ORGAPVNET:
BUILDING A REALISTIC ROADMAP FOR ORGANIC BASED PHOTOVOLTAICS

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ABSTRACT: Solar cells with active layers, partially or fully based on organic materials, are the subject of large interest, both from R&D-actors as from large investors. This interest is fuelled by the rapid developments in the field of organic based devices with certified efficiencies between 5 and 6% for full-organic devices and 11% for dye sensitized solar cells, the potentially very low cost of these devices, mechanical flexibility and light weight. The low cost potential is based on the use of low-cost materials and substrates and the very high production speeds which could be reached by roll-to-roll processing. In addition, organic photovoltaic devices take profit of the developments in neighbouring fields like Organic LED's and thin-film transistors, which could create synergetic effects similar to what was observed for crystalline Si solar cells which took benefit from the large knowledge and equipment base, built up in the micro-electronics sector. Notwithstanding all these promises, there is a strong need to define correctly the technical and scientific challenges, to outline the way these challenges have to be tackled and to define the markets in which these organic photovoltaic devices could create large impact. This is done in the frame of the European Project ORGAPVNET. The paper aims at bringing this information in a concise form to the broader PV-community to improve the understanding of this emerging field, to explain how this information is going to be used to build a dedicated roadmap and to explain the synergies which exist with other fields of organic devices.

Keywords: Organic Solar Cell, Polymer, Dye-Sensitized

1 ABOUT ORGAPVNET

1.1 OrgaPVNET-consortium

To draw a realistic Roadmap for organic based solar cells, a European Coordinated Action project was initiated by the main players in this field. This project with the Acronym "OrgaPVnet", started end 2006. Given the numerous universities, institutes and companies involved in several aspects of organic solar cells, it was decided to structure the partnership by selecting 1 representative institute/country which consolidates the information for all the interested parties in their respective countries.

1.2 OrgaPVNET-activities

The activities are structured according to the main challenges for organic solar cells i.e. improving performance and stability and bring organic photovoltaics to the marketplace. There are 6 Expert Working Groups (EWG's): Materials and Cell development, Characterization and Modelling of Organic Solar Cells, Cell and Module Performance, Sealing and Stability, Technology for large volume production of organic and hybrid solar cells, Analysis of Socio-economic & Environmental Impact of the organic solar cells. Within these Expert Working Groups, an extensive state-of-the art has been prepared for each of these aspects. This was not only based on desktop literature research, but was backed by a number of Workshops and Symposia where experts (including non-European experts and experts from neighbouring domains) presented their vision and experiences. Thanks to this effort, a comprehensive report was compiled identifying the material development issues, the crucial development aspects of cell and module technologies, their upscaling, the sealing challenges, the needs for standardized tests and the key markets to be addressed.

1.3 OrgaPVNET: Roadmapping methodology

The basic question is: what are the figures to make OPV a "viable" technology. This will be subdivided according to three "vertical themes": materials, device process and structure and production technology. The fourth theme is "horizontal" and is related to the final application product. For the three "vertical themes", a link is made with the topics as described in the annex on "Emerging and Novel PV-Technologies" of the Strategic Research Agenda of the European PV Technology Platform. This ensures consistency between the different roadmap exercises on European level. For each one of these topics, a questionnaire is built up and sent to global stakeholders of R&D-actors, manufacturers and end-users. The questionnaire will probe for each of the vertical issues themes the issues efficiency, stability and areal cost. For the application, the issue of necessary lifetime will be probed.

2 STATE OF THE ART OVERVIEW

The overview of the State of the Art is organized according to the Expert Working Groups.

2.1 Material and Cell development

The main driver behind the research activities towards improved photoactive materials for full organic cells and DSC is to realize an optimal overlap with the solar spectrum. For full organic solar cells, distinction is to be made between material development for p-type organic materials for solar cells and material development for n-type organic materials for solar cells. For the development of n-type materials, standing issues like the lack of selectivity and efficiency to produce these compounds as well as the difficulty of stabilizing the nanomorphology of the polymer/PCBM blends are the main drives to find alternatives. In addition, purity, molecular weight, polydispersity, defect structure, electronic structure (control of the positions of Highest Occupied Molecular Orbital - HOMO and Lowest Unoccupied Molecular Orbital - LUMO), charge carrier mobilities and local nanoscale organization are all crucial parameters in the design of optimal materials and nanocomposite blends.

