Volume production of customized organic photovoltaics

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Abstract

To realize power generation everywhere, customers and designers are eager for PV solutions offering total design freedom for seamless integration into everyday life. This trend becomes even more important if the 'mega city' development is taken into account: more and more people will live in city environments in the future while classical PV technologies do not offer proper solutions for this context. Accordingly, the next wave of renewable energies will not be standalone products like today but will rather be a kind of integrated functionality. Organic photovoltaics (OPVs) already broaden applications as they are manufactured on polymer foil where the final product is thin, flexible and semi-transparent. However, OPV modules are commonly printed/coated in form of stripes that limits their design layout and integration. Therefore, the current state of the OPV manufacturing process needs to be modified to allow fabrication of free patterns and fully customized devices. In this contribution we present the approach pioneered by OPVIUS in the evolution of OPV towards customization in large volumes to meet customer expectations. Starting with modifications on the slot-die, we also describe advances in patterning and printing technologies that allow realization of free shapes on devices. For the first time we also present a three-dimensional (3D) OPV module produced using mass production techniques.

Introduction

OPV is a renowned solar technology for its thin and semi-transparent properties. Organic polymer materials allow easy formulation and empower OPV to be realized in roll-to-roll (R2R) formats by printing or coating. This gives OPV several advantages over conventional photovoltaic technologies in terms of upscaling toward serial and high-volume production. Moreover, the flexibility of OPV allows easy integration into any structure or product. This enables photovoltaic power generation to be no longer limited to open field or rooftop installations and could potentially save acres of land for the future or give access to environments where no open space is available by definition, such as big cities. This is further backed by the capability of adding aesthetic value to products and structures, which is a highly desirable property especially if it comes down to emotional products like buildings including facades.

The state-of-the-art organic (semiconductors) materials allow a wide range of coating and printing technologies to be implemented toward fabrication of OPV. Reports suggest improved device performances using novel polymer blends to the most widely used P3HT:PCBM heterojunction [1, 2]. Besides the performance, the polymers also possess unique characteristics of being able to reflect a different colour at different angles. This makes the OPV portfolio quite vibrant in comparison to other photovoltaic technologies.

With regard to the OPVIUS approach for functional processing, slot-die coating has proven to deposit functional OPV layers with a very high cross-directional uniformity [3-6]. However, unlike the printing methods the slot-die coatings are incapable of producing patterns as they are a highly unidirectional process. Therefore, OPV development studies using slot-die coating technique are also carried out in layouts that are unidirectional or otherwise termed as 'stripes'. Most of today's publications are based on this very standard on which the cells are produced and evaluated. Only recently there have been reports about OPVs being produced in free-form patterns/designs, but only OPVIUS is currently operating its production on this scheme [7, 8]. Besides slot-die, printing technologies are also currently in discussion – like among others inkjet printing, which gained industrial interest due to the possibility of being able to print free shape forms as printing is based on drop-on-demand principle. The inkjet process allows printing ink in the desired place on the moving web [9-12]. However, it faces several issues related to ink rheology and morphology of printed layers and finally also reflects a much higher initial investment if compared to slot-die. In this contribution, we expand the potential of the OPV by accompanying slot-die coated layers with suitable additional patterning and printing techniques [13-17].

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Evolution of customized OPV

Based on the pioneering work done at OPVIUS, OPV layouts produced via R2R process is shifted from stripes toward uniform flood coat at full web width. This is possible by modifying and developing the slot-dies to coat wide areas and with a high uniformity. In addition to the slot-die modifications, selective laser patterning with

