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STRUCTURAL IMPROVEMENT OF ORGANIC PHOTOVOLTAIC CELL (OPVC) TOWARDS HIGHER EFFICIENCY

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Abstract. The organic photovoltaics cell (OPVC) is very promising owing to their potential of providing environmentally safe, flexible, lightweight, and inexpensive photovoltaic cell. There are, however, main unsolved problems of low power conversion efficiency. Up to now only about 6% power conversion efficiencies on the device level have been realized. The efficiency of OPVC is limited by several factors. One such factor is the limited overlap of the absorption spectra of organic materials with the light spectrum. A lot of efforts already made on the material development to better match the light spectrum. Another potential alternative method is the enhancing spectral coverage of OPVC. To enhance spectral coverage and photon harvesting, the structural improvements of the OPVC are very crucial. However, lesser effort has been paid in understanding the structural effects. This paper will discuss the structural improvement for higher efficient OPVC, and integrating them to address the future needs of the photovoltaic technology sector. Recent developments in photovoltaic architectures, geometries that result in the efficiency of OPVC are presented. The term “photovoltaic” is used here for the unspecified (including solar) light source rather than only “solar”. The review can serve as a guide for increasing the efficiency of OPVC in energy industry.

1. INTRODUCTION

Organic semi-conducting materials can produce electricity via the photovoltaic effect, with the field generally called organic photovoltaics (OPV) [1]. OPV has the potential to offer low cost, mass produced, photovoltaic (PV) energy generation [2]. However, the field of organic photovoltaics cell (OPVC) is young, exciting, and full of promise. Therefore, further study is required to increase efficiency, improve lifetime, and reduce production costs before the low cost goal can be achieved. Up to now main efforts have focused on the improvement of the PV conversion efficiency, and in recent efforts about 6% white light efficiencies on the device level have been realized. It is generally considered that a minimum power conversion efficiency of 10% is needed in order to enable realistic applications, in building integrated organic photovoltaics [3].

Current research toward improving efficiency is focused on developing new materials and on improving morphology. Besides these, increasing the light absorption also can increase the efficiency. Because, unlike conventional inorganic PV cells, light absorption in organic PV cells leads to the generation of excited bound electron–hole pairs, commonly known as excitons [4]. To achieve substantial energy-conversion efficiencies, these excited electron–hole pairs need to be dissociated into free charge carriers with a high yield [5]. What is needed is a photovoltaic device having efficient light absorption in thin photosensitive layers, resulting in high energy-conversion efficiency, with attendant materials and cost saving merits [6].

The straightforward technique to improve the photon absorption is the increase of thickness of the absorbing/active layer. However, this thickness is generally restricted (<150 nm) by the limited

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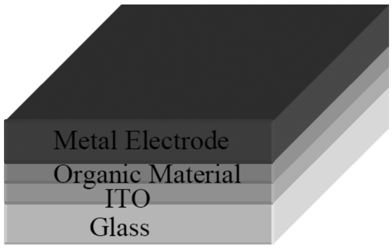

Fig. 1. Schematic structure of a typical single layer Organic Photovoltaic cell.

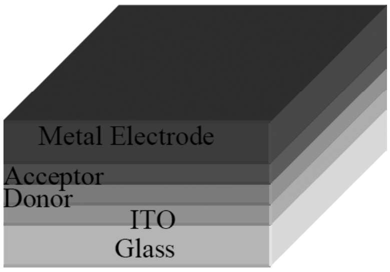

Fig. 2. Schematic structure of a typical two layer Organic Photovoltaic cell.

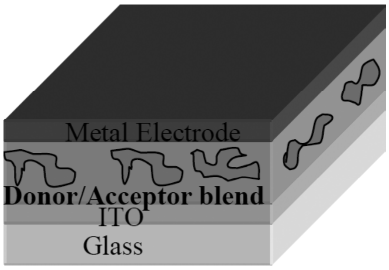

Fig. 3. Schematic structure of a typical bulk heterojunction Organic Photovoltaic cell.

charge carrier mobility [7]. A potential alternative to increase the photon density is the light guiding to the active layers. The use of light guiding systems can increase the total path length of light into the active material without the need of increasing its physical thickness. When light travel a longer distance in the active layer by multi-pass path, the higher percentage of photon is absorbed [8] towards higher efficiency. Therefore, the structural improvements of OPVC are becoming as vital part of photovoltaic research. Our purpose of this review is to have a better understanding of the structural improvement of the OPVC in manufacturing from laboratory to commercial package.

