Solar Cell Technology Innovation Center at MTA MFA

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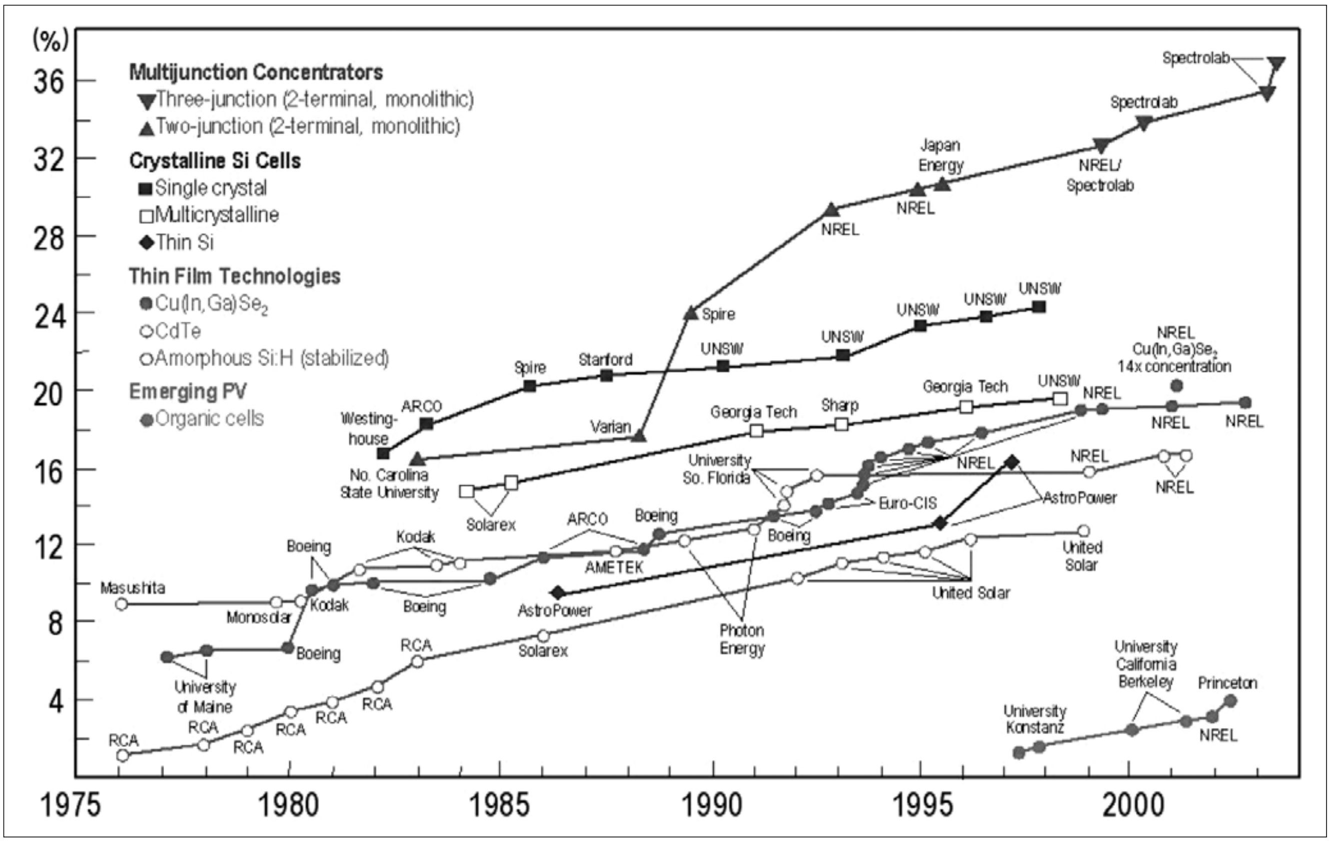
This paper introduces to the reader one of the largest facilities of the solar cell research and development in Hungary – the Solar Cell Technology Innovation Center. The R&D equipment is an integrated vacuum system designed and built for the preparation of thin film Copper Indium Gallium diSelenide (CIGS) solar cell layer structures. The facility was built on the premises of the Hungarian Academy of Sciences by the Energosolar Co. in the frame of a main project funded by the Hungarian National Office for Research and Technology. This paper reviews the layout of the solar cell structure and the equipment for its preparation, introduces the main materials science issues raising in the CIGS system and presenting challenges for the research.