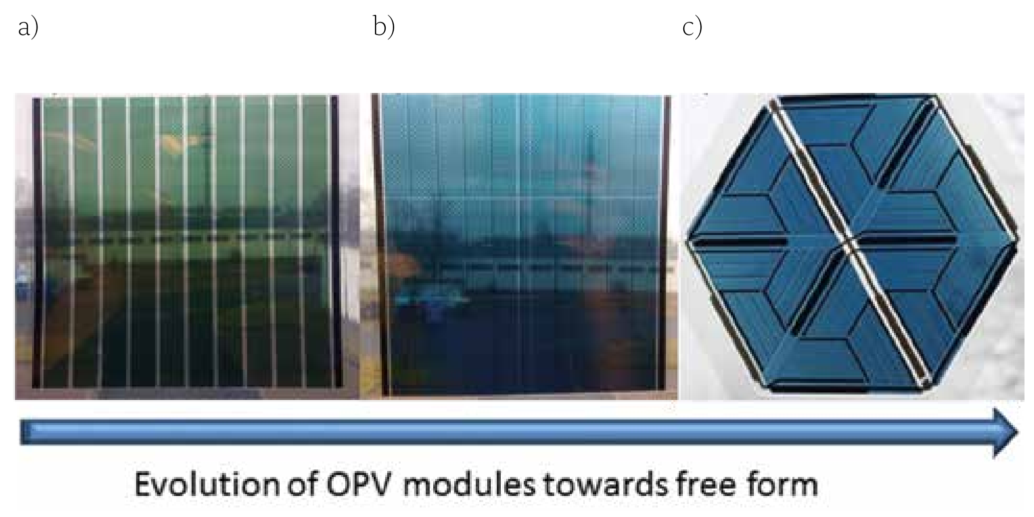

Figure 1. Evolution of large area R2R fabricated OPV applications towards free shape and customization based on laser scribing; a) module with separated stripes, b) module with uniform colour across web width and c) free-form module.

precise registration techniques is integrated into the production process. The laser patterning process allows the creation of patterns and digital shapes that are limited only by the imagination of the designers. Figure 1 shows the evolution of OPV modules from lines to free shape and pattern based on laser patterning technology. Based on continuous evaluation, the process of mass producing custom-designed OPV has been greatly simplified and realized at a serial production level. By integrating state-of-the-art patterning, printing and 3D conforming technologies along with the slot-die coated layers it is possible to make cells and consequently modules in a free-form design. This opens the door to new product applications where other photovoltaic technologies might not be suitable.

Being able to selectively remove the coated layers overcomes the need to make deposition based on stripes. This many-a-time also increases the total active area of the device. This is because each stripe is conveniently placed to prevent the wet films from merging during the coating and allow a serial connection to be made without electrical short circuit. This can be observed in Figure 1a where the area between two coloured stripes is quite visible as they are designed to be couple of millimetres apart to prevent the merging. This zone between the stripes is often considered as 'Aperture loss' as there is no charge generation in this region [18]. However, in a patterned layout, the already deposited and cured layers are selectively removed using a fine laser scribing tool. Many technical lasers used for scribing are capable of delivering cuts that are few micrometres in width. Therefore, very fine structures can be created by separating coated

Figure 2. Mass produced window curtain product based on 3D shaped OPV panels.

Figure 3. OPV tree that mimics banana leafs and fits into natural surrounding (chameleon effect).

layers into multiple cells. In Figure 1b the area between any two cells is hardly visible as it is very finely structured thereby allowing the stripes to be wider in comparison.

The ratio of the device active area to its total size is technically termed as Geometrical Fill-

