Enhancing photon harvesting in organic solar cells with luminescent concentrators

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The authors report on the application of luminescent concentrators on organic solar cells fabricated zinc-phthalocyanine and C_{60}. These solar cells have their main absorption in the wavelength range between 600 and 800 nm. Below 600 nm, the low absorption limits the quantum efficiency. Luminescence concentrators are used to overcome this limitation by spectrally shifting blue and green light towards the red and waveguiding it to the solar cell. With a second solar cell harvesting the red light transmitted through the concentrator, the photocurrent density is increased compared to a single solar cell of equal active area from about 8.5 up to 10 mA/cm^2. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2735671]

The discovery that conjugated organic molecules can be conducting and semiconducting led to the development of organic solar cells.[1,2] Major research effort is put into synthesizing new materials and developing new cell concepts to increase the efficiency, which has resulted in about 5% power conversion efficiencies in organic solar cells.[3–5]

An important feature of organic solar cells is the limited spectral range of absorption in organic dye molecules. The most efficient solar cells at present are harvesting mainly the blue, green, and yellow parts of the solar spectrum. An important step is the availability of organic materials absorbing further into the red and infrared parts of the spectrum, so-called low energy gap materials. However, these most often have an absorption which is weak in the blue and green parts of the spectrum. This spectral trade-off is not always positive.

A promising way to enhance the efficiency of these solar cells is to use "antenna systems" of absorber materials that do not take part in the charge generation and transport mechanisms but will donate the energy from photons absorbed in the blue and green spectral ranges to the red absorbing solar cell materials.[6]

Luminescence concentrators use organic dyes with high photoluminescence quantum yields that concentrate and redshift the incoming light and couple it to a waveguide. The solar cell is fixed to the waveguide and can thus collect light from a large area that has been converted to the narrow red emission spectrum of the dye. Luminescent concentrators have been proposed previously for silicon solar cells.[7–9]

In the following, the use of a luminescent concentrator together with low energy gap organic solar cells is studied. The organic solar cell is based on a blend of zinc-phthalocyanine (ZnPc) and fullerene C_{60}.[10–12] An approximately 70 nm thick film of poly(3,4-ethylene dioxythiophene) doped with poly(styrenesulfonate) (PEDOT:PSS) (Baytron P) is spin coated on a 0.75 mm thick glass substrate covered with a 200 nm thick transparent electrode of indium tin oxide. After thorough drying, a 60 nm thick film of a blend of ZnPc:C_{60} followed by a 30 nm thick film of C_{60} is thermally evaporated in high vacuum ($<10^{-5}$ mbar). This active layer is covered by a 100 nm thick evaporated aluminum electrode.

The luminescent concentrator is a $3\times15\times15$ mm^3 polymethyl methacrylate plate fabricated by thermal polymerization of a methyl methacrylate solution (Plexit) doped with 0.007 wt % of the Makrolex fluorescence red G dye from Bayer with a luminescence quantum yield of 89%. It is fabricated by the Fraunhofer IAP and has been used already in conjunction with a silicon solar cell.[9] The absorbance spectrum of the concentrator plate is shown in Fig. 1(b) together with the luminescence spectrum of the used dye.

Two solar cells are used on different sides of the concentrator plate: the "bottom cell" has an active area of 15×15 mm^2 and the "side cell" of 3×15 mm^2. Both are fixed onto the respective sides of the concentrator plate, as shown in Fig. 1(a). The glass substrate of the side cell is bonded to the Plexit plate by highly transparent two-component epoxy glue. As the waveguiding properties of the plastic plate have to be conserved, the bottom cell is just loosely placed onto the concentrator, leaving an air gap. Aluminum mirrors are applied to the other small faces of the concentrator plate with an air gap to increase the waveguiding towards the side cell.

I-V characteristics and incident photon to collected electron (IPCE) efficiency spectra of both solar cells are measured before and after application to the concentrator plate. The light source for the *I-V* characteristics is a Steuernagel solar simulator adjusted by a calibrated silicon diode to give a 100 mW/cm^2 AM1.5 illumination. IPCE spectra are recorded by monitoring the short circuit current of the solar cells with an SRS830 lock-in amplifier using the chopped, monochromated ($d\lambda<2$ nm) light from a Xe lamp as illumination. The incident light is focused in a 3×2 mm^2 spot which is moved across the surface of the concentrator.