Besides materials development, new device approaches and light management strategies are applied with the aim to further increase efficiencies. In this respect, both for DSC and Polymer PV (see fig.1), multijunction approaches lend itself perfectly for reaching higher efficiencies. Recent results, as shown in Figure 1 provide ample evidence of this.

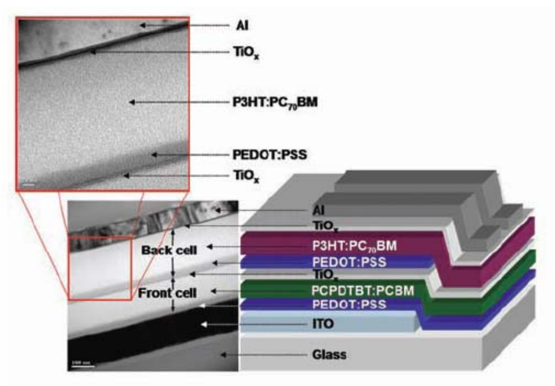

Figure 1: The organic multijunction device structure (right) and TEM cross-sectional image (left) of the polymer tandem solar cell [1]

2.2 Characterization and Modelling of Organic Solar Cells

Characterization and modeling are critical activities for advancing PV technologies. Modelling provides insight in the potential efficiencies (see e.g. [2]

As a technology starts to mature, empirical approaches to increasing efficiency can become less productive. Widespread use of characterization tools beyond the simple IV can help explain why materials and processes that “should” improve efficiencies, do not, and thus point a more direct way toward further work. The need for characterization and modeling increases as the technology advances towards production. Specificly, the essential element of both the dye sensitized and full-organic solar cells is in their nanoscale structure, allowing them to efficiently dissociate excitons into free charge carriers. Over the last years one has seen a tremendous progress in the nano-scale characterization of these devices, not only from the structural point of view (TEM of organic layer structures, characterization of local composition and crystallographic features, …) but also from electrical (Electrical Force Microscopy) and opto-electrical point of view (local current generation, …). This has resulted in improved understanding of the time evolution of nanomorphology and its effect on performance. A system which has been subject of thorough investigation is the P3HT:PCBM system where the effect of drying time, annealing temperature and solvent on performance and nano-structure has been unraveled.

A survey has been made on some of the key parameters like light absorption, nanoscale structure, charge generation, recombination and transport, contacts and stability that need characterization and modeling and the availability of suitable characterization and modeling tools. The result of this survey is shown in Table 1.

	Characterization		Modelling	
	Dye-sensitized	All Organic	Dye-sensitized	All Organic
Efficiency, Current, Voltage	Good	Good	Good	Good
Composition	Good	Fair		
Morphology				
Domain Size and Arrangement	Good	Fair/Poor*		
Domain Composition	Good	Poor*		
Interface Composition	Fair/Poor*	?		
Light absorption and profile	Good	Good	Fair/Good	Fair/Good
Excited state conversion to free electron and hole– related to short-circuit current				
Exciton Diffusion	n/a	Fair	Poor	Poor
Exciton Conversion			Poor	Poor
by Electron transfer	Good/Fair	Fair*	Poor	Poor
by Energy transfer	n/a	Fair/Poor	Poor	Poor
Surface Pair creation	?*	Poor*	Poor	Poor
Surface Pair conversion	?	Poor*	Poor	Poor
Dye Regeneration	Fair/Poor*	n/a	Poor	n/a
Free Charge Transport to Surface of Contacts – related to short-circuit current				
Carrier Mobility/Diffusion Constant	Fair	Good/Fair	Fair	Fair
Carrier Density and Distribution	Fair/Good	Fair/Poor*	Fair	Fair
Recombination Rate Constant	Fair	Poor	Fair	Fair
Carrier Recombination Losses	Fair*	Poor	Fair	Fair