1. Introduction

The worldwide market of renewable energy sources (and especially the photovoltaic cell market) is currently in the phase of dynamic extensive growth. This is due to political factors (increasing concerns about global warming, the Kyoto and Rio protocols) as well as to rapid technological development. The production of photovoltaic (PV) cells and modules increased by 35% over the last decade and reached the 1 GW per year level in 2004. The largest segment of the production is based on crystalline silicon (c-Si) technologies.

In the same time the PV industry has to face the limited feedstock of crystalline and polycrystalline silicon and this problem became a bottleneck for the production. Although silicon is one of the most abundant ele-

Figure 1.
Cell efficiencies of different type solar cells versus production year (Source: www.nrel.gov)



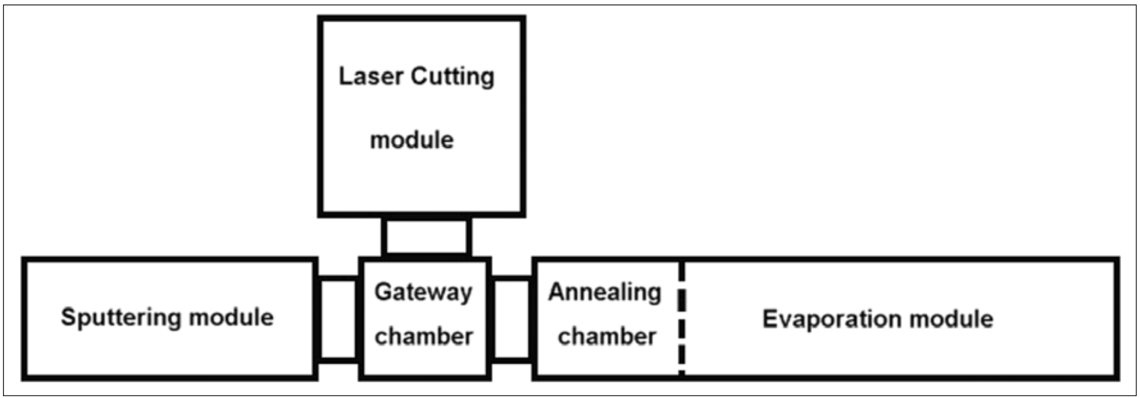


Figure 2. Schematic layout of the integrated vacuum system

ments available in the Earth's crust, the production of solar grade (crystalline) c-Si is an expensive and energy-consuming process. According to reliable market studies this will lead to the saturation of the global solar cell production at the ca. 3-4 GW per year level within the next decade [1-3].

These factors gave impetus to the development of *non-silicon based thin film* solar cells. The most promising alternative to silicon is the copper-indium-gallium-diselenide (CIGS) based thin film PV cell. CIGS already emerged as an ideal choice for PV material in the 80's and the research and development of this material gained momentum in the recent years.

The main advantages of $CuInGaSe_2$ for PV application are the followings:

– a stable chalcopyrite structure,
– p-type conductivity easily achieved by Cu-poor growth processes, and
– very good feasible cell efficiency (current value of laboratory record is 19% while commercially available products have 11%).

This value is very promising compared to the 12,7-13,5% typical efficiencies of c-Si modules, moreover, laboratory research shows the possibility of further improvement. *Fig. 1.* summarizes the trends of cell efficiencies of different solar cell types (based on the data of the US National Renewable Energy Laboratory).

The largest Hungarian R&D project of this promising field started in 2001. The aim of the project was to build an integrated vacuum technology system suitable for the deposition of a CIGS solar cell layer structure, for the development of the complex technology and for the education and training of professionals. The project was financed by the Hungarian National Office for Research and Technology (NKTH). A leading enterprise of the Hungarian vacuum technology industry that time – Kraft Rt. – played the role of initiator in the project. This company was also the first leader of the R&D consortium, but for various reasons handed over this role in 2004 to the Research Institute for Technical Physics and Materials Science of the Hungarian Academy of Sciences (MTA MFA).

