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Study of organic photovoltaics by localized concentrated sunlight: Towards optimization of charge collection in large-area solar cells

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Large-area organic solar cells are known to suffer from a major efficiency decrease which originates from the combination of a voltage drop across the front electrode and the voltage-dependent photocurrent. In this letter, we demonstrate this efficiency loss on large area, indium tin oxide free cells with a hexagonal current collecting front grid, by measurements of light intensity dependence of the cell performance. The results show a major difference in the cell performance measured under localized and uniform illuminations. Subsequently, we demonstrate ways in which the current collecting efficiency could be raised. © *2011 American Institute of Physics*. [doi:10.1063/1.3656276]

The main challenge in organic photovoltaics (OPV) yet to be solved is the development of devices that unite high efficiency, stability, and processability of large area solar cells. Intense research is directed towards the development of such cells with a bulk heterojunction (BHJ) where donor-type conjugated polymers and acceptor-type fullerene derivative, such as [6,6]-phenyl-C61-butyric acid methyl ester (PCBM), are mixed to form the photoactive layer.[1] Serious progress has been achieved in the improvement of photovoltaic (PV) performance of BHJ solar cells; while the best power conversion efficiency (PCE) reported eight years ago barely reached values higher than 1%, certified efficiencies beyond 8% are state of the art today.[1]

However, the OPV PCE is known to be limited by the cell area. Most of the record efficiencies (see, for example, Table I in Ref. 2) were reported for ultra-small BHJ OPV cells (with area $\ll 0.4\,\mathrm{cm}^2$, a low area limit for the PCE measurements suggested in the recent editorial report[3]). Recently,[2] we suggested that this PCE deterioration is mostly due to the fact that the resistive transparent front contact (indium tin oxide (ITO) in the majority of OPV cells) causes a non-negligible voltage drop across the cell area, which in turn limits the photocurrent (considerable decrease in the cell short-circuit current density J_{SC} and fill factor FF). This effect amplifies with cell area and the sheet resistivity of the transparent front contact. The voltage drop can be dealt with by the employment of a highly conductive Ag current collecting grid, which prevents the voltage drop across the front contact and improves PCE of large area cells.[4,5]

In this letter, we report light intensity dependence of the key parameters (open-circuit voltage V_{oc}, J_{sc}, FF, and PCE) of a large photoactive area ($\sim$4 cm^2) ITO-free cells with poly(3-hexylthiophene) (P3HT)/PCBM BHJ and transparent anode, based on solution processed high conductive poly(3,4-ethylenedioxythiophene):polystyrene sulfonate (PEDOT:PSS) in combination with a honeycomb Ag printed current collecting grid [Figs. 1(a) and 1(b)]. The grid printing and the cell preparation is described elsewhere.[4,5] Honeycombs structure provides homogenous current distribution in case of four bus-bars devises, which were used in this study. Additionally, because of a lot of grids intersections, such grid structure is more preferable for current collection, in the case of defects in some area of the grid, in comparison with lines structure. At the same time, honeycomb structure provides less surface coverage with the same pitch size in comparison with square grid structure.

Prior to the transportation to Sde Boker, Israel, for concentrated sunlight study, the current-voltage (J-V) characterization was performed in the Holst Centre with a simulated one sun (100 mW/cm^2) AM1.5G irradiation using a xenon-lamp-based solar simulator Oriel (LS0104). Figure 2 depicts the comparison between the J-V curves of two cells. The front contact in one cell was made from highly conductive PEDOT, while the other cell uses the same layer with the addition of an Ag grid (shown in Figs. 1(a) and 1(b)). It is

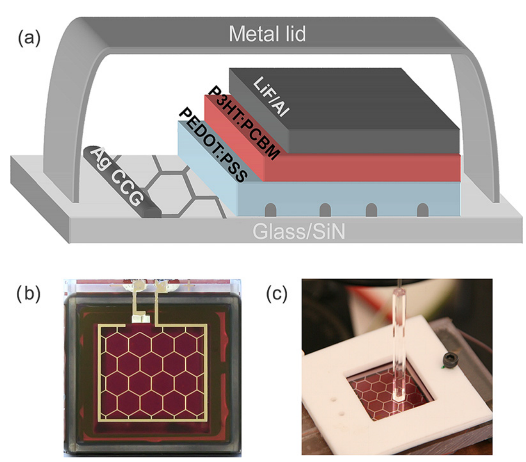

FIG. 1. (Color online) OPV cell under the study. (a) Schematic of device architecture. (b) Photograph of the front surface. (c) Localized illumination of the cell.

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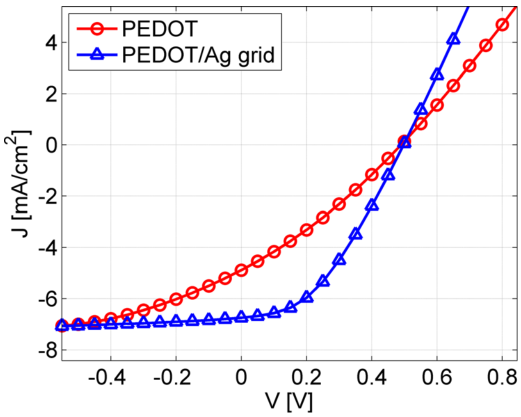

FIG. 2. (Color online) A comparison between *J-V* curves of the two ITO-free cells (with and without an Ag grid) measured under a simulated one sun irradiation.

clear that although the grid causes some cell shading, overall it enhances the cell efficiency.