2. DIFFERENT STRUCTURES OF ORGANIC PHOTOVOLTAICS CELL (OPVC)

The first organic thin film solar cells, which were constructed in 1958, suffered from short lifetimes and very low efficiencies compared to inorganic cells being developed. Beside the materials development, structural improvements are also playing an important role to increase the efficiency to their counter part [9]. Initially the structural improvement is accomplished with addition of planar multilayer structure, such as two layer cell, three layer cell, stacked cell and tandem cell. The later development is on the basis of light trapping effects, such as surface texturing, diffraction gratings, buried nanoelectrodes, micro-lense, and multireflection structures are the most proposed solutions. Finally, the OPVC is also proposed on the photonic structure, such as optical fiber and waveguide technology. The above-mentioned structural developments are therefore described in the subsequent section.

2.1. Single layer cell

The first organic solar cells were based on single thermally evaporated molecular organic layers sandwiched between two metal electrodes as depicted in Fig. 1. In such single-layer cells, the built-in potential is derived either from the difference in work function of the electrodes or from a Schottky-type potential barrier at one of the metal/organic interfaces. In both cases, the photovoltaic properties are strongly dependent on the nature of the electrodes [10]. Another characteristic of such single-layer cells is their poor fill factor, which can be usually, attributed either to a large series resistance associated with the insulating nature in organic photoconductors. The main losses in single layer structures are due to short exciton diffusion lengths and recombination of the excited charge carriers [11].

2.2. Two-layer cell

For overcoming the above-mentioned serious limitation of single-layer cells, the two-layer cell is then demonstrated [12] as depicted in Fig. 2 with the introduction of an electron acceptor layer between the active material and the negative metal electrode. Thus both the exciton diffusion range and the poor shunt resistor can be improved. However, the donor and acceptor materials have to be in close proximity at the hetero-junction for efficient exciton dissociation. The optimum length scale is in the range of the exciton diffusion length, typically a few tens of nanometers. On the other hand, the thickness of the active layer should be comparable to the penetration length of the incident light, which for organic

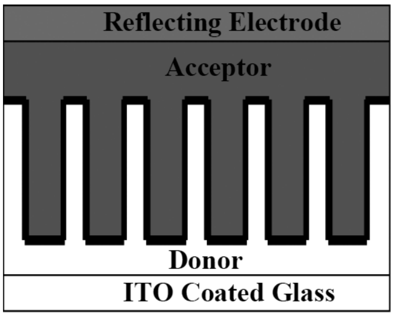

Fig. 4. Schematic structure of a typical ordered hetero-junction Organic Photovoltaic cell.

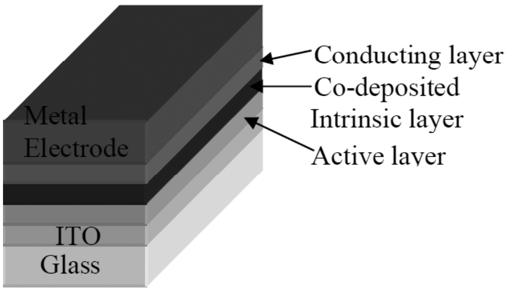

Fig. 5. Schematic structure of a typical three layer Organic Photovoltaic cell.

semiconductors is typically 80–200 nm. This bi-layer geometry guarantees directional photo-induced charge transfer across the interface. Since both types of charge carriers travel to their respective electrodes in pure *n*-type or *p*-type layers, the chances for recombination losses are significantly reduced [13]. However, the interfacial area and thus the exciton dissociation efficiency of this type are still limited. To improve, the following modified hetero-junctions are developed.

Bulk hetero-junction cell: Higher interfacial areas and thus improved exciton dissociation efficiencies can be achieved, if both the electron donor and electron acceptor layers are prepared in a mixture as depicted in Fig. 3. These so-called bulk heterojunctions can be deposited either by co-sublimation of small molecules or by spin-coating mixtures of polymers [14]. Bulk hetero-junctions have the advantages of being able to dissociate excitons very efficiently over the whole extent of the solar cell, and thus generating polaron pairs anywhere in the film. The disadvantage is that it is somewhat more difficult to separate these polaron pairs due to the increased disorder, or that percolation to the contacts is not always given in the disordered material mixtures. Also, it is more likely that trapped charge carriers recombine with mobile ones [15]. Furthermore, the magnitude and polarity of the open-circuit voltage in this two-layer system show a stronger dependence on the nature of the organic interface than on that of the electrode-organic interfaces. It appears that the electrodes simply provide ohmic contacts to the organic layers. The efficiency of these architectures is limited primarily by the narrow absorption width of the donor material. Although, the bulk hetero-junction, can be used to achieve efficient light absorption and charge separation, they will impede severely charge transport and are difficult to use in multilayered structures [16].

