



HipoClGS: enamelled steel as substrate for “thin film” solar cells



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Introduction

Global solar cell / photovoltaic (PV) market:

- significantly growing market
- continuously increasing production capacities
- conventional PV technology based on crystalline-Si wafer technology focusing on cost reduction
- **new generation of thin-film PV technologies**



Thin-film solar cells

Advantages:

- the thin-film solar cells are less expensive than the older c-Si wafer cells
- they can be grown on flexible substrates as metal foils or polyimide films
- they are also less fragile than c-Si cells and easier to handle

The flexible substrates enable the production of the monolithically connected flexible modules with high speed roll-to-roll manufacturing systems

The main **disadvantages** of the thin-film solar cells are in general:

- their lower efficiency
- their relatively more complex structure

Different types of thin film solar cells

Different types of thin film solar cells:

- amorphous silicon (a-Si) and thin-film silicon (TF-Si)
- cadmium telluride (CdTe)
- **copper indium (gallium) diselenide - CIS or CIGS**
- TiO_2 dye-sensitized solar cell (DSC)

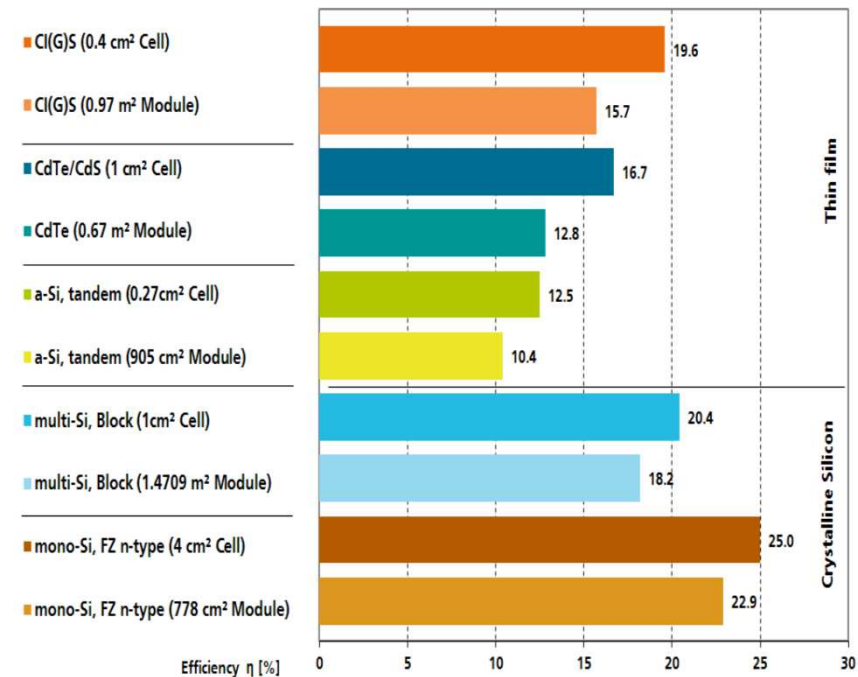


Figure 1: Efficiency Comparison of Technologies - best Lab Cells vs. best Lab Module

The HipoCIGS project

- **CIGS** (Cu(In,Ga)Se_2) highly efficient flexible solar modules
- to develop **innovative flexible substrate materials**
- to create deposition processes enabling the inline and/or roll-to-roll production
- funded by the **European Commission under the FP contract No.241384**
- 8 different companies and institutes : ZSW (D), Flisom (CH), EMPA (CH), MCT GmbH(D), WUT(PL), TATA Steel Europe (D), TNO (NL) and **PRINCE Belgium (B)**
- **PRINCE: identify and to develop the best suitable and best high-temperature stable enamel, to be used on thin steel foils as substrate**