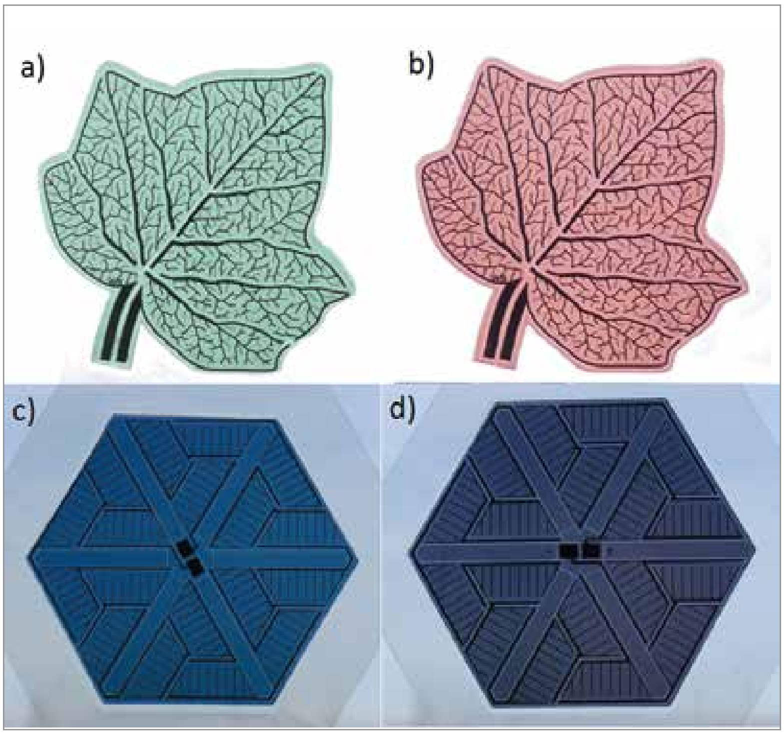

Figure 4. Colours of OPV modules based on different photoactive compounds currently available in large scale production without additional colour filter; a) green, b) red, c) blue and d) grey/purple.

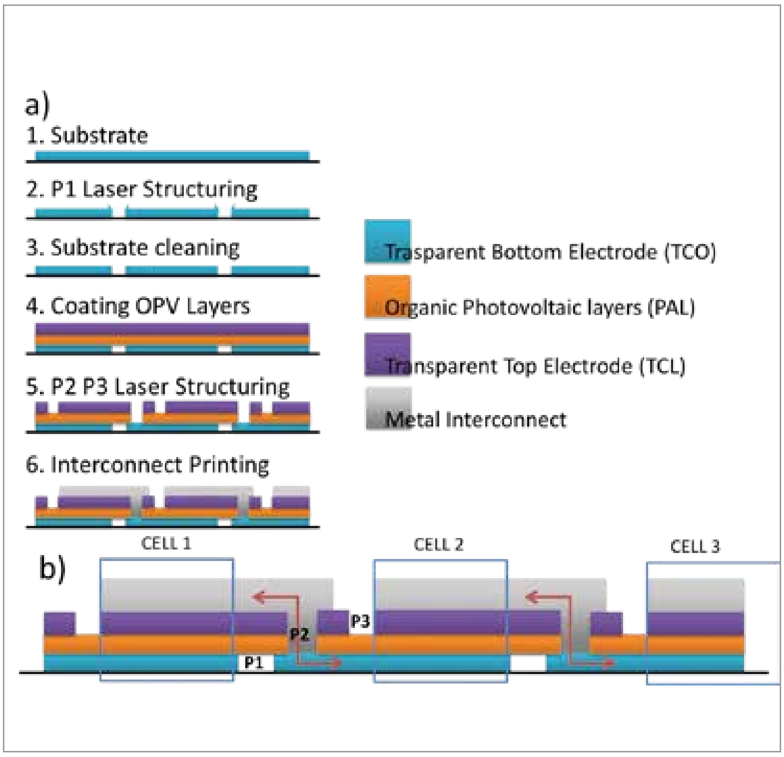

Figure 5. Schematic illustration of the patterning technique; a) a cross-sectional step-by-step laser structuring process and b) cross-section view of the OPV serial interconnection indicating the charge flow after the Z connection is established.

Factor (GFF). The GFF of a module could be raised from approximately 70% in the case of stripes to >90% for a free-form laser patterned layout [19]. Accordingly, the generated power output of the module can also be increased by 20%.

Taking one step further we obtain the free-form. Instead of connecting the cells merely linearly (Figure 1a and Figure 1b), the module shown in Figure 1c consists of cells that are connected planarly across the two-dimensional plane of the coated layers [20].

Conforming printed electronics in 3D shape is a natural next step and recently this process began to take off from the ground in volume production of OPV applications (www.suncurtain.solar). Figure 2 shows a window curtain product based on 3D shaped panels.

Another attribute influencing the product design is its colour. Semi-transparent OPVs are desired in vibrant colours to extend their integrity to the final product and allow it to blend in with its surroundings - for example, OPV trees that mimic real banana leafs and perfectly fit into green urban areas exhibiting the chameleon-like effect (see Figure 3).

Currently, OPV modules in green, red, blue and grey can be produced in large volume without any colour filters, as Figure 4 presents.