Ordered hetero-junction cell: The approach of the ordered hetero-junction is further expected to be a better performing configuration as shown in Fig. 4. Here the small distance between donor and acceptor species facilitates for high dissociation probabilities. Consequently, as high charge carrier collection at electrodes is facilitated by “carrier highways” of single species, preventing competing processes of interfacial recombination. This highly ordered morphology on the nano-scale however requires some advanced structuring process, preferably via self organization [17].

2.3. Three layer solar cell

The excitons can easily be dissociated into free charges by the built-in electric field at the P-N junction, when an intrinsic layer is added into the device structure. The structural diagram of device with an intrinsic layer is as shown in Fig. 5. Its main purpose is to augment the volume of depletion region to increase the size of effective light absorption area, thereby allowing more excitons to be dissociated into free charges [18]. However, as the intrinsic layer is a poly-molecular thin film formed by co-evaporation of two different materials, its conductivity is reduced, which increases the series resistance of device. Also as the series resistance of solar cell is inversely proportional to fill factor (FF). Any increase in intrinsic layer thickness would cause increase in short-circuit current while FF becomes smaller. But, when the thickness of intrinsic layer increases to 30 nm, short-circuit current becomes lower. This is because intrinsic layer is a blend of different materials, which makes it easier for carriers in intrinsic layer [19].

2.4. Stacked organic solar cells

A more efficient structure can be constructed by stacking two cells on top of each other as depicted

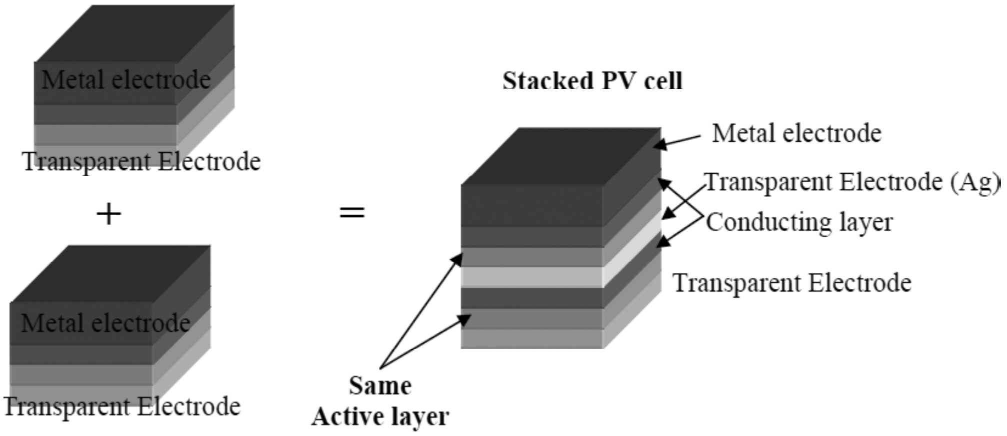

Fig. 6. Schematic representation of a typical stacked Organic Photovoltaic cell.

