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Challenges of vacuum roll-to-roll processing of organic solar cells and encapsulation processes

Heliatek uses an efficient roll-to-roll process in vacuum and inert atmosphere to manufacture highly flexible solar films. Our product Heliafilm(R) consists of a multi-layer system of organic small-molecular materials which is deposited in vacuum onto a pre-structured PET/TCO substrate and successively encapsulated into a barrier film system to protect it from water and oxygen.

This process enables a high throughput, high yield and low costs in addition to individual design for customization.

The Heliafilm has unique properties compared to standard or inorganic thin film PV modules. An ultra-light weight product of lower than 500 gram per square meter with a thickness below 1 mm is produced.

Different organic materials and stack designs provide different appearances of the Heliafilm. So we are able to tune the color of the film from grey to blue or green shades. By changing the second electrode material with a semi-transparent one, a solar film with a transmission of light up to 50 % is realized with an efficiency of 6 %. For opaque solar films an efficiency of 13.2 % was shown by the end of last year.

These properties generate new and exciting applications which are created together with our customers and partners – especially for buildings as active facades, and in the field of automotive.

Heliatek develops and synthesizes the absorber materials for the on lab level. When matured, Heliatek transfers these lab results to an in-house pilot line with the complete process from unstructured film material to final OPV product.

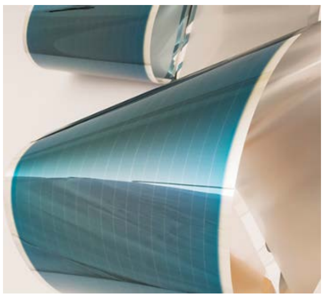

Figure 1a: roll-to-roll encapsulation tool *b: HeliaFilm*

The pilot manufacturing line for flexible OPV film manufacturing consists of three main roll-to-roll tools for the processing of polyester films with a width of 300 mm:

1) Laser tool for structuring of the TCO coating on PET film,

2) Vacuum deposition tool for the organic stack with electrode layer including laser structuring processes,
3) Encapsulation tool for the lamination of the active film between barrier films.

In the front end tool 1 the handling of substrate will be done in an inert nitrogen atmosphere and transferred after the process in a cassette to the vacuum tool 2 without breaking the nitrogen conditions. After deposition the organic stack and application of a protection back film the material will be moved under inert atmosphere to the encapsulation tool 3. This tool is part of the so call back end process which is placed directly after the active solar film is produced. The lamination process in the encapsulation tool will be done also in an inert atmosphere and is discussed later.

Vacuum processing of OPV films

After the structuring of the TCO coated substrate to separate the first electrode by a laser P1 process the film is transferred to the deposition tool.

The deposition of the multi-layer organic stack including a second electrode is done in high vacuum process to form the OPV on top of the substrate. After organic and metal layer deposition the P2 and P3 laser process separate the different active areas to create the solar cells. This monolithic integration is shown in Figure 2.

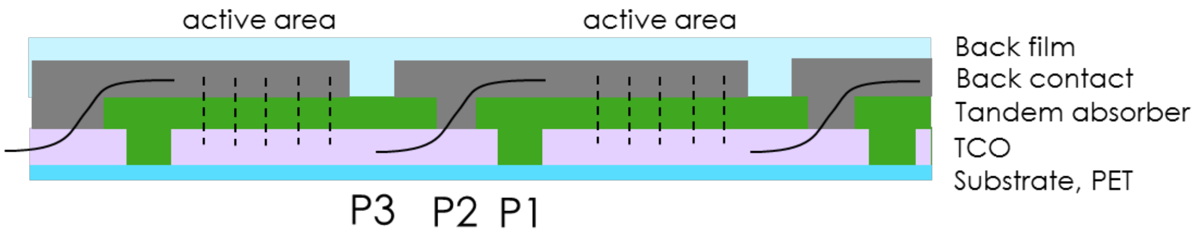

Figure 2: cross section: OPV module after front end process

The active layers are sensitive against moisture and oxygen and extremely smooth. Therefore a handling under vacuum in the tool and inert atmosphere in the cassette afterwards is needed. The surface protection of the layers is done by a protection film lamination after the deposition and before winding the substrate to the cassette.

During the deposition process the film is handled without touching the active area to prevent damages of the sensitive layers. In case of the pilot manufacturing tool a length of about 50 m without front side touch is realized in vacuum by the unique design of the tool.

Encapsulation process for OPV films

After the transfer of the cassette from the vacuum tool to the encapsulation tool the lamination of barrier films occurs to protect the sensitive active materials from moisture and oxygen. These processes are handled under inert nitrogen atmosphere.

The active substrate is encapsulated between two barrier films at the front and back side. Before the lamination the barrier films are pre-treated by a corona process and applied with adhesive. On substrate back side a bus bar is laminated to collect the current out of the OPV structure. After the lamination process a treatment step for curing the adhesive is done and the laminate will be transferred out of the tool to normal atmosphere. The result of the encapsulation process is shown in Figure 3.

