TOWARDS LOW COST, EFFICIENT AND STABLE ORGANIC PHOTOVOLTAIC MODULES

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ABSTRACT: This article describes how the Solliance Organic PhotoVoltaics (OPV) shared research Program addresses efficiency, lifetime and production costs for (near) future OPV applications. The balance of these three parameters depends of the envisaged application, but at the end, OPV should be able to compete somehow with Si PV in the future. Efficiency improvements are realized by developing new materials, , by exploring and optimizing new device structures and novel interconnection technologies. Lifetime improvements are realized by using stabilized device stacks and materials and by applying high end flexible barriers. Production cost control is done by using a home made Cost of Ownership tool which guides towards the use of low-cost materials and processes.
Keywords: Organic Photovoltaics

1 INTRODUCTION

The growing interest in organic photovoltaics (OPV) is caused by their promise for low cost energy conversion. In order to have an impact on the power generation market on the longer term, OPV should combine high power conversion efficiency with low production costs and long term stability.

The Solliance OPV shared research program, a joint initiative of imec, ECN, Holst Centre and the Eindhoven University of Technology, together with its industrial partners, offers a complete set of skills and technologies to enable fast and efficient technology transfer to future OPV manufacturers.

Depending on the end-application envisaged and the estimated annual production for that application, Solliance developed a Cost of Ownership combined with a Life Cycle Analysis modeling tool to select the most appropriate materials, device lay-outs and production processes.

Starting from molecular/materials engineering and material choices, device and module optimization, and using different production scenario's, it will be explained how the Solliance OPV Program is able to identify and actually demonstrate OPV manufacturing routes that yield much better values for the final module efficiency, lifetime and projected production costs.

2 PREPARING THE MANUSCRIPT

OPV devices with high power conversion efficiencies (PCE) can only be reached by a combination of novel high performing materials and an optimum device stack, the latter consisting of the right layer thicknesses for optimal light capture in the photo-active layer, the right selective charge conductors at both sides of the photoactive layer and the most optimal and fine-tuned processing conditions. The Solliance OPV shared research program focusses on the development and testing of new high performing materials, the development of improved interlayers, new device designs and novel interconnection technologies to achieve high active area coverage.

2.1 Single Junction solution processed OPV Cells

The OPV team of imec was able, within a collaboration of Solvay and Polyera to reach a certified PCE value of 8.3% for a single junction inverted OPV cell design by using a novel p-type polymer semi-conductor [1]. Novel interlayer processing based on the use of TiOx has allowed creating a very efficient inverted architecture in which parasitic optical absorption losses were strongly minimized. This architecture has in the mean time proven to be widely applicable on a broad range of active materials, polymers as well as evaporated small molecules, and recently has enabled to cross the 9% efficiency barrier (internal result).

2.2 Tandem solution processed OPV Cells

The OPV team of the Eindhoven University of Technology was able to produce a 8.24% efficient solution processed polymer tandem solar cell using efficient small and wide bandgap polymer:fullerene blends. For this, they synthesized a novel small bandgap p-type polymeric semi-conductor based on a di-keto-pyrrolo-pyrrole-oligothiophene copolymer (PMDPP3T). They demonstrated [2] that a PMDPP3T:[60]PCBM layer can be used to make a 8.24% efficient tandem cell that employs PCDTBT:[70]PCBM [3] as the complementary wide bandgap absorber (Figure 1).

2.3 Single Junction solution processed Modules

As steady increase in power conversion efficiencies for individual (small) OPV cells is extremely important for future real life applications, fabrication of high efficient larger area modules is the next step towards an uptake of the manufacturing industry and the consumers. The OPV team of imec, together with Solvay and Plextronics, was able to produce a certified 5,5% efficient 8-cell module with an aperture area of 25 cm2. This module had only about 7.5 % active area loss by using a mechanical scribing process for the interconnections in between the neighboring cells. Currently, laser scribing is being evaluated to determine how these interconnects can be made in an accurate way on an industrial scale. [4].