Under direct illumination, the side cell device shows the typical behavior of an organic solar cell produced from ZnPc and C_{60} [Fig. 2(a)]. A short circuit current density (J_{sc}) of around 10.5 mA/cm^2 is accompanied by an open circuit voltage (V_{oc}) of around 360 mV and a fill factor of 0.39. The IPCE spectrum corresponds to the sum of the absorption spectra of the used materials and shows significant photon-

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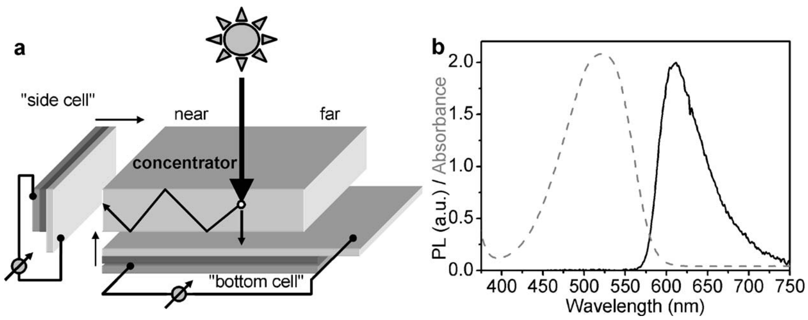

FIG. 1. (a) Schematic representation of the concentrator device. (b) Absorbance (dashed) and photoluminescence (solid) spectra of the concentrator plate.

to-electron conversion efficiencies in the range between 600 and 750 nm, while below 580 nm the low absorption limits the IPCE.

After the solar cell is attached to the luminescent concentrator, it stands perpendicular to the incoming light and receives only light that is coupled into the waveguide by the luminescent dye. The J_{sc} measured now over the full area of the concentrator plate amounts to 2.8 mA/cm^2. As the active area of the concentrator plate is five times bigger than the side cell active area, the absolute photocurrent of the side cell increases by a factor of 1.3 with the concentrator in comparison with the cell under direct illumination.

The waveguiding mechanism is visible in the IPCE spectra of the side cell attached to the concentrator [Fig. 2(b)]. A clear correlation between the absorption spectrum of the dye inside the concentrator plate and the IPCE spectrum can be discerned. This is due to the fact that only light which is absorbed and reemitted by the dye can be efficiently waveguided to the solar cell.

The luminescence spectrum of the dye overlaps with the maximum in the conversion efficiency of the solar cell. Thus, the light absorbed by the dye in the concentrator can be