Free-patterning methodology

OPVIUS GmbH has developed and demonstrated fully free-form modules with different colours being produced at large scale. Based on the developed process, custom-shaped module designs are created to meet customer requirements for successful applications. The key behind the process is to produce patterned OPV modules without compensating the overall device voltage.

Structuring the layers to disconnect them becomes essential for semi-transparent large-area OPVs to improve device performance and obtain high voltages. The reason behind the performance loss is because the conventional transparent metal oxide electrodes (e.g. indium tin oxide (ITO)) as well as the printed top electrode are not capable of transporting charges over large distances, which results in ohmic losses. These conductivity issues are overcome by separating the electrodes and extracting the charges from smaller areas or cells. Multiple cells are interconnected in series to comprise a module. A serial interconnection will increase the device voltage whereas parallel connection will add the currents to provide increased amperage. The technology developed at OPVIUS uses the freedom of the laser ablation process over a fully coated wide web, where cells are realized in virtually any customized shape and position. An overview of this process is presented in Figure 5. The cells are scribed digitally by laser and then are interconnected within the 2D plane to bring out the desired device shape. From that step, modules can be formed in a 3D shape too.

A step-by-step process diagram for a serial interconnection using the process developed at OPVIUS is shown on Figure 5a. The laser step "P1" is structuring the bottom electrode (typically referred to as "TCO" – Transparent Conductive

Oxide). The P1 cut also separates each cell of the device. This step is carried out prior to actual coating on the manufacturing line.

A large area coating covering almost the entire substrate width is carried out over the structured bottom electrode. By coating wide areas, the freedom is provided to produce modules of varying sizes. Alterations were made on the slot-die setup to enable them to coat wide areas. The challenges of uneven ink distribution inside the channel are overcome by suitably designing the meniscus flow guides.

The cut made during the P1 process is a very crucial part of the device and must be isolated from any conductive material, especially the top electrode. This is to maintain a high parallel resistance and prevent shorting of the device. The architecture of the OPV device enables separation of the top electrode and the P1 as a series of semi-conducting layers are coated prior to the top electrode. In other words, the top electrode is separated from the P1 cut – i.e. from open TCO flanks – by the organic layers that are coated earlier. After the layers are coated, the next stages of patterning are carried out. In the later patterning stages, "P2" and "P3" are subsequently performed. The P2 is carried out adjacent to the previously made P1 cut. It removes all coated layers and exposes the bottom electrode of the adjacent cell. The role of P2 is to form a contact area for a serial interconnection with adjacent cell. The P3 is carried out to interrupt the top electrode (TCL). This reduces the parallel shorting.

By contacting the top electrode of a cell with the P2 cut of the adjacent cell a "Z" connection is established, as Figure 5b shows. This so-called, "Z" connection between the opposite poles of adjacent cells establishes the serial interconnection. As the contact is made available by the action of P2 structuring, the electrodes need to be connected depositing a conductive layer. A patterned deposition is crucial to prevent any electrical short circuiting and to only connect the said electrodes. This is achieved by depositing using a screen printing technique. The conductive ink is pressed through a screen based on the desired form. Screen printing is very versatile as it allows 2D patterned depositions to be made seamlessly. By changing the layout of the screen, various shapes can be made as desired. The process is also highly scalable and by modifying the mesh and/or printing specifications a wide range of ink viscosities can be handled to produce high quality prints [21, 22].

Challenges in process development

The production environment is quite dynamic and distinctive in comparison to the laboratory process. Constantly varying heat profiles as well as large-scale handling of the materials make the production process difficult to control toward precise reproduction of quality and performance of devices. Therefore, determining the process window and process steps for large-scale production is a challenging task as direct benchmarking with lab devices often doesn't go hand-in-hand.

To achieve highly functional devices, the deposited OPV layers need to be carefully cured to create the right morphology. In a controlled laboratory process this exact same curing can be reproduced on consecutive modules as they are separately handled in sheets. In the R2R process the drying dynamics are slightly different since the web is constantly moving. Hence, reproducing the exact same conditions as that of a lab process is a quite complex task. A cold web upon entering the oven has already passed a certain distance before the right curing temperature is obtained. This ramp-up time can be compensated either by increasing the oven temperature or reducing web speed. The latter is not desirable as it slows the production.