3 LIFE TIME

Internal factors that could negatively effect the (operational) lifetime of OPV devices and modules, like e.g. intrinsic instability of materials, reactive impurities, reactive interfaces, ... should of course all be avoided as much as possible. Today, external factors like temperature, light and atmospheric ingredients like O2, H2O are considered as the main root cause factors for a gradual degradation of OPV devices and modules. A comprehensive review on this topic has been published recently by N. Grossiord et al. [5]. In real life, light can of course not be omitted for operational reasons, but partially filtered (e.g. UV) if needed for stability reasons. Temperature variations are part of real life as well and are also difficult to avoid, but differ substantially depending on the targeted application in which OPVs will be used. Air ingredients are always present on earth, but by using appropriate barriers and encapsulation materials and technologies, large part of these harmful air ingredients can be excluded. These three main root cause factors are almost always present simultaneously. Some of these can sometimes activate or accelerate another one, making a systematic study of the occurring deterioration mechanisms rather complicated. Generally it is believed that for long term outdoor stability (e.g. > 20 years) stable materials and device stacks will be needed together with stable interconnection technologies and high end packaging materials and technologies. Apart from these three potential harmful ingredients, overall mechanical stability for flexible devices, chemical stability of the packaging material (e.g. animal secretions, salt in the neighborhood of sea shores, hail, …), and others, will also play important roles for future applications.

Two of the approaches of the Solliance OPV program in order to come to stable OPV modules, will be exemplified further.

3.1 Choice of low water sensitive materials

As mentioned above, a complete inhibition of water ingress by using cost-affordable flexible packaging for > 20 years will be extremely difficult. Hence, electro-active materials and device stacks that are less vulnerable towards water will definitely also be needed.

The OPV team of imec discovered that the PEDOT/PSS, a Hole Transport Layer or Electron Blocking Layer (HTL/EBL often used in OPV devices, caused a rather fast degradation of inverted OPV devices upon exposure to ambient air conditions. This is probably due to its hygroscopic nature. An alternative HTL/EBL based on evaporated or solution processed MoOx showed a drastic slow-down of the degradation at atmospheric conditions. This indicates that by selecting appropriate electro-active materials, basic stability of OPV devices can already be improved substantially.

3.2 High end flexible barriers

Within Holst Centre a high end barrier and encapsulation has been developed for flexible Organic Light Emitting Diodes (OLEDs). As these devices often need a cathode with a quite low work function for efficiency reasons, this cathode is extremely sensitive to water induced degradation. Hence, barriers with extreme low water vapor transition rates (WVTR) are needed in order to keep these OLEDs stable in time. For this application, Holst Centre developed a transparent and flexible packaging stack and technology with a WVTR of 10-6 g/day.m2. Regular OPV devices with a composite transparent electrode based on printed silver and printed highly conductive PEDOT/PSS, a spin coated P3HT:PCBM layer and an evaporated LiF/Alu top electrode were produced on top of this flexible barrier and subsequently encapsulated with the complementary thin film encapsulation. A similar slow decrease of the PCE value of about 5% was observed when exposed to 1 sun and 45°C during 1.000 hours with devices produced on glass and encapsulated with a metal lid containing a getter (Figure 2). This indicates that the thin film barrier and encapsulation developed at Holst Centre for OLEDs, looks very promising for stabilizing OPV devices as well.

4. UP-SCALING, COST AND ENVIRONMENTAL IMPACT OF THE MATERIALS AND PROCESSES

4.1 Cost of Ownership Calculations

The OPV team of Holst Centre together with ECN, developed a highly detailed Cost of Ownership (CoO) tool in order to be able to calculate the cost determining factors for a final OPV production plant with pre-defined processes and a pre-defined production capacity. By using this CoO tool for a hypothetical R2R fab for solution processed OPV modules with an annual production of 250 MWp, it could be concluded that the cost for OPV production is mainly (60%) determined by the cost of the materials.

The most important material cost-drivers are Indium Tin Oxide (ITO), the barrier and the silver. Hence, last years R&D focus was to find an alternative for the expensive ITO on PET. This finally resulted in the use of a printed silver grid and a printed highly conductive PEDOT/PSS as a low-cost, transparent composite electrode. Replacing the PET + barrier with a metal foil, whilst keeping the thin film encapsulation unaffected, also results in a major cost saving. Further, by a hypothetical change from printed silver to printed copper, work that is currently in progress, a third major cost saving can be obtained.

Applying only these three cost saving measures for a hypothetical starting cell efficiency of 12%, which results in a 9.3% aperture module efficiency without applying yet sophisticated interconnection techniques by just printing the interconnects, can result in a overall production cost of about 0,5 $/Wp (Figure 3).