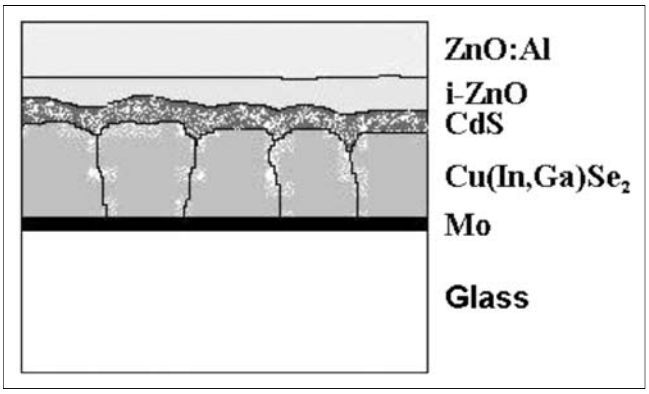


Figure 3. Schematic cross-section of a CuInGaSe2 solar cell structure

Another industrial partner in the consortium was Electrical Drives and Vehicle Electronics Ltd. (VHJ Kft.), while further academic partners were the Institute for Nuclear Research of the HAS (MTA ATOMKI) in Debrecen, Department of Optics and Quantum Electronics of the Science University of Szeged, and the Department of Electron Devices of the Budapest University of Technology and Economics (BME EET).

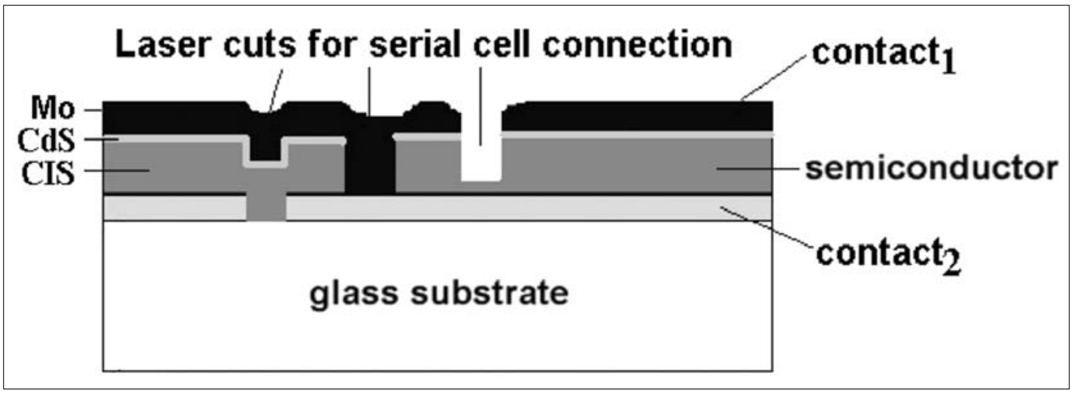


Figure 4. Laser cut in the layer structure and cells connected in series

2. Structure of the integrated vacuum system

In the frame of the project mentioned above an integrated vacuum system was built at the premises of the MTA MFA (completed in 2007) which is suitable for the deposition of CIGS solar cell layer structure on a 30x30 cm^2 glass substrate. The system was designed and built by Energosolar Co. *Fig. 2.* represents the schematic layout of the equipment, while *Fig. 3.* shows the cross-section of the layer structure to be deposited in the system.

In order to form the solar cell structure the CIGS semiconductor layer has to be inserted between two contact layers (in this case between a Mo back contact and a ZnO top window layer) and the whole layer sequence has to be deposited onto the surface of a glass substrate. In order to achieve this goal an integrated vacuum system consisting of four main modules was built:

- Deposition of the contact layers is by magnetron sputtering while the deposition of the CIGS layer is carried out by vacuum evaporation. Therefore the main layer growth units in the system are the sputter- and the evaporation chambers.
- In order to obtain a solar module with the proper terminal voltage the deposited layers have to be segmented and the individual cells have to be connected in series electrically. Therefore, proper grooves have to be formed in every deposited layer according to *Fig. 4.* Formation of these cuts is made by focused laser beam, this technological function is located in the laser cutting chamber (Fig. 2.)
- The fourth processing unit is the gateway chamber situated in the middle of the system. This module ensures the bidirectional movement of the glass substrate between the technological units.