The structure of CIGS solar cells

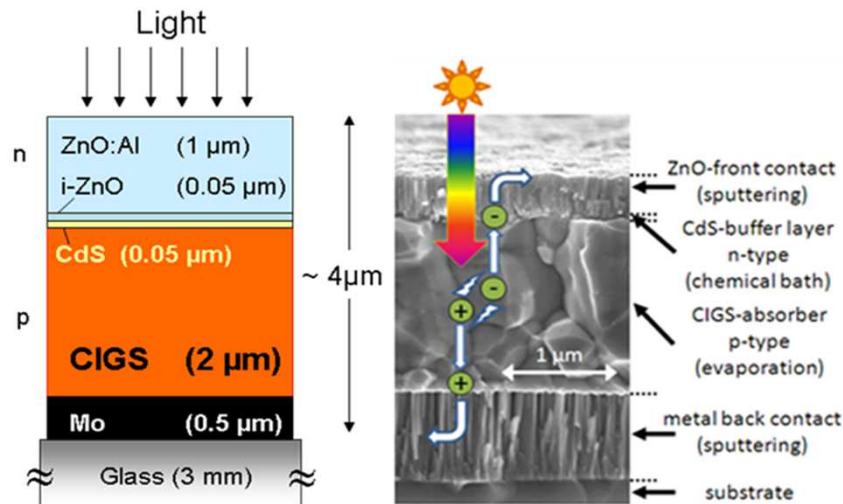


Figure 2: Schematic cross-section of a standard CIGS solar cell

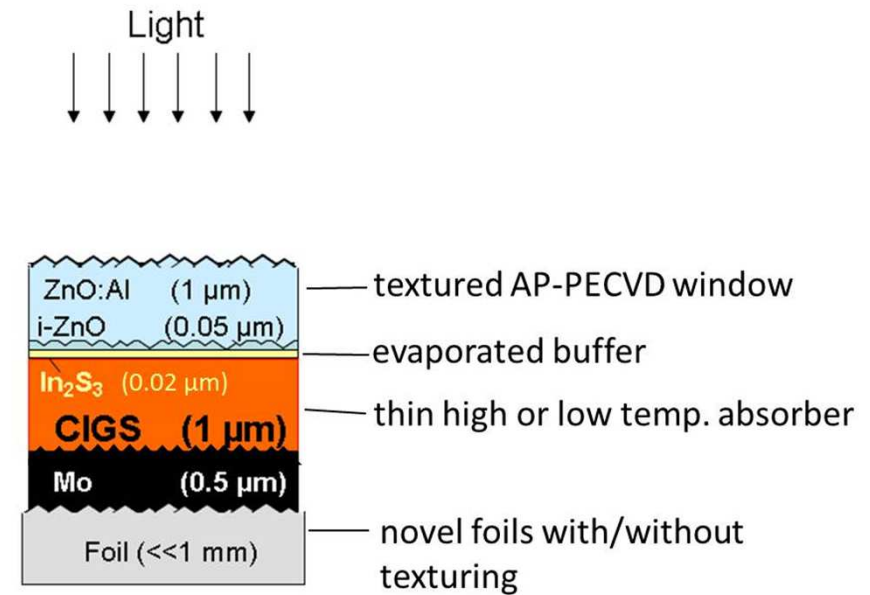


Fig. 3 Schematic cross section of the new HipoCIGS solar cell on flexible substrate

Why do we want to enamel the metal foils?

Advantages by the multiple technical functions of an enamelled steel foil:

- back side corrosion protection
- electrical insulation
- high-temperature stability
- surface smoothening and hardening
- alkali source for the doping of the CIGS semiconductor
- diffusion barrier against metal foil components

The target is to combine the advantages of a glass surface with the advantages of a metal foil

Challenges of the HipoCIGS project

The **transfer of the knowledge and efficiencies** from CIGS on a glass substrate to CIGS on flexible foils in general is a big challenge, due to:

- **high temperatures** up to 650 °C during the formation of the CIGS absorbers which are favourable to achieve high quality and efficiencies
- contamination of the absorbers by **diffusion of undesired elements** out of the substrate (metal foils) which needs to be controlled
- the need for external **Na doping** [1] out of the substrate to increase the conductivity and to limit the average grain size of the absorber
- the need to realize **efficiencies** of the solar cells at least comparable to a glass substrate
- a potential mismatch of the **thermal expansion** of the layers and substrates, which could lead to delamination and the appearance of cracks

Requirements for the substrates

The requirements for the substrates are:

- allow sufficient layer **adhesion**
- adjusted **thermal expansion** coefficient
- **low degassing** of the substrate
- **no bubble formation** in a vacuum at 650 °C nor in a selenium vapour
- high **thermal and chemical stability**
- **flexibility** to enable roll-to-roll processing

