PRIMA

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Deliverable 4.5 – Report of benchmarking and cost-assessment of plasmonic nanostructures in organic ~~and DSSC~~ cells.

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1 Introduction

This deliverable concerns the benchmarking and assessment of the use of plasmonic light trapping strategies for organic solar cells. It was originally intended also to include a benchmarking and assessment of dye sensitized solar cells (DSSCs), but due to the no-go decision for continuation of DSSCs (ML11, M24), this activity has ceased and therefore is not included in this deliverable.

2 Benchmarking

2.1 *Organic solar cell commercialization*

Organic solar cells are until now *not an industrialized product*. Therefore, it remains a highly challenging task to present an overall picture of the cost structure to be expected for OPV production. The topic of life cycle assessment/analysis (LCA), energy payback time (EPBT), and costs is starting to receive some attention, but only at the academic level until now. The picture of the state-of-the-art is represented in the references provided at the end of this document, constituting a set of 14 publications (to the best of our knowledge) that have been published on the broad topics of LCA, EPBT, costs, IP analysis (and freedom to operate), and marketing [1-14].

Making this a bit more of a concern are a number of other factors. One, that the cost structure and EPBT are highly dependent upon the expected application. For example, mobile applications compared to building integrated (BIPV) systems demand different designs, and are illuminated with considerably different light intensity and spectra throughout the day. Secondly, the major commercial entity involved in the OPV field for years, the start-up company Konarka, recently closed its doors [15], risking to derail the momentum in this burgeoning field, especially as efficiencies continue to increase and break new records (12% at time of writing) [16].

2.2 *Current thinking on cost structure*

In order to frame the discussion, let us try to suggest some figures for overall module cost, in order to determine whether or not it would be justifiable to utilize plasmonic enhancement. Let us assume that:

- We target an overall cost of 0.50 €/W (a pretty low number it should be noted)
- We target a 10% efficient OPV module (realistic given the 12% state-of-the-art)
- The module operates under standard AM1.5G conditions (not likely for first OPV products in mobile or BIPV, but nevertheless this is an example) of 1000 W/m^2

This means that the solar module produces 100 W/m^2 of area, meaning an areal cost of 50 €/m^2. We can assume that an antireflection coating may gain us ~5% photocurrent due to the improved incoupling, and a similar 5% is what we have shown within Prima for OPVs (see D3.5 and Ref [17]). *Both* of these optical strategies together can therefore cost ~5 €/m^2 (since they can bring a 10% improvement, they can take 10% of the cost at maximum). So the question remains as to whether the established Prima process [17] can be applied at the level of ~2.5 €/m^2, in order to justify its inclusion in an eventual OPV product.

In Fig. 1 (left) we show the balance of module (BOM) costs for a 1 m^2 OPV module, reproduced from Ref [7]. What we see is that the module costs are dominated by the materials costs, making up nearly 2/3rd of the total. Looking in a bit more detail concerning the breakdown of the various materials costs in the pie chart at the right of Fig. 1, we can notice that the electrodes (both the transparent one and the reflective back contact) dominate the costs. In this example, Ag was used as the back reflective electrode, the same as we utilized within Prima for our plasmonic enhancement process. Therefore, one might think that the Prima process [17] is intrinsically unsound and expensive. But, it would not be a difficult task to reduce the costs of this component. One could think for example to utilize a very thin layer of Ag (perhaps 10 nm instead of the 200+ nm considered here), followed by the deposition of a much less expensive metal, such as Cu or Al.