A 10^{-6} mbar end-vacuum can be achieved in the large chambers by using oil diffusion pumps. The chambers are separated by pneumatic latches. The valves, latches and the elements of the transport mechanics are controlled by a purpose-made software integrated into the system.

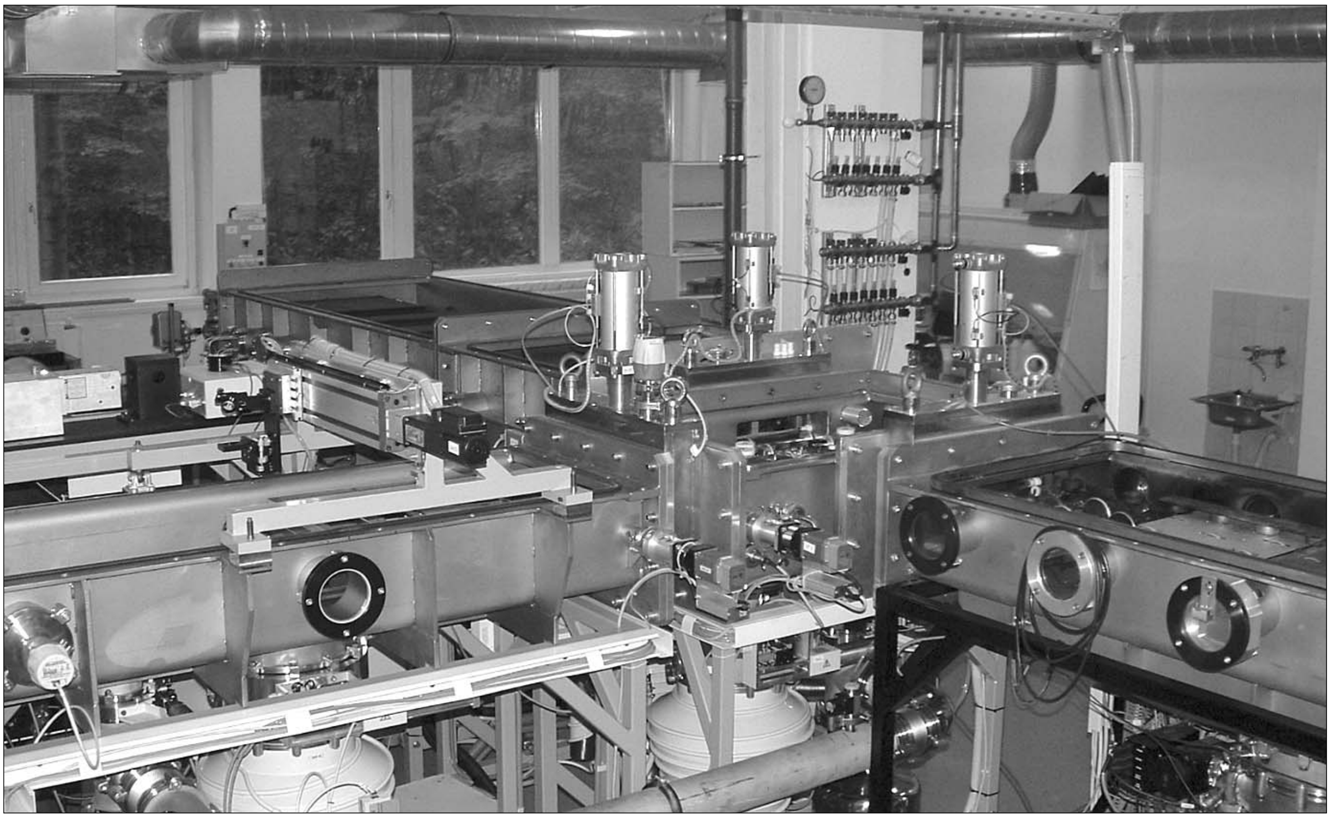
Deposition of the transparent conductive contact layer (ZnO window layer) is performed by reactive sputtering. The sputtered target is a metallic Al-Zn alloy while the reactive deposition takes place under argon-oxygen plasma. The aluminium is incorporated into the material as an n-type dopant and thereby provides the proper conductivity for the transparent contact layer.