The optimal substrate should additionally be:

- **cost effective**
- allow **easy handling** and have high **environmental stability**

⇒ low carbon ED steel

- 0.7 - 1.0mm: for development and the production of mini-modules
- thinner, more flexible, 0.5mm: for producing of large size modules

Requirements for the enamelling process

- Avoid **surface defects**
- Limit **bubble structure** growth in the enamel layer
- Guarantee enamel **adherence** to the steel substrate
- Give **dielectric properties** to the enamel layer

Two systems to achieve good adherence:

- degreased steel - ground coat (Co and Ni containing) - dielectric coat
disadvantage: lower high-temperature stability without bubble formation and degradation due to the T_g (*glass transformation temperature*) of the ground coats
- **degreased, pickled and nickeled steel - dielectric coat (direct-on)**
advantage: the nickel layer limits the gas reactions of the steel

The 2nd system was chosen as being more suitable for the CIGS process.

The way to fulfil the requirements

- **Adjusting the pre-treatment** (pickle/nickel) procedure
- **Developing specific dielectric enamel compositions** with high T_g (min. 620 °C), reduced bubble formation and adjusted thermal expansion coefficient
- **Testing enamelled substrates as an alkali source** with well defined ratio and concentration of Na and K

Results

- SIMS measurements (ZSW) confirmed:
 - **that alkali diffused out of the enamel layer** into the CIGS layer
 - **that the enamel layer blocks the diffusion of Fe from the foil.**

This means that the enamel layer plays the role of a **diffusion barrier** and as well as a **precursor layer** during the high temperature CIGS processes [1, 3]

- The **K diffusion hinders the inter-diffusion** of CIGS elements during the growth of the absorber and improves by this the efficiency

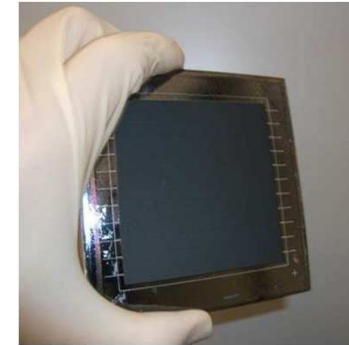


Fig. 4a Mini – Module

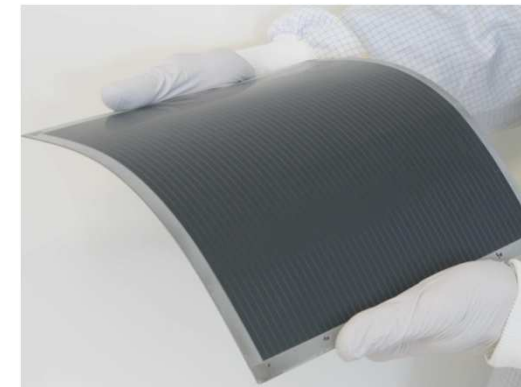


Fig. 7 Solar module on enamelled steel 23 X 30 cm²

Efficiencies obtained

The cells on enamelled steel showed a **higher efficiency** compared to cells on glass reference substrates:

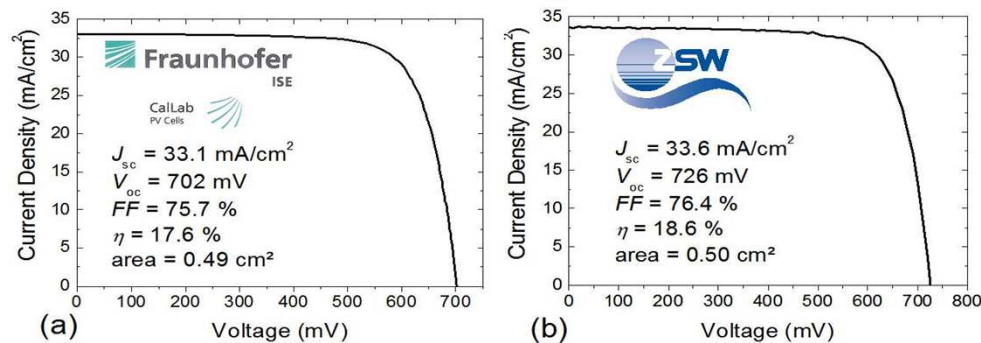


Fig. 6 JV- curves of record-breaking cells on enamelled substrate: measured by ISE (left) and ZSW (right) [1]