An important question is if the "gridded" cell achieves the highest performance controlled by the properties of the cell photoactive layer or it still suffers from the limited charge collection? We will demonstrate below that it is possible to address this question by the comparison of light intensity dependence of the cell performance measured with uniform and localized illumination of concentrated sunlight.

Concentrated sunlight experiments were performed in Sede Boker using the fiber-optic/mini-dish solar concentrator[6,7] (see Figure S1 in supplementary material[8]). Study of OPV using this outdoor/indoor test facility was described in details elsewhere.[2,9,10] Sunlight collected and concentrated outdoors were focused onto a transmissive (quartz-core) optical fiber of 1 mm in diameter and then delivered indoors onto the solar cell being tested [Fig. S1(a)[8]]. Uniform illumination of the cell photoactive area was achieved with an 8 cm long square cross-section kaleidoscope, matching the area within the rectangular bus-bar (2 by 2 cm^2), placed between distal fiber tip and cell [Fig. S1(b)].

Localized illumination, with an illuminated area almost matching a single hexagon of the honeycomb Ag grid (5 mm size) was achieved using a proper 5 cm long hexagonal light homogenizer [Fig. 1(c)].

Figure 3 compares J_{sc}, V_{oc}, FF, and PCE measured under various concentrations (up to 10 suns) of uniform and localized illumination. Localized illumination of different hexagons over the cell area gave identical results.

It is clear that the results in the localized mode show superior J_{sc}, [Fig. 3(a)], FF [Fig. 3(c)], and PCE [Fig. 3(d)] values as well as considerable shift towards high intensities of the PCE peak [Fig. 3(d)], and linear regime of J_{sc} [Fig. 3(a)]. Such behavior is characteristic for OPV (due to the above mentioned combined effects of the voltage-dependent photocurrent and the voltage drop over the front contact system)[2] and has not been observed for inorganic PV cells (the latter exhibit voltage-independent photocurrent). It should be noted that the reported PCE behavior in the localized illumination mode is not influenced by small possible leaking of the incoming light in the front 0.7 mm thick glass (estimated length of such leaking is much less than 0.7 mm). This is due to the fact that all incoming light in this mode is absorbed within the cell, and the PCE only requires the measurement of the maximum output electrical power produced by the cell and incoming light power and does not depend on the illuminated area.

On the other hand, the reduced V_{oc} and its sub-linear behavior at high intensities (in a semi-logarithmic plot) for the localized illumination [Fig. 3(b)] is a well known effect in inorganic PV that is attributed to the large area dark diode connected in parallel to the small illuminated sub-cell.[7]

Previously,[2] we demonstrated that, contrary to J_{sc} and FF, V_{oc} of uniformly illuminated OPV cells does not depend on their area.[2] Thus, the V_{oc} drop in the localized mode can be compensated in the PCE calculation by taking the uniform V_{oc} values. PCE calculated by this manner is shown by an upper curve in Figure 3(d). This compensated PCE curve with a maximum of ~3% at 1 sun represents the low bound[7] for the PCE if the uniformly irradiated cell would have the size of one hexagonal unit. The observed difference of 600% (relative) in PCE at 1 sun of the entire 4 cm^2 device and that of one hexagon reflect the difference between the photovoltaic

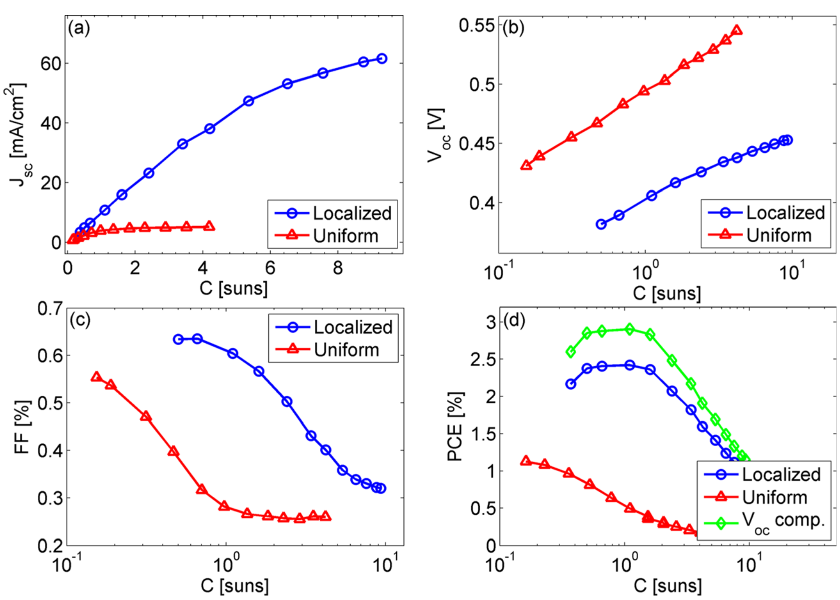

FIG. 3. (Color online) A comparison between the key parameters of uniformly and localized illuminated cells: (a) J_{sc}, (b) V_{oc}, (c) FF, and (d) PCE. The V_{oc} compensation of the PCE is made by a constant 1.22 factor based on the uniform/localized V_{oc} ratio.