Of course, much more can be undertaken to decrease further the production cost of OPV modules: larger production plants, higher efficient devices and modules, looking for other lower cost materials and also very important, increasing the production yield. As a low production yield will result in the generation of a substantial amount of scrap, which in turn is made of expensive materials, the scrap costs can be really high. It is calculated that even for typical industrial viable individual process yields, the scrap cost can be as much as 1/3th of the overall cost.

Within the eco-system of Solliance, a dedicated program on this important topic is currently running.

Starting from (1) defect prevention by e.g. novel S2S and R2R equipment design for low particle generation, optimized working procedures and new cleaning technologies, via (2) inspection and detection by e.g. the development of novel inspection technologies and tools for extreme small particle detection, the development of fast and high accurate layer thickness measurement techniques and tools and creating fast feedback loops for automated correction in case drifts in the process are occurring and finally (3) developing of repair strategies in case an OPV module with fatal defects can still be repaired by a (local) impact of e.g. a laser.

4.2 Environmental Impact of Production

The OPV team of ECN uses the commercial and widely used software Simapro in conjunction with its integrated Ecoinvent 2.0 database to calculate the environmental impact of the individual materials and processes. It is found [6] that for sputtered and patterned ITO on PET, compared to a printed silver grid, the embedded material energy is similar: ca 15 MJ/m2 for both options. The difference is in the embedded energy for the processing: ca 35 MJ/m2 for ITO versus 20 MJ/m2 for printed silver. Large part of the latter comes from the thermal sintering process, which takes typically 10 to 30 minutes. Flash sintering, a novel fast annealing approach, can bring this value much lower, as sintering is now feasible within several seconds.

Needs to be said that for power-generating applications, the embedded energy on the module level is on the order of ~300-500 MJ/m2, which is by far the lowest value compared to all other PV technologies. The largest part comes from the encapsulation scheme with a contribution of ~200-400 MJ/m2.

Anyway, thanks to these very low embedded energy values, it is shown that the environmental profile of polymer-OPV is highly competitive with other thin-film PV technologies on a m2 basis as demonstrated by an Energy Pay Back Time (EPBT) < 1 year for example which is similar to the conclusions drawn earlier by Krebs and Roes [7].However, when expressed on a Wp basis or in the ultimately most relevant kWh basis, this competitiveness is (partially) lost due to the lower module efficiency and lifetime expectancy. For polymer-OPV to become an environmentally viable power-generating PV technology these latter two parameters (module efficiency and lifetime) necessarily need to be further improved. Regarding the transparent ITO electrode, the replacement of this compound by alternative electrode materials - which are not based on indium - is desirable, primarily from the point of view of indium scarcity. Such alternatives should ideally not be based on silver though, which is expected to face its own critical supply/demand imbalances in the near and longer term future as well. Therefore, work in progress is on-going to replace printed silver by printed copper.

4.3 Low-Cost OPV Production Scenario

As a result of the above explained CoO calculations and the LCA results, Holst Centre and ECN developed an all-solution processed OPV device, with a low-cost production potential and a low environmental impact. It is shown that these all-solution processed inverted devices, consisting of six subsequently solution processed electro-active layers on glass (printed Ag/HC-PEDOT/ZnO/P3HT:PCBM/PEDOT/printed Ag) have equal PCE's compared to the standard lab devices prepared on glass (ITO/PEDOT/P3HT:PCBM /Li/Al (regular device structure) or ITO/ZnO/P3HT:PCBM/PEDOT/Ag (inverted device structure)) [8].

Once this all-solution processed device stack was proven to be feasible and equal performing compared to the reference cells, optimization of the composite electrode was further elaborated. As this composite electrode consists of a high conductive current collecting grid and a lower conducting transparent PEDOT/PSS layer, two settings of the grid were needed to be further optimized. First of all, the maximum distance between the grid lines, whether they consist of parallel lines, triangles, squares, polygonal structures, will be determined by (1) the conductivity of the transparent electrode (the newest generation of PEDOT/PSS can yield 200 Ohm/Sq with transparencies for the visible light as high as 95%), (2) the actual IV characteristic of the OPV device (efficiency, but mainly current at maximum power point), (3) the average expected light dose for a given application (outdoor versus indoor) and (4) the maximum accepted efficiency losses caused by the resistivity in the PEDOT/PSS for a given application. Theoretical modeling and experimental verification of the modeling results, yields optimum grid distances of about 2 and 3 mm, for outdoor applications with average currents flowing through the single cell devices of about 10 mA/cm2. These grid line distances can be rather easily obtained by standard printing processes like ink jet or screen printing.