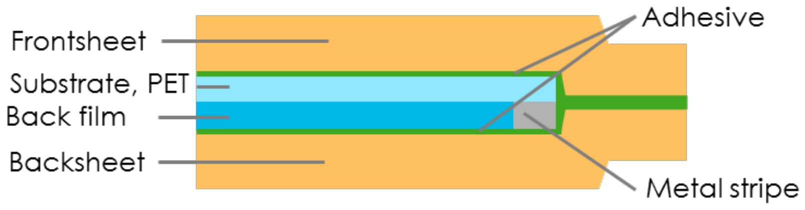

Figure 3: cross section: module out of the back end

Inert handling

During the process, the encapsulation tool is flooded with nitrogen. The level of oxygen can be controlled by an oxygen sensor. The base level has to as low as possible and in the actual tool in the range of 100 ppm to protect the substrate during the process.

In this work the influence of the process of pre-treatment with an exhaust equipped to remove generated process gases will be discussed.

After loading the cassette, nitrogen flooding of at least half an hour is needed to reduce the oxygen concentration to the base level. At tests a dramatically increase of that level could be observed due to the process of pre-treatment. The root cause was indicated to be the exhaust of the pre-treatment process. When opening the valve the nitrogen is removed out of the process chamber and due to leaks in the chamber air from the outside is contaminating the inside. In Figure 4 the standard process is presented and the dramatically increase of the oxygen level of around 20000 ppm can be seen.

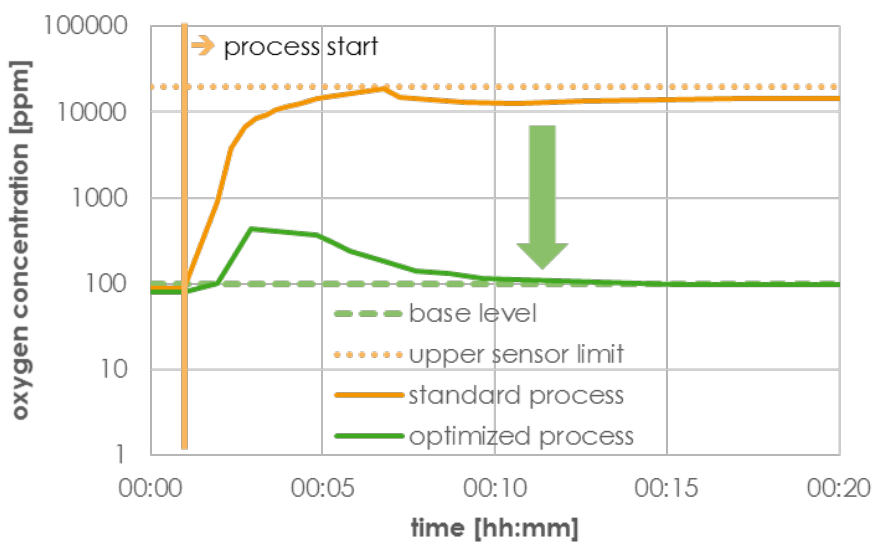

Figure 4: oxygen level for standard and optimized process

After detecting and closing the leakages in the tool and optimizing the exhaust gas flow the oxygen tracking during the process was repeated and the optimized process shows only a slight increase of the oxygen level at the beginning of the process but stable conditions after 10 minutes.

Another impact to the oxygen level inside the tool occurs at the exchange of barrier film due to reload of new films. In that case the tool is opened partly by a door at the barrier film winder and the other tool chambers are locked by valves.

But also a slight contamination of the atmosphere by air is assumed and the effect on the active solar cells was checked by electrical measurements.