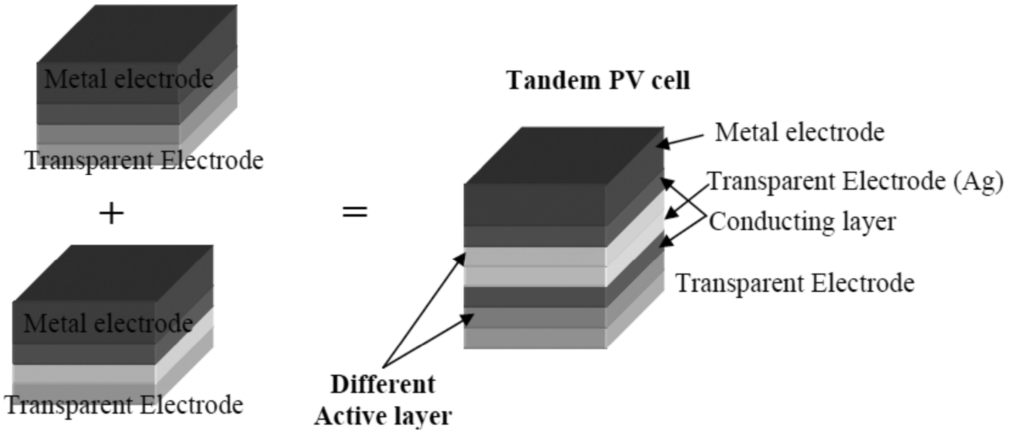

Fig. 7. Schematic representation of a typical tandem Organic Photovoltaic cell.

in Fig 6, and thus can be increase the overall absorption width of the solar cell. In stacked structure, two separate single PV cells are jointed by a transparent electrode. This stacked structure is equal to two single cells in series, so the open circuit voltage is improved, and the short circuit current is also improved [20]. However, the number of excitons generated in each layer is not identical in actual devices. Due to the differences, some excess electrons or holes are assumed to remain near the internal electrode even when majority of electrons and holes recombine in the internal floating electrode (IFE). The IFE should act as a place where hole and electron currents are connected without potential loss due to alignment of the Fermi levels with adjacent organic layers although partial loss of current occurs owing to unbalance of exciton produced in each hetero-junction. Therefore, a problem of stacked cells is the requirement of transparent contacts [21]. When the same active material is used for the different individual cells of the stacked device, it is termed as 'stacked cell' in contrast to a so called 'tandem solar cell', where different active material need to use for the different individual cells of the stacked device.

2.5. Tandem organic PV cell

Tandem cell is the improved version of the 'stacked cell' where different active materials are used for the different cells of the device as shown in Fig. 7. It has developed to increase the photon absorption by stacking two or more single cell in series connection in which active polymer with different absorption characteristics are linked to use a wider range of the PV spectrum. The light which is not absorbed in the bottom device can further impinge on the top cell. Thus, by balancing the optical absorption of each cell, it would be possible to enhance the efficiency of a 'tandem cell' [22]. However, there are some strict requirements in forming the tandem cells. In positioning the high and low bandgap materials, the illumination should first strike the absorber with the high bandgap because the light with

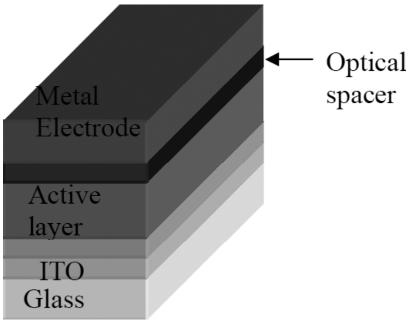

Fig. 8. Schematic representation of Organic Photovoltaic cell with light trapping effect using optical spacer.

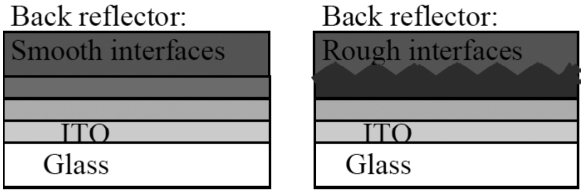

Fig. 9. Schematic representation of Organic Photovoltaic cell with light trapping effect using back reflector.

high energy will be absorbed with a high output voltage. Furthermore, this material should be transparent for low energy light which can be passed on to the second absorber with the lower bandgap [16]. One would usually contact the top and the bottom cells separately which is the reason why these tandems are also called four terminal devices. Due to the separate connections of top and bottom cells they do not require current matching which makes the combination of bandgaps quite flexible. A major disadvantage of tandem cells is the need to equate the photocurrents generated in each of the cells in order to achieve the highest power conversion efficiency [23].

2.6. Light trapping OPV structure

One key problem in optimizing organic solar cells is to keep the charge carrier transport paths as short as possible in order to minimize recombination losses during the charge carrier extraction. A partial solution to the problem is represented by the reduction of the active layer thickness. However, the reduction in active layer thickness, increase the loss of a large fraction of the impinging light. Another alternative technique to improve the efficiency is by increasing the photon flux inside the solar cell or by increasing the optical path length of the light. One of the possible routes for this could be through methods of light trapping. Trapping light in the active film will enable an improved absorption and hence allow the use of thinner films [24]. Light trapping is usually achieved by changing the angle at which light travels in the solar cell by having it to be incident on an angled surface. Several following important light trapping schemes have been proposed to enhance the quantity of light absorbed in OPV cells.

