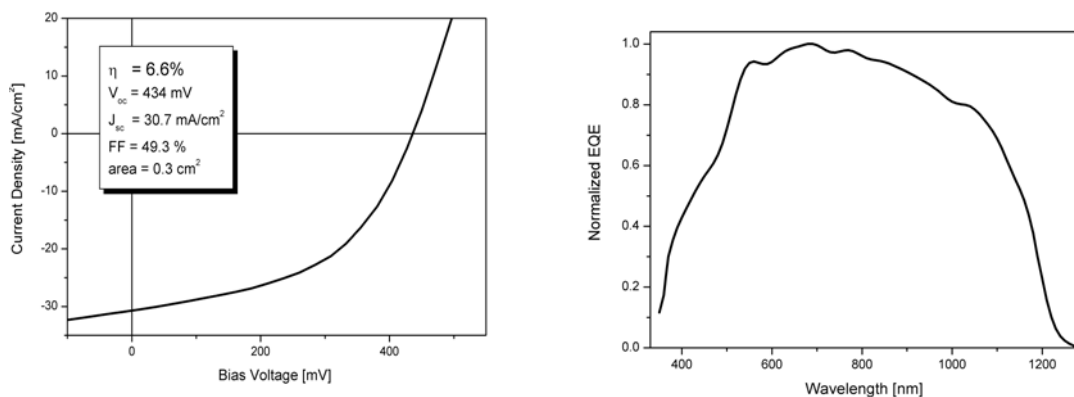


Figure 5: Current-voltage characteristic (left) and quantum efficiency (right) of a CIGS solar cell on Al foil. Neither Na was incorporated in CIGS absorber nor any AR coating was applied. This 6.6% efficiency is the highest value of efficiency reported to date for CIGS cell on Al foil. Addition of Na in CIGS will further increase the cell efficiency.

Scaling-up of Mo, CIGS, CdS, ZnO/ZnO:Al deposition processes were started to grow layers on 30 x 30 cm² size substrates. A big effort has gone for in-house assembly of the CIGS deposition system

with self designed and constructed mechanisms for substrate heater, in-line movement of heated substrates, linear thermal evaporation sources (**figure 6**). The objective was to learn about the challenges of in-line movement of heated polymer foil and evaporation sources of Cu, In, Ga, Se for large area coating. Since such evaporation sources and in-line movement mechanisms were/are not commercially available, customised development was started.

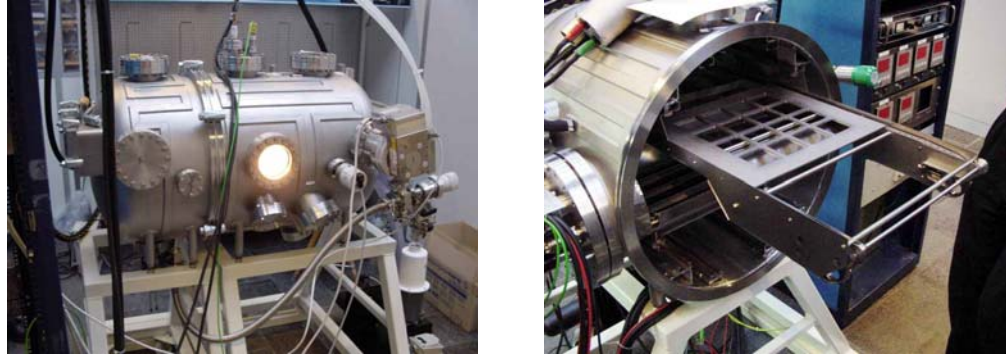


Figure 6: Pictures of in-house developed large area CIGS vacuum deposition system.