Alternatively, the polymer-based web (e.g. polyethylene terephthalate (PET)), used as a substrate for printed electronics, undergoes deformation at elevated temperatures used for drying printed or coated layers when handled under tension during the R2R process. This introduces a dimensional inaccuracy on the material that hinders registration of the subsequent steps thereby forcing the production to follow a strict heat budget [23].

In high volume material processing that involves extended production times, the ink

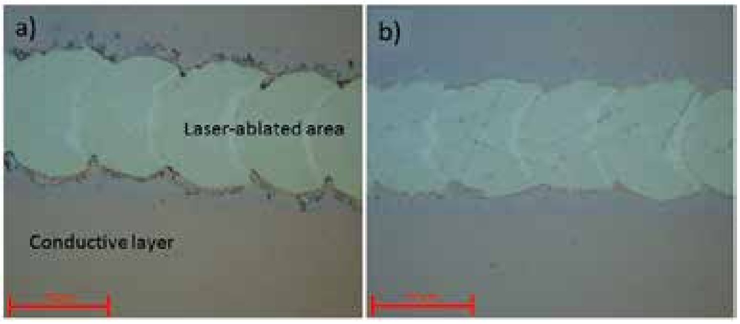

Figure 6. Optical microscopy image of P1 cut separating the TCO; a) before cleaning, b) after cleaning.

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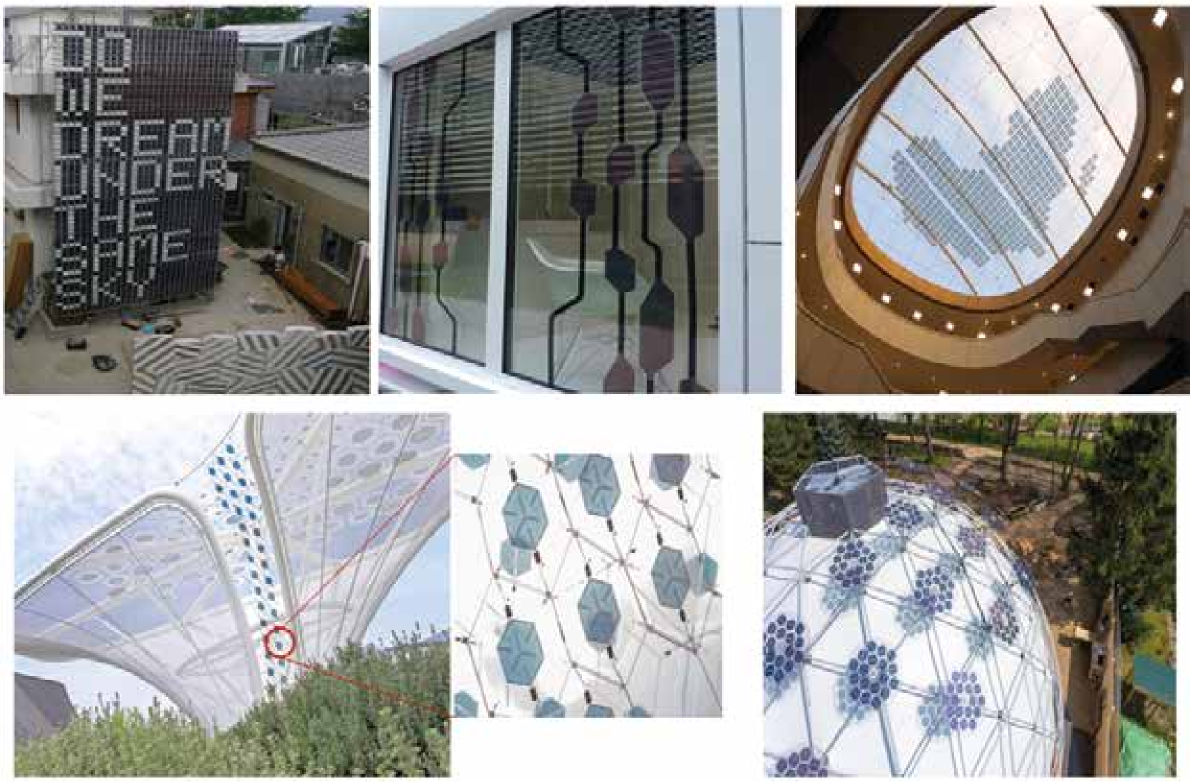