Determinants of open-circuit voltage				
Band offsets in cell			Fair	Fair
Work function of materials	Good	Good/Fair	Fair	Fair
Interface Charge/Field	Fair/Poor*	n/a	Fair	Fair
Voc values lower than band offset			Fair	Fair
Charge density , distribution	Good	Fair/Poor	Fair	Fair
Recombination rates	Good	Good	Fair	Fair
Contribution of inherent shunts	Fair	Fair	Fair	Fair
Contribution contact potentials	n/a?	Fair		
Determinants of the Fill Factor				
Series resistance	Good	Fair	Fair/Poor	Fair/Poor
Charge separation a.f.o. potential	Fair	Fair/Poor*	Fair/Poor	Fair/Poor
Eecombination losses.a.f.o. potential	Fair	Fair*	Fair/Poor	Fair/Poor
Contribution of contacts	Fair/Poor	Poor	Fair/Poor	Fair/Poor

Table 1: Ability to measure cell parameters (characterization), and to determine the underlying factors controlling those values (modelling). The ratings Good/Fair/Poor are to be taken loosely as they take into account the existence of the tools, the degree to which they have been applied, and the usefulness of the information which resulted. Ratings with "*" indicate important areas for immediate work, "?" indicates importance not known.

2.3 Cell and Module Performance

Most of the efficiency values reported or claimed for Organic Based PV (OBPV) have not yet been certified by an internationally recognized PV test and measurement laboratory and measurement methods are not settled. In spite of the STC, for OBPV in general all kinds of ill-defined efficiencies have been reported, based on measurements performed under a large variety of conditions. The main reasons for this are due to: lack of awareness of the norms, inadequate measuring equipment, inaccurate measurement/definition of the often very small cell areas, no masking. This makes a meaningful comparison of efficiency values, measured at different laboratories extremely difficult. This has not been very critical so far due to the early stage of development of OBPV and the small cells that were commonly produced in the laboratories. However, in recent years the R&D community increased considerably in size which has resulted in efficiencies approaching the levels where they could be put in first commercial applications. This stresses the importance of performing accurate and standardized performance measurements for cells and modules with the aim to get uniformity in efficiency results that can be compared from lab tot lab, despite variations in measuring equipment (see e.g. [3].

The main objective of the activity of EWG3 is: to define measurement procedures for the efficiency determination of OBPV cells and modules that simulate both indoor AND outdoor circumstances to guarantee meaningful comparisons from lab tot lab and with other PV technologies. An important task is therefore to motivate and educate the OPV community to adopt these (modified) standards for rating device performance. Additionally, relevant accelerated ageing procedures and field tests for organic based solar cells are to be specified to be representative for in-and outdoor behaviour.

The photoelectrochemical dye-sensitized Solar Cells need adapted measuring protocols which are different from the standards used for other PV technologies. This is mainly due to relatively slow charge transport phenomena occurring in these type of cells, i.e. slow mass transport of ions and slow transport of electrons via trapping and deptrapping from surface states in TiO_2 nanopartculate networks.

The state-of-the art record efficiencies at standard test conditions and sometimes measured in recognized certification labs are included in Table 2.

Type	Efficiency (%)	Realised
Dye Sensitized Oxide (liquid)	11.3 (not yet certified)	EPFL
	10.4 (1 cm^2)	Sharp
	11.1 (0.2 cm^2)	
	8.2 (26.5 cm^2): module	
	8.2 (18.5 cm^2): module	Sony
	Confirmed by AIST	
Dye Sensitized Oxide (solid)	5 (< 1 cm^2)	EPFL
	not confirmed	
Molecular solar cells (single junctions + tandems)	5-6 (< 0.1 cm^2)	Princeton
	not confirmed	
Polymer: fullerene	5.15 (1 cm^2)	Konarka
	5.9 (< 0.1 cm^2)	Plextronics
	Confirmed by NREL	
	~ 6 (< 1 cm^2): tandem	UCSB
	not confirmed	
Polymer: Polymer	1.5-2.0 (0.1-1 cm^2)	Potsdam, ECN, Cambridge
	not confirmed	
Hybrids (Polymer + inorganic SC)	2.4 (< 1 cm^2)	Cambridge
	not confirmed	

Table 2: An overview of maximum power conversion efficiencies for the various OBPV concepts measured at "AM1.5" condition

2.4 EWG4: Sealing and Stability

Apart from enhancing the solar efficiency of dye and organic solar cells, the development of long-term stable cells is crucial for the overall acceptance and the gradual increasing market introduction of Organic based PV. As dye- and organic solar cells contain either liquid or gelified electrolytes or easy to oxidize organic conducting materials, they have to be hermetically encapsulated. The requirements on sealing technologies are high. Recent developments like glass frit sealing of DSC and transparent barrier coatings on foils give realistic hope, that long-term stability for outdoor photovoltaic use can be achieved.