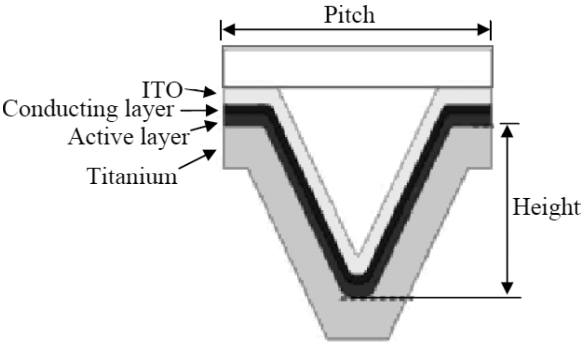

Fig. 10. Schematic representation of Organic Photovoltaic cell with light trapping effect using micro-textured.

2.6.1. Light trapping by using thicker active layer with optical spacer

An alternative approach is to change the device architecture with the goal of spatially redistributing the light intensity inside the device by introducing an optical spacer between the active layer and the Al electrode as sketched in Fig. 8. Although this revised architecture would appear to solve the problem, the prerequisites for an ideal optical spacer limit the choice of materials: the layer must be a good acceptor and an electron-transport material with a conduction band edge lower in energy than that of the lowest unoccupied molecular orbital (LUMO). Titanium dioxide is such a promising candidate as an electron acceptor and transport material [25].

2.6.2. Trapping light by using back reflector

Enhancing light-trapping in thin solar cells is also achieved by a back reflector that re-confines light within the absorber layer. Back reflector with both smooth interfaces and rough interfaces are depicted in Fig. 9. Such textured back reflector is usually used to scatter light at the interface through large reflected angles. This increases the optical path length within the cell, and therefore it is necessary

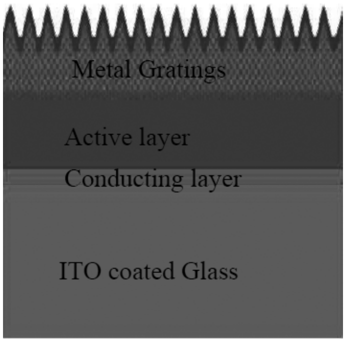

Fig. 11. Schematic representation of Organic Photovoltaic cell with light trapping effect using diffraction gratings.

to scatter as much light as possible in oblique directions for higher efficiency [26].

2.6.3. Trapping light by micro-scale textured surface

Another way to improve light trapping can be a textured, grating-shaped OPV cell geometry as shown in Fig. 10. Submicron or micron structures can modify the incident wave momentum in such a way that the incident light remains trapped in the solar cell active layer due to total internal reflection at the interfaces [27-28]. This results in increased absorption in the active layer, and facilitates the use of layers with optimum thickness with regard to the electrical properties. The perceived optoelectronic benefits of using these light trapping structures have led to the recent development of embossing being successfully applied to the patterning of polymer OPVs, leading to a significant increase in generated photocurrent [29]. The superiority of textured geometry in terms of light trapping is clearly demonstrated by the simulation results [30].

2.6.4. Light trapping by diffraction gratings

Diffraction gratings also can be used for light trapping purpose in OPVC as shown in Fig. 11. Integrating diffraction gratings in optical thin film systems can serve to optimize existing systems or can even give rise to novel systems. Depending on the geometric parameters of the diffraction grating, the absorption in the active polymer film can be significantly increased for a certain interval of the spectrum. Sub-wavelength gratings known as an antireflective structure [31] have been also incorporated into organic solar cells [32].

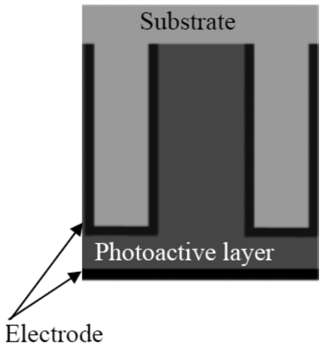

Fig. 12. Schematic representation of Organic Photovoltaic cell with light trapping effect using buried electrode.