Figure 7. High volume custom designed free shape OPV modules and integrated to urban architecture.

consistency can vary over time and this could lead to a changed morphology of the coated layers. Factors such as particle agglomeration or changes in material viscosity can be caused by extended periods where the ink remains loaded in the reservoir. This could lead to a difference in the coated layer and identifying such effects on produced material requires careful analysis of devices from various parts of the roll.

Additionally, debris and warping at the edges of the ablated spot are created due to the laser ablation of the TCO. Depending on the level of contamination a subsequent cleaning step is required. The difference in the laser flanks prior and after the cleaning process is presented in Figure 6a and 6b, respectively. The debris is cleaned from the substrate before the coating. This minimizes particle accumulation and hence defects during the coating process. The cleaning however requires mechanical force to be applied on the substrate as the debris on the laser flanks are melt residues that are stuck onto the substrate after the ablative process of the laser. If the cleaning is not performed with care and in a controlled manner scratches can be made which will influence the performance of the fabricated devices.

To realize free-patterning, registration between each successive step to that of the previous is a key criterion. The P1 structuring being the first of the process steps, will determine the origin for further registration steps to be based upon. Offsets between P1, P2 and the P3 discussed in the 'Free-patterning methodology' section are introduced to reproduce the registration made during P1 until the final conductive layer is printed to make interconnection. The total interconnection zone is the area between the P1 and P3 as shown in Figure 5. The so-called, interconnection zone is inactive and does not contribute toward charge production. As discussed earlier, this region does not belong to the active are as there is no charge generation. The challenge is to minimize the offsets and increase the active area of the module. To produce a market-competitive OPV module, these offset distances must be less than 1mm. The registration accuracy within this regime falls into few micrometres. Achieving precise registration in this regime on multiple instances makes the process quite demanding.

Overcoming major challenges and integrating laser structuring to a large-area manufacturing process allowed the creation of customized and complex structures. Figure 7 shows customized OPV products fabricated by OPVIUS integrated in large urban architectural structures that are installed around the globe.

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Future trends

The current state of OPV production has been expanded and developed toward making OPVs that don't hinder the expectations of designers. The OPVIUS OPV technology uses standard off-the-shelf equipment to realize the production allowing CAPEX to appear generally low. As discussed in the earlier sections the production does come with challenges. They can be overcome by reducing the complexity of the problem. Development is being carried out at OPVIUS to reduce the current back-forth processing between the laser and the coating machine by being able to carry out all the laser stages (P1, P2 & P3) within one single step after all the functional layers are coated. This potentially broadens the OPV catalogue without having to hinder the existing production setup. The methodology to structure the product at the late stage ensures a constant stockpile of coated OPV films made at an increased throughput. The process also reduces the production time as cleaning the substrate might not be necessary.

Alternatively, development studies are also being carried out to find an alternative to the currently used TCO material. The present TCO material comprises rare earth metals, which could mean high material scarcity and increased costs in the future. Alternatives to such materials are developed and tested using production conditions and equipment.

Free-shape OPVs can be integrated into other manufacturing technologies of plastics, like injection moulding. This will widen the application area and allow better integration with manufactured parts, for example for gadgets or consumer electronics.

It is expected that in the near future it will be possible to produce more complex 3D shapes and patterns for OPV devices. In order to realize that, new, more conformable materials, equipment and process steps need to be incorporated into high volume production processes. A higher level of integration with our surroundings (nature, urban furniture, etc.) is expected when new colours of photoactive materials will be available for large-scale production. Currently, it is possible to apply colour filters; however they can reduce the PCE of the devices. Furthermore, modules with different colours can relate to each other in a form of mosaic giving a more attractive look.

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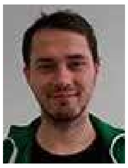

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