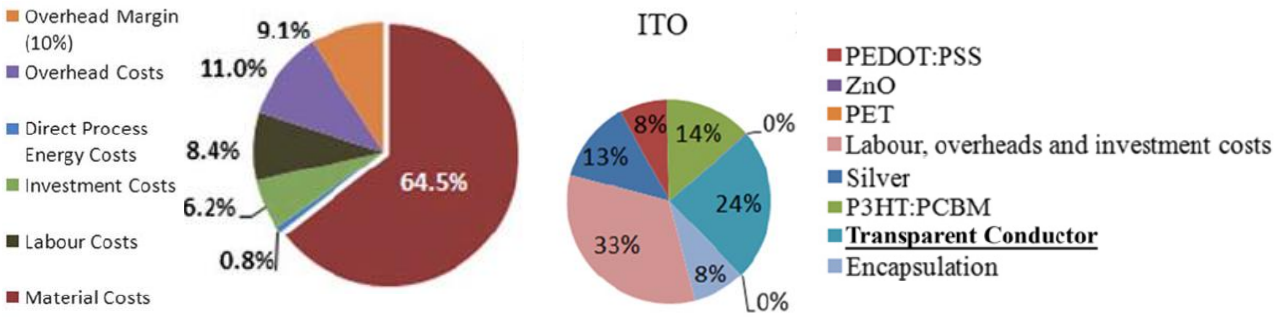

Figure 1. Left half: Balance of module (BOM) costs of a 1 m² OPV module, from Ref [7]. Right half: The breakdown on the minimum cost per m² of various materials within OPV modules, from Ref [9].

Therefore, on cost arguments, one might think that removing Ag entirely is an important aspect which would compromise the structure demonstrated in Prima [17], but in fact the Ag layer can be vastly reduced in thickness (and therefore cost) as mentioned above.

2.3 The generalizability of the 'Prima' process

Organic solar cells are rather unique within the PV field in that devices are heavily material-dependent. What we mean is that there are many options for material choice, not only for electrodes, substrates, etc., but also for active absorbing layers, interlayers, buffer layers, etc. This means that a process developed to aid the performance of one material system or device architecture may not directly apply to another material system.

To test the generalizability of the our established process for plasmonic OPV enhancement [17], we enlisted BASF as an advisory member. In this capacity, they have made available to us a sample of one of their high performance materials, providing a significantly better performance (6.5%) compared with the P3HT:ICBA active layer utilized in Ref. [17] giving ~5% power conversion efficiency. Notably, the photocurrent of the BASF polymer is very high, owing to very broadband absorption, and quite red-shifted from that of P3HT.

What we found with the BASF polymer was that we could effectively make the patterned rear electrode on top, ***and*** that we could target the correct wavelength range to increase absorption (sorry, data not shown for confidentiality reasons)! However, despite the increase in absorption, the photocurrent of the cell was not increased, but rather decreased. This was attributed to the fact that the BASF polymer layer is thinner than that possible with P3HT, and in fact too thin to realize a saturated absorption in the entire wavelength range (except for the absorption edge) as was possible with P3HT. Making layers with this thickness resulted in compromised electrical performance. P3HT is a special case in this regard, as layers can be prepared with sufficient thickness to allow for saturated absorption, enabling the success of our approach. In tests with thinner layers of P3HT, it should be noted, we observed a similar performance decrease. Only by utilizing thicker layers were gains possible. The rear plasmonic structure that we have developed may be an effective light scatterer, *but it is also an extremely effective absorber*. This means that without sufficiently saturated absorption in wavelength ranges outside the absorption edge, parasitic absorption will hurt device performance in the end.

Therefore, the process we have developed, while it works for the case of P3HT, does not seem to work well for other systems, owing to increased parasitic absorption. This may mean to try to work on other light trapping techniques, strategies less plagued by parasitic absorption compared to plasmonic approaches. For example, there are very recent examples in the literature where gratings are embossed into the polymer, and then a contact is evaporated on top [18-20]. These examples are likely non-plasmonic, but potentially light trapping nonetheless. To be fair, Ref [18] does not claim plasmonics, whereas Refs [19] and [20] do, but without sufficient proof, rendering them ambiguous. It also remains to be seen whether the pressure (and heat) associated to the embossing process are the reasons for the performance improvement, with little function from the grating itself.

3 Conclusions

According to the fact that light trapping strategies can account for an approximately 10% improvement in OPV device performance, it seems reasonable that such strategies can be adopted at the costs assumed for OPV fabrication. In our example, we assumed 0.50 €/W for an OPV (an aggressive number), allowing ~5 €/m² for a suitable light trapping strategy. ***We think that this is possible.***

However, our work with additional active layers has taught us that our approach based upon hole-colloidal lithography (HCL) [17] may not be suitably robust and generalizable to apply to *all OPV active layers* and produce plasmonic enhancement. Therefore, we recommend to try other strategies, perhaps embossing/stamping of a mold prepared by nanoimprint lithography. Such a strategy has been shown to improve OPV cells with layers thinner than what we have attempted [18-20], meaning that parasitic absorption might play less of a role. However, it should be cautioned that while these studies showed this approach to result in a performance improvement, the exact role of light trapping remained a bit ambiguous.

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