We have been able to deposit Mo, ZnO/ZnO:Al layers on 30x30 cm² size substrates using a second hand refurbished sputtering equipment. Though the deposition equipment for CdS buffer layer and CIGS evaporation were installed during this project and several growth and characterisation experiments were performed to investigate thickness and compositional properties of layers, it turned out that the size of the CIGS evaporation chamber (already existing before the start of this project) is too small for 30x30 cm² size substrates. However, we could successfully develop substrate heating and in-line movement mechanism for 30x30 cm² size polymer foils. **However, further work is needed for improvement of evaporation sources and design of a new CIGS deposition system is necessary; such a system should have in-situ diagnostics for process monitoring and control of evaporation fluxes and layer properties.**

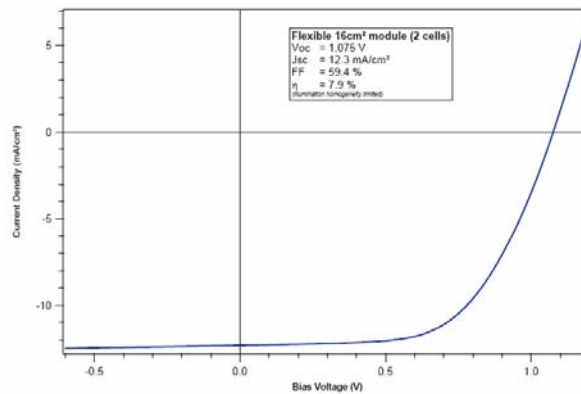


Figure 7: J-V curve of 16 cm² mini-module obtained by connection of two large area cells with metal grids.

Strategies to develop solar modules were evaluated considering the options of monolithically interconnected cells (obtained through laser scribing and patterning) or connection of large area solar cells with metal grids. We could develop mechanical scribing for Mo layers on polymer foils, but optimisation of the scribed layers as a function of sputtering condition is not completed. Processes for application of metal-grids by evaporation on large area solar cells has been developed. In our preliminary experiments we have already achieved 8% efficiency (Voc = 1.075 V, Jsc = 12.3 mA/cm², FF = 59.4 %) mini-module of 16 cm² size by connecting two large area cells on 25 cm² foil (**figure 7**). We are not yet well equipped for large area devices and we believe that better equipment and facilities would reduce losses and improve the large area module efficiency. Flexible mini-modules to run small ventilator-fans have been developed to demonstrate an application possibility (**figure 8**).

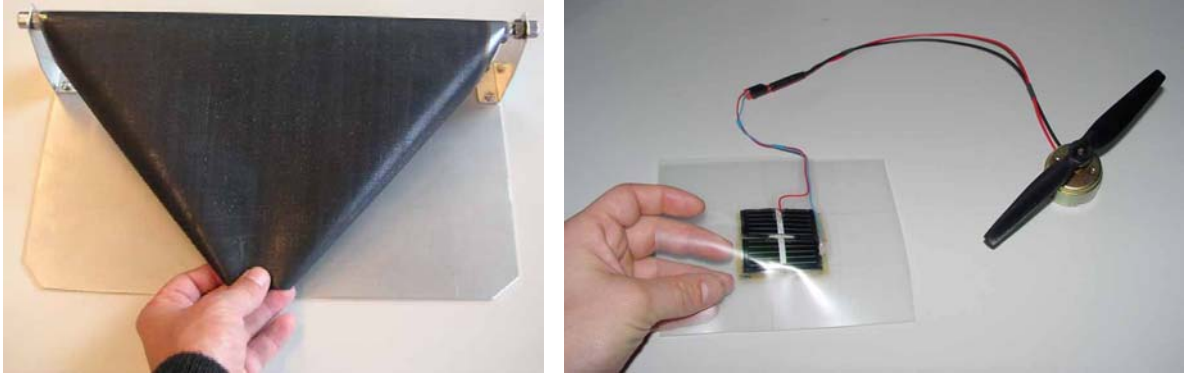


Figure 8: Pictures of flexible CIGS solar cell layers on a roll (left) and flexible mini-module to run a ventilator-fan.

In order to either fully or partly replace the Mo contact in CIGS solar cells with a suitable back contact and buffer layer exploratory works were performed by developing CIGS solar cells on transparent conducting oxide (e.g. ITO) coated glass substrates. A buffer layer of MoSe_2 providing low resistance quasi-ohmic contact was obtained by selenization of a thin sputtered Mo layer on ITO. CIGS solar cells were grown on these substrates using conventional technology as described above. The purpose was to prove that MoSe_2 layer can facilitate a “quasi-ohmic” transport of carriers across the CIGS back contact.