The most sophisticated and most critical parts of the system are the evaporating sources containing graphite distributor pipes. The line sources consist of four point sources and their proper dimensioning and arrangement ensures the thickness uniformity of the evaporated layers.

Deposition is carried out by using the co-evaporation method. Individual sources evaporate the elemental source materials (Cu, In, Ga, Se) while the final crystalline structure and morphology is determined by an appropriate thermal annealing programme in the preheating/cooling chamber (Fig. 2.)

Fig. 5. shows a photograph of the vacuum system.

Figure 5.
The integrated vacuum system with the laser cutting chamber in the foreground



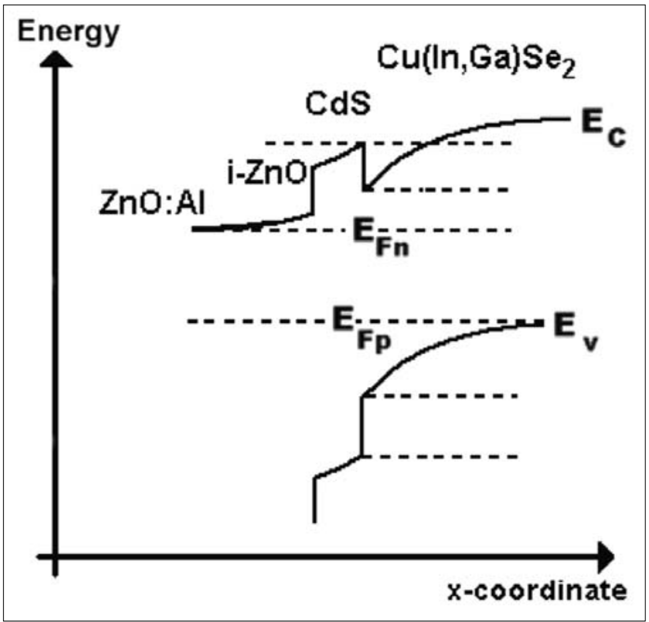


Figure 6.
Band structure of a CIGS solar cell layer sequence [4]

3. Materials science issues related to the $CuInGaSe_2$ material system

The high optical absorption of the direct semiconductor chalcopyrite makes solar cells based on very thin absorbers feasible. However, it also means that the incident sunlight is absorbed close to the surface. Assuming, it would be possible to dope chalcopyrite in a well controlled manner it would still be challenging to reach high efficiency with homojunction solar cell since the major part of carriers generated between the surface and the pn-junction would be lost by the surface recombination.

This problem is avoided by introducing the heterojunction concept with window (transparent conductive ZnO)-layer and absorber layer. Due to the wide band gap of the window layer, the absorption is shifted away from the surface to the internal hetero-interface The most effective approach to lowering recombination lies in minimizing the density of electrons or holes at the interface, which requires appropriating doping band line-up (matching) and interface charge.

The structure should contain an n-window – p-absorber heterojunction *(Fig. 6)*, where the Fermi-level at the interface is close to the conduction band and where the Fermi-level intersects the midgap energy at a short distance from the interface in the absorber. The interface charge should be positive to assist in establishing the structure.

Deposition of a CIGS layer structure with optimal properties therefore necessitates the study of the following five materials science issues:

– characterization of the shallow acceptor levels formed under Cu-poor growth conditions (these make possible the p-type autodoping of the material);
– formation of the optimal band gap by changing the In/Ga ratio in the layer, and formation of a graded band gap CIGS layer;
– study of the effect of the grain size distribution on the layer properties;
– study of the Na outdiffusion from the substrate glass;
– deposition of a buffer layer between the CIGS and transparent conductive ZnO contact by vacuum-technology compatible means (Fig. 6.).