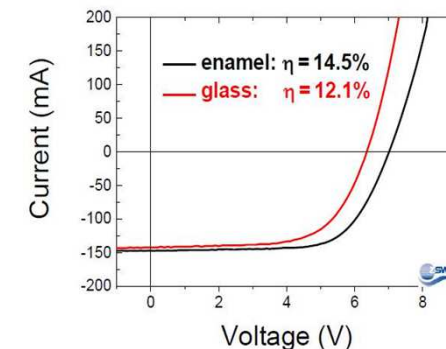


Fig. 4b: inline 10 cells, $A=48\text{cm}^2$; IV-curves

For **higher voltage solar modules**, an **efficiency of 12.9%** was achieved on a large area enamelled substrate **versus an efficiency of only 11,6%** of the glass reference substrate [1, 3].

Conclusions

The use of enamelled steel as substrate for CIGS solar cells shows many advantages:

- The enamel compositions allow effective **doping** of the CIGS absorber without need of any external Na supply. Also a K doping is possible. The CIGS alkali doping by the enamel can be precisely adjusted.
- The enamel layer acts as a **diffusion barrier** and effectively **blocks Fe diffusion** into the CIGS absorber.
- The use of enamelled substrates allows **higher efficiency** than the reference soda lime glass substrate.
- The enamel back side acts not only as corrosion protection, but also as an **insulation layer** for monolithic interconnection of the cells on the conducting metal substrate.
- The flexibility of the thin, enamelled sheet allows the **roll-2-roll** production.

Obstacles to be solved

The enamelled sheet substrates at this time are still at higher **costs** due to the chosen more expensive pre-treatment/enamelling process (pickling and nickeling) of the steel foils.

If the substrate temperature of the CIGS process is too high (higher than the T_g temperature of the enamel) and heating and cooling ramps are too fast, **shrivelling of the enamel layer** appears and could hinder the cell and module production [1]:

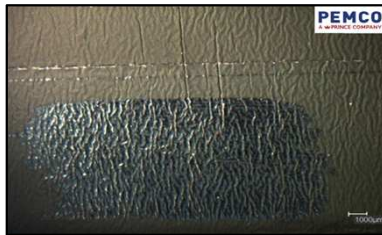


Fig. 5 Shrivelling of the enamel layer

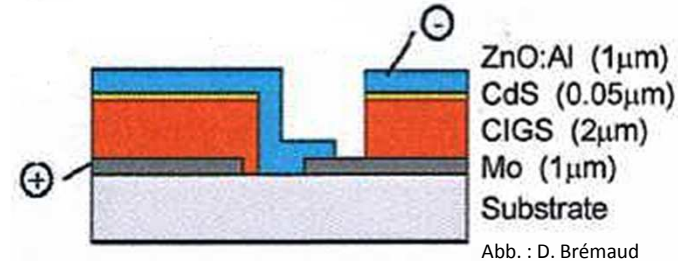


Fig. 6 Laser structured/mechanically scribed trenches

Generally, **scribing/patterning technologies** for flexible substrates to create the needed trenches are not yet fully developed on industrial scale

Outlook

The mentioned main disadvantages of higher costs and the shrivelling of the enamel layer will have to be addressed in a consecutive project.

It should be also possible to further improve considerably the already existing advantages by a further optimization of the enamel composition.

In view of the market interest in improved properties, it is highly probable that CIGS-technology on enamelled substrates will become a real opportunity for the enamel sector, as it was possible to demonstrate the **high potential of enamelled steel for thin-film solar cells as an alternative to rigid glass substrates.**



This project was submitted to the “Steel-innovation price 2015”, a competition of the German steel industry.

Acknowledgements and References



wishes you a sunny day



Photo: D.Jacobs

Acknowledgements and references:

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3. R. Wuerz, et al., CIGS thin-film solar cells and modules on enamelled steel substrates, Solar Energy Materials and Solar Cells (2012), doi:10.1016/j.solmat.2012.01.004.