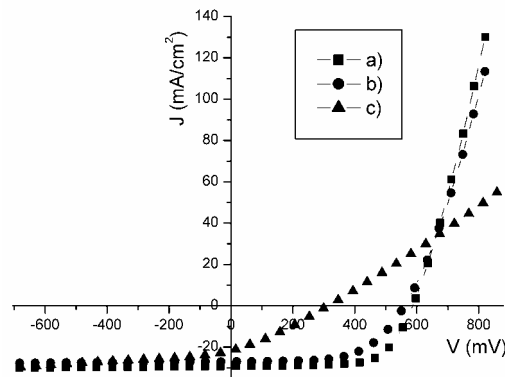


Figure 9: I-V characteristics under AM1.5 illumination of CIGS solar cells in substrate configuration with ITO/ MoSe_2 back contact (a and b) and with ITO back contact (c). To form an intentionally grown MoSe_2 intermediate layer on ITO back contact, for cell (a) the Mo was selenized at 450°C , for cell (b) at 580°C for 30 min. Cell (c) was processed in the same run as cell (b), but covered during the selenization.

First solar cells on ITO back contact with intentionally grown MoSe_2 intermediate layer showed clearly a better photovoltaic performance than without the MoSe_2 intermediate layer, and efficiencies of up to 11.8% were achieved in substrate configuration (figure 9). The details of photovoltaic parameters are given in table I. These results prove that MoSe_2 layers can be used as buffer layer for quasi-ohmic contact and to develop high-efficiency CIGS solar cells on a variety of back contact materials.

Table 1: Photovoltaic parameters for solar cells with and without intermediate MoSe₂ layer between ITO back contact and CIGS; for specifications please refer to Fig. 9 and the text.

Sample, back contact	(a) ITO/MoSe ₂	(b) ITO/MoSe ₂	(c) ITO
selenization temp. [°C]	450	580	580
U _{oc} [mV]	585	559	314
I _{sc} [mA/cm ²]	29.3	27.1	21.6
FF[%]	68.9	60.8	29.6
η[%]	11.8	9.8	2.0

4. Conclusions

The project has been completed and several milestones of this ambitious project have been successfully met, while more work, especially on up-scaling of CIGS deposition and further increasing the efficiency of flexible solar modules is needed. This project has contributed towards the achievements of: i) Improvement in the efficiency world record of flexible CIGS solar cells to 14.1%; ii) prospects for >15% efficiency cells by reduction of reflection losses; iii) development of large area cells with grids and 8% efficiency on 16 cm² in the preliminary development; iv) in-house development of large area in-line deposition system for CIGS layers; v) 6.7% efficiency CIGS solar cells on Al foils and prospects for efficiency improvements; vi) CIGS solar cells on transparent back contact (ITO) by application of MoSe₂ layer which improves the efficiency from 2% to >10%. Unfortunately, resources and project duration were inadequate for improving the large area deposition system and processes. Further work is needed for improving the large evaporation sources and to apply process diagnostic tools for monitoring of in-line growth on large area. Module development on foils is another challenging area requiring technical developments. It is hoped that further support will facilitate the development of highly efficient large area flexible CIGS modules based on the innovative concepts of ETH for “low temperature” processing of CIGS cells and their interconnection on flexible substrates.

5. References

- [1] D. Brémaud, D. Rudmann, G. Bilger, H. Zogg, A.N. Tiwari, Conference Record of the 31st IEEE Photovoltaic Specialists Conference, Orlando, 2005, p. 223.
- [2] D. Brémaud, D. Rudmann, M. Kaelin, K. Ernits, G. Bilger, A. N. Tiwari, E-MRS 2006 Spring Meeting, Nice, France, 29 May - 2 Jun 2006, to be published in *Thin Solid Films*