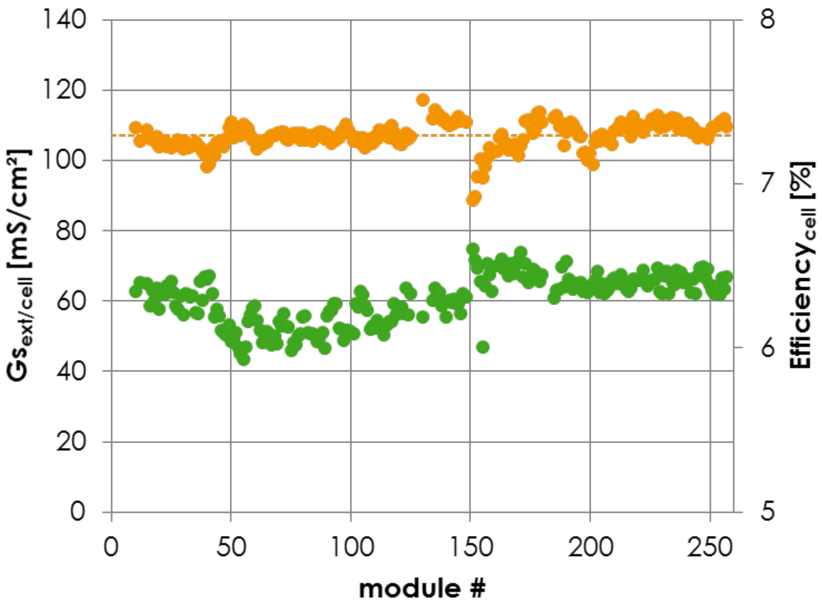

Figure 5: efficiency and conductivity per module #

In Figure 5 the same electrical parameters are shown for the encapsulation of 255 modules. After module 150 the process was interrupted and the barrier films exchanged. It's clearly visible that the conductivity (Gs_{ext}) of the cells decreased directly after the film exchange but within the 20 modules after the restart turned in to the expected values again. The overall efficiency of the cells is nearly stable. The differences before and after changing the film is indicated to different film material with slightly different transmission values.

Upscaling of lab results to manufacturing processes is one of our goals. The achievements in the lab were demonstrated to be successfully transferred into the pilot line. As a result the I-V curve of a solar film with key values are shown in Table 1 and Figure 6.

Table 1: aggregated data

parameter	value
V_{OC}	41.15 V
I_{SC}	1113.5 mA
FF	66.4 %
V_{mpp}	31.89 V
I_{mpp}	953.6 mA
P_{mpp}	30.409 W

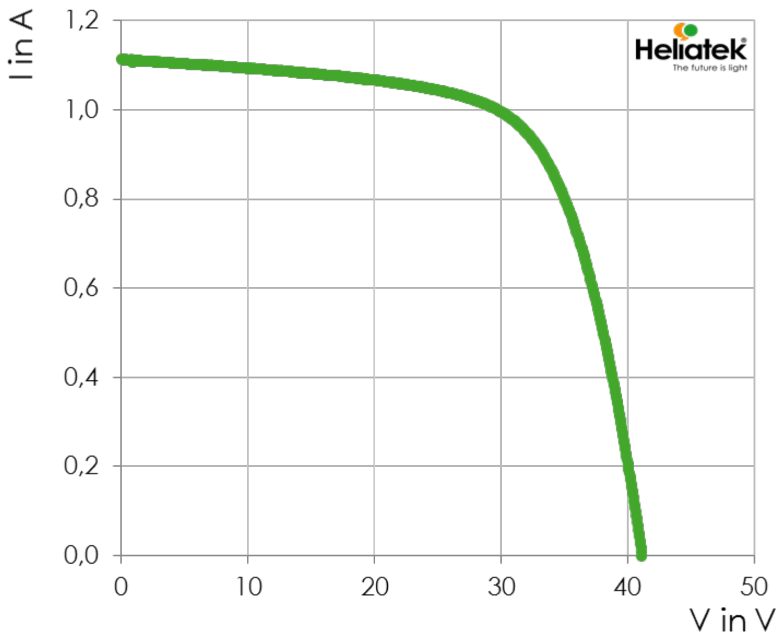

Figure 6: I-V-curve from a module out of the production

A power conversion efficiency of 7.7 % and a fill factor of 66.4 % showing the capability of the pilot manufacturing process for a tandem OPV stack structure and repeated the lab results.

Summary

In this work a complete roll-to-roll process for OPV manufacturing is presented. The in-house OPV stack developments in the lab were successfully transferred to the roll-to-roll pilot manufacturing line. Measurements of the produced solar cells show comparable electrical properties with a highest power conversion efficiency (PCE) of 7.7 % for the active area.

At a distance of about 50 m the film handling is realized without touching the deposition side of film under vacuum conditions. Furthermore the encapsulation under inert conditions and the improvements of the pre-treatment process with lower oxygen content in the chamber are shown. This improvements enable a stable and reproducible encapsulation process and the influence of the barrier film exchange to the conductivity Gs_{ext} can be observed.

The pilot manufacturing line gives the chance to supply a larger area of Heliafilm to realize first pilot installations together with our partners. Solar films are installed and tested under real conditions and the results will be used to further improve the film to fit the market requests.

Next generation of manufacturing tools

Actually the main focus targets some issues that are encountered in our current small-scale pilot-production line. This addresses the challenges connected to an upscaling of our technology to industrial manufacturing. Therefore a new project called Fab2 is started with the following requirements

- upscaling the film width to 1200 mm together with the deposition and other process equipment,
- small foot print of the manufacturing tools,
- accurate film handling to adjust the laser structuring exactly including a defined film temperature during the depositions,
- sequencing of proven laser patterning across wider web,
- improved encapsulation process to increase lifetime further,
- implementation of flexible layout in width and length of the product.

Therefore the next generation of OPV production tools will be deployed in Dresden with a higher throughput, improved yield and uptime together with low cost manufacturing.

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