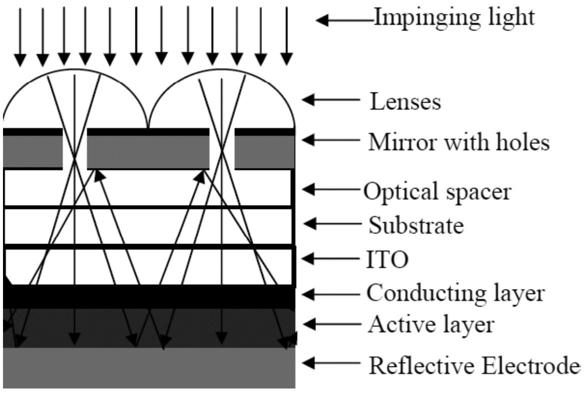

Fig. 13. Schematic representation of Organic Photovoltaic cell with light trapping effect using microlense.

2.6.5. Light trapping with soft embossed gratings

Another soft lithography technique, soft embossing can be applied for patterning sub-micrometer topographical features on large areas of an active polymer layer. This grating is used to enhance the performance by trapping light into the polymer film. One way of reconciling these different requirements is to trap light into the polymer layers by diffraction into guided modes in the thin polymer films [29]. Soft lithography is a set of gentle processes that can be used for patterning in polymeric devices, such as micro-contact printing [33], replica molding [34], self-assembled monolayers, and put-down & lift-up techniques.

2.6.6. Light trapping by buried nano-electrode

The concept of light trapping by buried nano-electrodes is based on an electrode configuration as depicted in Fig. 12. One electrode is planar and the other electrode is orientated perpendicular to the

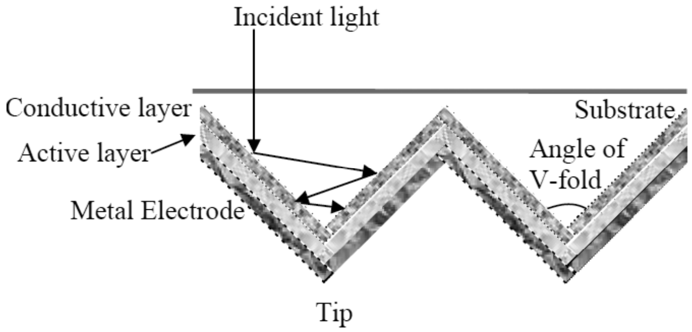

Fig. 14. Schematic representation of Organic Photovoltaic cell with light trapping effect using folded structure.

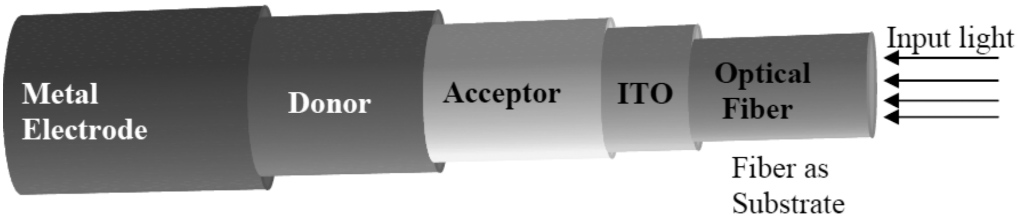

Fig. 15. Schematic representation of Organic Photovoltaic cell with light guiding effect using optical fiber.