If only a 5% area coverage over the conductive grid is accepted, this would mean that the grid line widths should not exceed 100 – 150 µm. Although this should be feasible again by using ink jet or screen printing, it is on the edge concerning the speed of ink jet printing (the smaller the printed features, the slower the printing process) and on the edge of rotary screen printing, where the highest industrial resolutions obtained so far are 80 µm. Therefore, the partners of the Solliance OPV program have dedicated activities on these new challenges for printed OPV devices and modules: printing of sub 100 µm features at high speeds and with high topology. The latter originates from the fact that high topologies will create lower sheet resistances in the current collecting grids, resulting in the possibility to create larger individual cells with low resistance losses. This in turn, with a given, preferably minimized (non-active) interconnection, will automatically yield higher efficient modules, as the total inactive area will become lower. Compared with ITO on PET foils with typical values of 60 Ohm/Sq and a transparency between 85% and 90%, a conductive grid with 1 Ohm/Sq and a surface coverage of only 5% should have definitely its advantages.

Unfortunately, this can only be reached by applying conductive structures with high topologies, resulting in incompatibility of the application (printing or coating) of the subsequent electro-active layers, i.e. the transparent conductive PEDOT/PSS layer. To overcome this issue, several embedding strategies were developed. As a result, the conductive grid can be embedded either directly in the barrier or in any embedding material, depending of the requirements of the final application.

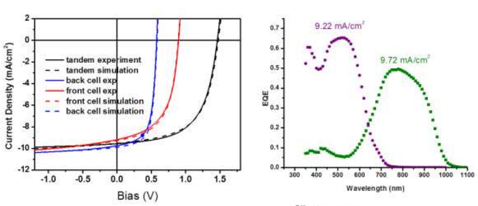
Once a flat, but highly conductive grid can be produced, the subsequent sub-micron thick electro-active layers will need to be deposited on top of that. For this, up-scalable non-contact deposition techniques are under research at the Solliance partners: slot die coating and spray coating, with different patterning approaches and ink jet printing with dedicated layer leveling strategies. As top electrode, a coated metal layer for non transparent applications can be used. Or alternatively, for semi-transparent applications or for applications/production processes where the substrate is non-transparent, again, a printed conductive grid in combination with highly conductive PEDOT/PSS can be applied. As this grid is now at the outermost position of the device stack, embedding is not needed anymore.

This is still work in progress, but the latest results are very encouraging and allow ultimately printing any form or shape of high efficient OPV modules, dedicated to a given application, at relevant production speeds with well-controlled layer qualities and high overall production yields. Figure 4 shows a prototype R2R fabricated module using partially the above mentioned production technologies.

5 APPLICATIONS

By using the all-printed OPV approach, variations in the final OPV module layout are quasi infinite. Any form or shape can in principal be manufactured at low cost, as well as any color (of course with some efficiency sacrifycing) for all kind of aesthetical reasons. Also semi-transparency can rather easily be addressed for dedicated applications. Several real and visionary application examples will be addressed.

6 ILLUSTRATIONS



Tandem	J_{sc} (mA cm^{-2})	V_{oc} (V)	FF	PCE (%)
Simulated	9.5	1.47	0.59	8.25
Experiment	9.6	1.46	0.59	8.24

Figure 1: (a) Measured and simulated IV-curves of the regular tandem cell, (b) Measured and simulated cell characteristics with a measured PCE of 8,24%, (c) Photoactive materials used for the regular tandem cell and (d) the corresponding EQE [2].