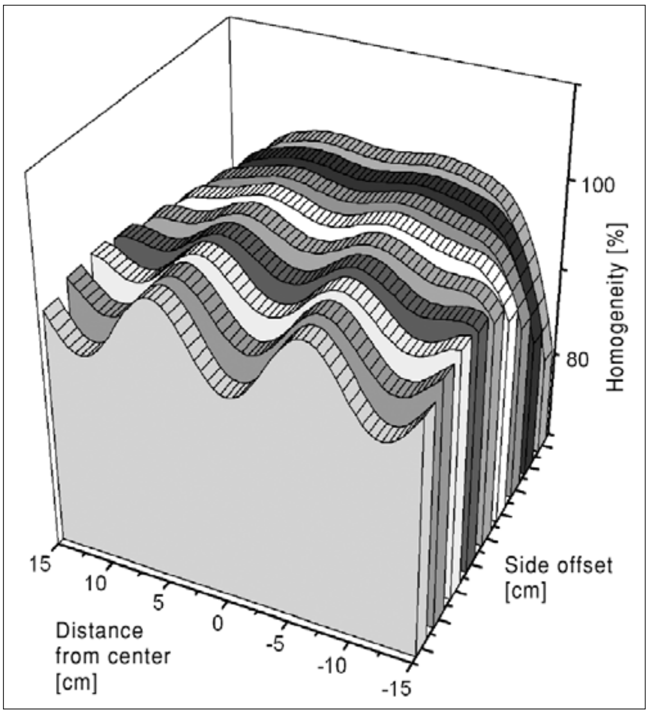
The results of the experimental work already carried out in the Solar Cell Innovation center can be summarized as follows [5-14]:

• The effect of the deposition parameters on the quality of Mo contact layer and the ZnO:Al window layer were studied in detail in the sputtering module. An optimal technology was elaborated together with the necessary conditions for reproducibility at room temperature. The obtained layer has the specific resistance of 1.7x 10^{-4} Ωcm, which is compatible with the best results published in the literature albeit with heated substrate.

• From our processing experience we determined that deviation from the optimal composition in the ZnO layer (towards the metallic as well as ceramic direction) can be monitored by spectroscopic ellipsometry. This allows the in-line integration of an efficient measurement technique into the system.

• The technology for selective laser cutting of ZnO and Mo layers was successfully elaborated in the laser module in cooperation with the researchers from the Department of Optics and Quantum Electronics of the Science University of Szeged.

Figure 7.
Dependence of lateral thickness homogeneity of evaporated CIGS layers as a function of the source geometry



• A process for wet chemical deposition of CdS buffer layer between the CIGS and transparent conductive ZnO contact (Fig. 6.)

• A computer model for the thickness uniformity of layers deposited from line sources was developed on the basis of evaporation experiments from an individual source. This model served as a basis for the design and construction of the evaporation chamber.

The materials analysis support required by the Solar Cell Innovation Center is provided by MFA and the other academic institutes in the consortium. The complex system of analyses and characterizations includes the following items:

1. Morphology study by Scanning Electron Microscopy SEM–FESEM (MFA)
2. Elemental composition analysis by Electron Dispersive Spectra (EDS) (MFA)
3. Elemental composition and phase analysis by X-ray diffraction (MFA)
4. Photoluminescence analysis (MFA)
5. Ellipsometric layer thickness and composition analysis (MFA)
6. Electron spectroscopy (XPS) and Secondary Ion Mass Spectrometry (SIMS) (ATOMKI)
7. Surface potential measurement (Kelvin probe method) and open circuit voltage measurements (BME EET)

5. Summary

This paper is an overview of the Solar Cell Technology Innovation Center which was built by a Hungarian R&D consortium at MTA MFA. This unique facility in Hungary is suitable for the development of process sequence for CIGS solar cells. It consists of a closed cycle vacuum pilot production-line equipped with laser cutting facility and in-line measurement techniques, an is applicable for:

– processing R&D purposes;
– professional training and education;
– support of the marketing activity of the industrial partner;
– pilot production of 300x300 mm^2 CIGS photovoltaic modules with an efficiency of ca. 12%.

The results of the project are also documented at http://www.mfa.kfki.hu/Napelem-CIS/.

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