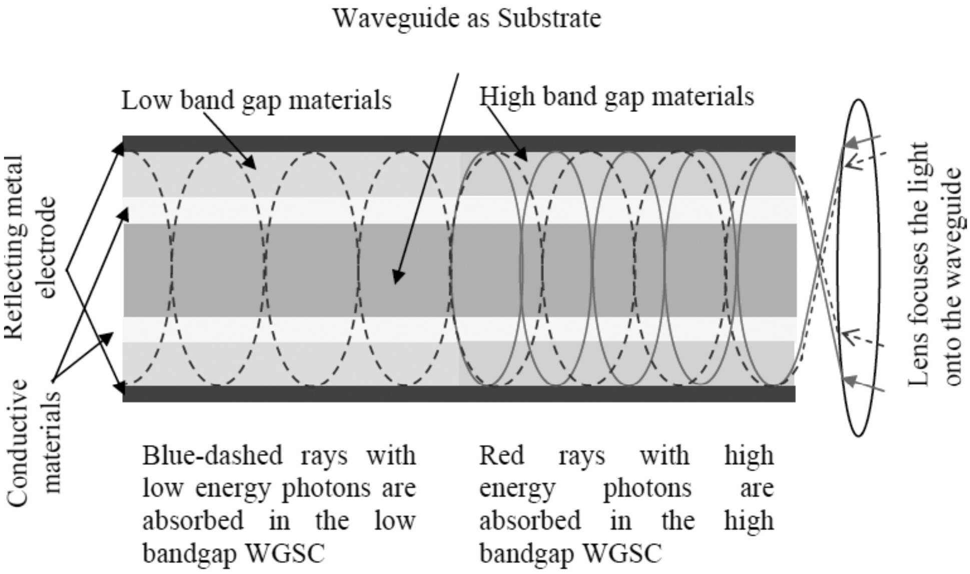

Fig. 16. Schematic representation of Organic Photovoltaic cell with light guiding effect using optical waveguide.

substrate surface forming a lamellar structure. Low mobility charge carriers will be collected at the lamellar electrodes, whereas high mobility charge carriers are collected at the planar electrode and hence deep cavities and narrow lamellae should be desirable [35].

2.6.7. Light trapping with micro-lens

It is the technique, where the scattering and light trapping features are separated from the active layer in order to avoid the possibility of electrical defects. A light trapping element is placed in front of a solar cell with limited absorption as shown in Fig. 13. The trap is transparent to collimated light in one direction, and highly reflective in the opposite direction, to both collimated and directionally random light. Thereby an efficient trapping mechanism of the direct component of sunlight can be implemented. As light bounces back and forth between the reflective metal surface of the cell electrode and the back surface of the trap element, multiple transits through the active layer will occur, thus increasing the probability of photon absorption [36].

2.6.8. Folded solar cell architectures

An additional and not less pronounced light trapping effect is due to multiple reflections and absorptions. In order to get such benefit from the enhanced light absorption under the illumination at inclined incident angles, a folded organic solar cell architecture has developed [37] as shown in Fig. 14. Due to the multiple reflections in the device, each ray sees many different angles of incidence to the active layer, when impinging on the folded geometry. The approach uses a V-shaped substrate and multiple reflections in the V-shape to enhance the photocurrent. This method is more effective than textured surfaces for thin-film cells. A reflective tandem polymer solar cell based on the geometry of a folded solar cell architecture was also proposed [38].

2.7. Photonics technology based OPVC structure

The concept of the photonic technology based photovoltaic device is that, if the radiant energy could be captured and forcing them to cooperate for improving light absorption by using specialty optical structure, the efficiencies could be raised significantly. Such structure can be implemented on both optical fiber and optical waveguide structure.

2.7.1. Optical fiber based OPVC

Typical optical fiber based PV, comprising a PV cell build around the core of an optical fiber as shown in Fig. 15. It would enable to produce electricity over optical fiber [39]. A fiber-based device can be realized by depositing the PV layer structure, concentrically around a fiber substrate by growth from solution or vapor phase [40]. Light can couple into the active layers through the outermost electrode or from the fiber core. In this architecture, propagating modes within the layer are playing a role on the photon absorption as well as performance of the OPVC device. Further improvement of light trapping can be achieved via external dielectric coatings, which could be coupled with protective coating for improved operational lifetime [41].

2.7.2. Optical waveguide based OPVC

The optical waveguide can also be used to design more sophisticated third generation photovoltaic devices. Fig. 16 schematically shows a possible design, based on optical concentration in conjunction with two waveguide solar cells mounted behind each other on the same waveguide. A lens focuses the light onto the waveguide entrance and energy rich photons of the solar spectrum (shown as dashed blue rays) are absorbed in the first waveguide solar cell which has a large bandgap. Then photons (shown as dashed-dotted red rays), propagate along the waveguide to meet the lower bandgap waveguide solar cell and are absorbed there [42].

3. CONCLUSIONS

Organic Photovoltaic cells (OPVCs) have gained much attention, and significant progress has been made recently in order to meet the requirement of environmentally friendly OPVC at low cost. This review is aimed at obtaining a better understanding of the structural improvement in fabricating OPVC. Within each area, major critical issues are discussed. Insights gained from this study are very useful for manufacturers to fabricate better OPVC with favorable performance. It is believed that only after the structure has been broadly learned, incorporated and the manufacturing infrastructure is built, would OPV be widely used and eventually replaces other conventional inorganic PV cell.

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