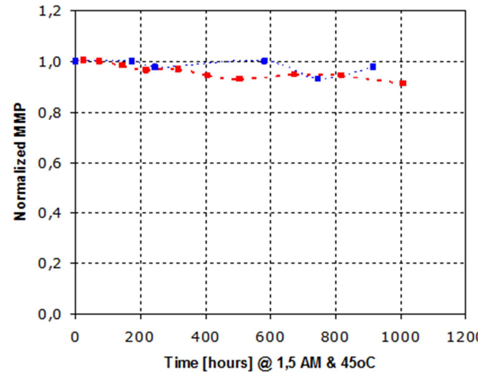


Figure 2: Normalized MPP plotted in function of time of 2 cm x 2 cm cells with the same layer processing and stacking (printed silver current collecting grid/ PEDOT:PSS/PAL/LiF/Al) but different encapsulation methods: Blue curve: OPV device processed on top of a multi-layer barrier stack on PEN and ‘‘closed’’ with a thin film barrier encapsulation and Red curve: OPV device processed on top of a glass substrate and ‘‘closed’’ with an aluminum lid containing a getter and an epoxy adhesive. [9].

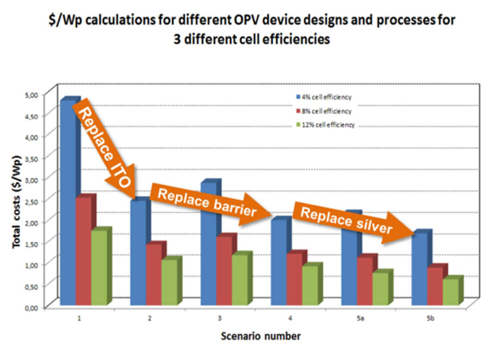


Figure 3: $/Wp calculations for different OPV device designs and processes for three different initial cell efficiencies.

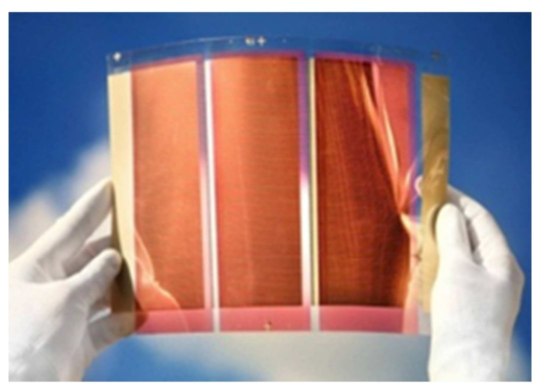


Figure 4: Picture of a R2R produced prototype of a all-solution based OPV module.

7. SUMMARY

In this proceeding article it is demonstrated that the

Solliance OPV Program offers a shared research program on OPV covering all important items towards a near future successful industrialization: starting from materials design and synthesis, optimizing high efficient devices, optimizing modules and implementing low-cost production processes.

8. ACKNOWLEDGEMENTS

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9. REFERENCES

[1] Hadipour et al., Adv. Energy Mater., 2011, XX, 1-6
[2] Veronique S. Gevaerts , Alice Furlan , Martijn M. Wienk , Mathieu Turbiez and René A. J. Janssen, Adv. Mater. 2012,
[3] a) N. Blouin , A. Michaud , M. Leclerc , Adv. Mater. 2007 , 19 , 2295 – 2300 ; b) S. H. Park , A. Roy , S. Beaupre , S. Cho , N. Coates , J. S. Moon , D. Moses , M. Leclerc , K. Lee , A. J. Heeger , Nat. Photon. 2009 , 3 , 297 – 303 ; c) S. Alem , T.-Y. Chu , S. C. Tse , S. Wakim , J. Lu , R. Movileanu , Y. Tao , F. Belanger , D. Desilets , S. Beaupre , M. Leclerc , S. Rodman , D. Waller , R. Gaudiana , Org. Electron. 2011 ,12 , 1788 – 1793 ; d) Y. Sun , C. J. Takacs , S. R. Cowan , J. H. Seo ,X. Gong , A. Roy , A. J. Heeger , Adv. Mater. 2011 , 23 , 2226 – 2230
[4] Tom Aernouts et al., presentation at OPV 2011 Philadelphia
[5] Nadia Grossiord et al., Organic Electronics, 2012, 13, 432–456
[6] Frank Lenzmann et al, Proceedings of 26thEUPVSEC 2011, 4AV.3.61, 3835 - 3839
[7] a) A.L. Roes et. al., Prog. Photovolt: Res. Appl. 2009, 17, 372; b) F. Krebs et al, Nanoscale, 2010, 2, 873.
[8] Sjoerd Veenstra et al, Proceedings of 26th EUPVSEC 2011, 1CO.9.1, 214 - 217
[9] Yulia Galagan et al., presentation at ISOS-3, Roskilde, 2010