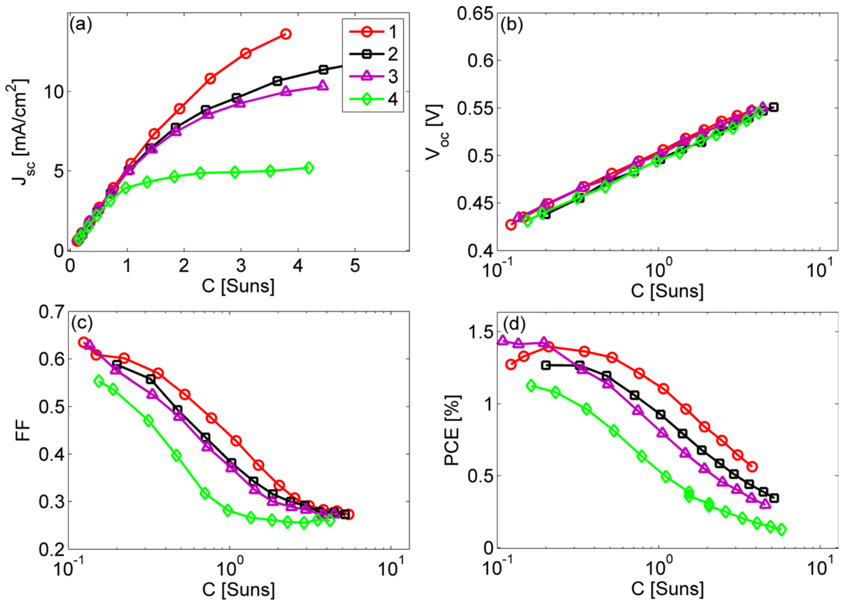

FIG. 4. (Color online) A comparison between PV performances for the four different contact geometries: (a) J_{sc}, (b) V_{oc}, (c) *FF*, and (d) *PCE*.

capabilities of the cells' "basic unit" and the performance of a whole device limited by the charge collection losses in the contact system. One can conclude that there is still a considerable efficiency loss even when the Ag grid is in use. In order to investigate the reason for this "bottleneck," we have realized four different geometries of the cell front contact system (fingers' and bus-bar' width) but having the same photoactive area (within the bus-bar) (Table I).

Results of localized illumination of cells 1, 2, and 4 were similar to the corresponding results shown in Fig. 3, while cell 3 exhibited poorer localized illumination performances due to the increased pitch size (not shown).

Figure 4 depicts the PV characteristics of these cells measured under uniform illumination of their photoactive area. According to our expectation, the width of the collecting fingers and bus-bar improved the cell performance dramatically, in spite of the associated increase of the shading. It is clear that cell 1 (with wide fingers and the bus-bar) exhibits the highest J_{sc}, *FF*, and *PCE* as well as a considerable shift of the PCE peak to the highest illumination level [Fig. 4(d)]. However, the problem of current collection losses has been solved only to some extent: the cells efficiency increased from 0.5% (for cell 4) to 1.1% at 1 sun, with a peak efficiency of 1.4% at 0.2 suns (for cell 1). This is still far from the PCE peak for the localized measurement which stands on $\sim$3% at 1 sun [Fig. 3(d)].

We will also note that device 3 (characterized by a larger hexagon pitch of 8 mm) but with wide fingers and bus-bar shows almost the same performance cell 2 having 5 mm hexagon pitch, wide bus-bar but narrow fingers.

TABLE I. Geometries of the front contact system of the cells. Wide finger width: 325 μm; narrow finger width: 215 μm. Wide bus-bar width: 1800 μm; narrow bus-bar width: 600 μm. Cell 4 shares the same geometry as the cell presented in Figures 1–3.

Cell	Fingers	Bus-bar	Hexagon pitch width (mm)
1	Wide	Wide	5
2	Narrow	Wide	5
3	Wide	Wide	8
4	Narrow	Narrow	5

All our results point out that further optimization of the cell contact system should include detailed study of the cell with independent variation of hexagon pitch (or distance between the fingers for other grid configurations), width and thickness of the fingers, and bus-bar. Since all of the current flows through the bus-bar making the periphery area a designated "bottle-neck" for the voltage drop (see Fig. 8 in Ref. 2), we suggest that the optimum contact system may have a non-uniform geometry with maximum shading (wide fingers or short distance between) near the bus-bar and minimum shading at the cell center.

In summary, large-area OPV cells suffer from PCE losses that can be dealt with by the introduction of a current collecting grid. However, localized illumination measurements show that there is still a significant difference between the photovoltaic capabilities of the cell's "basic unit" and the whole device. Additional optimization of the grid was shown to improve the cells performance, towards ideal charge collection and maximized efficiency.

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