It has been observed that dye sensitized cells, which are kept at intensities within the saturation part of the current-light function, recover to a large extent when they are kept in the dark. Nevertheless, it could indicate that cells exposed to day-night-cycles could be more stable than tests under continuous illumination indicate. These understanding points out once more that result from light soaking experiments could underestimate the lifetime of DSSC. With the N3-type ruthenium the stability amounts to 10 000 h of light soaking at 2_5 suns, which corresponds into ca 56 million turnovers of the dye without any significant degradation.

Polymer based solar cells must be protected from ambient air to prevent degradation of the active layers and electrode materials by reaction with water and oxygen; moreover, the materials must be photochemically stable and the nanoscale network donor-acceptor should be preserved. P3HT+C_{60}-PCBM, where thermal annealing was used to stabilise crystalline network, have shown the best results with less than 20% efficiency decrease after the 'thermally accelerated ageing test' (1000hrs at 70^{o}C under an inert atmosphere). Polythiophenes have also been reported with 'accelerated lifetime testing' for 4000 h –10,000 h that equals more than 1 year. Accelerated testing for 1 year corresponds to an operational lifetime of 3–10 years. The technology has thus reached a stage where a commercialisation can be anticipated in a short time span

2.5 Technology for large volume production of organic and hybrid solar cells

Organic and DSSC solar cells receive highest interest due to high potential huge productivity from lowest process costs via priting and coating production technologies. Printing and coating can be done in batch as well as in roll to roll processing. and is typically divided into solid-state (transfer), gas-phase (vacuum) and liquid-state deposition techniques. Production of photovoltaic modules requires at least web patterning of stripes to electrically separate the active layers into individual cells, which later are interconnected in series. All three classes of deposition processes can give either patterned or unpatterned films. Techniques for patterning of thin films can be divided into subtractive or additive methods. In the first case, an unpatterned film becomes patterned in a separate process step, by removing film from undesired areas (e.g., by lithography, laser patterning, embossing, or imprinting, …). In the case of additive methods, film deposition and patterning are done in the same process step. Solid-state printing typically starts from already prepatterned films. Alternatively, the pattern can be generated during the transfer process by a technique such as a laser transfer method. Patterned vacuum deposition is realized by shadow masking or by lift-off processes. Both processes have limitations in terms of resolution and registration. Shadow-mask processing requires specific precautions to prevent particles and to control the distance between the web and the mask. More sophisticated lift-off processes are used for the manufacturing of patterned Al films. Here, a fast-evaporating ink (e.g., an oil) is printed right before the film is run through the evaporation unit. During evaporation, the ink is released from the substrate, and adhesion of the metal is prevented. The best resolution and registration are gained with classical lift-off or photolithography methods, both of which require printing of a suitable photoresist. Liquid-state printing results directly in patterned films and is typically used when high resolution and registration are required.

In contrast, liquid deposition methods that result in unpatterned films are commonly called "coating" methods. Coated, unpatterned films can be converted into patterned films by subsequent combination with (subtractive) patterning steps (e.g., mechanical scribing or laser patterning).

A breakthrough has been achieved in the development of production methods for organic and DSSC solar cells during the past few years. Multiple printing and coating methods have been demonstrated to yield the required film specifications for device operation. Moreover, first companies succeeded in the roll-to-roll production of photovoltaic modules, where all layers are deposited by printing and coating methods at high speed and high yield. Roll-to-roll manufacturing of functional modules was the last missing piece of technology between development and commercialization, and the first organic solar cell products are expected to enter the market within the short term (see e.g [4] for bulk donor-acceptor heterojunction cells or [5]

3 CONCLUSIONS

The success of OBPV in penetrating existing and new PV markets will not only depend on lowest €/Wp. Building up sufficient confidence through use of well-standardized measurement procedures for indoor and outdoor conditions and well established, independently confirmed stability measurements is a must. The broad range of film application technologies providing similar results is an indication for ease of production. Lat, but not least, power availability (kWh/Wp/annum) and the importance of diffuse ligh [6] are certainly as important as cost/W_p. A dedicated effort in this domain is advisable to preserve the strong R&D-position of Europe and to allow valorization of this know-how in Europe.

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