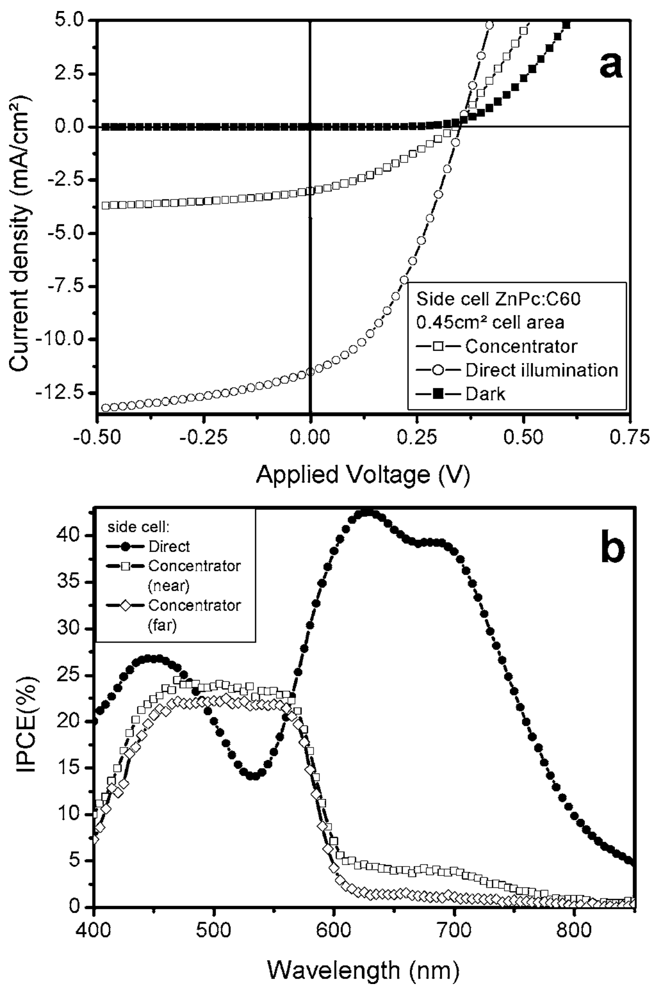

FIG. 2. (a) *I-V* characteristics of the side cell in the dark (solid squares), under direct 100 mW/cm^2 simulated AM1.5 illumination (open circles), and attached to the concentrator plate (open squares). (b) Incident photon to collected electron (IPCE) spectrum of the side cell under direct illumination (full circles) and attached to the concentrator plate [open squares: illumination close to the solar cell; open diamonds: illumination on the far side of the concentrator plate, as shown in Fig. 1(a)].

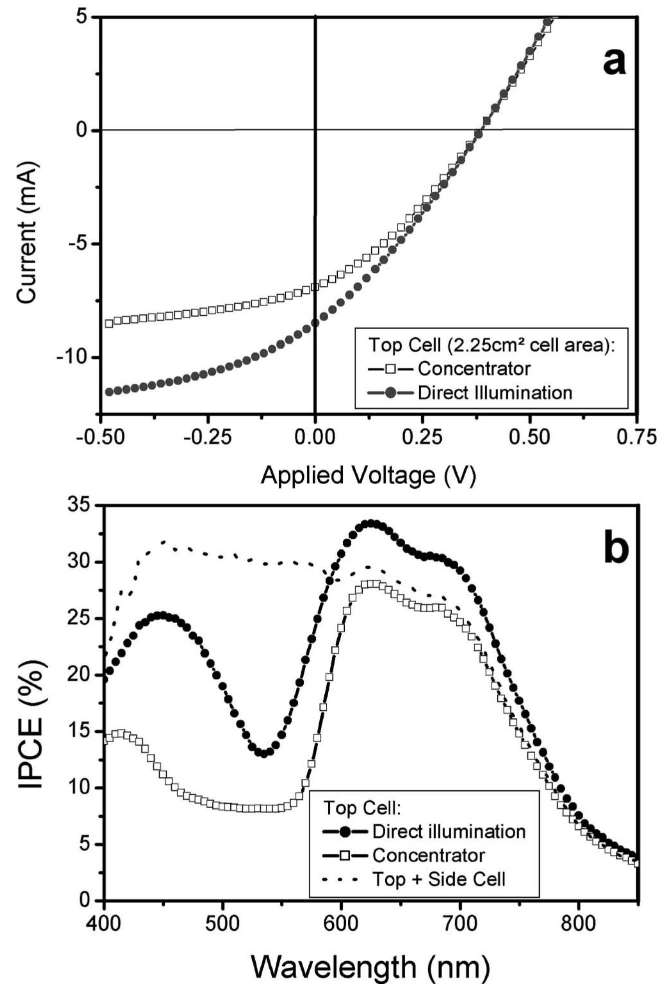

FIG. 3. (a) *I-V* characteristics of the bottom cell under 100 mW/cm^2 simulated AM1.5 illumination and direct (full circles) and through the concentrator (open squares). (b) Incident photon to collected electron (IPCE) spectra of the bottom cell under direct illumination (full circles) and through the concentrator plate (open squares). The dashed line is the addition of the side and bottom cell IPCE spectra representing the total conversion efficiency of the concentrator device.

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converted more efficiently in the solar cell attached to the concentrator than under direct illumination. This can be seen by the increase in conversion efficiency around 500 nm and illustrates the high efficiency of the waveguiding structure.

The IPCE spectrum measured near the side cell [Fig. 1(a)] shows only slightly higher conversion efficiencies of the waveguided light than the spectrum measured at the far end of the concentrator area. This indicates that also a larger concentrator area can be used to harvest energy with a side cell. In applications for silicon solar cells, usually concentrator size of 5×5 or $10\times10\ \mathrm{cm}^2$ is used with high efficiencies.[9]

Under direct illumination, the bottom cell shows ($2.25\ \mathrm{cm}^2$) a fill factor of around 0.3 as well as a J_{sc} of around $8.5\ \mathrm{mA/cm}^2$ due to its larger size [Fig. 3(a)]. The IPCE spectrum under direct illumination is similar to the side cell with lower values corresponding to the lower J_{sc}.

Together with the concentrator, the J_{sc} of the bottom cell decreases to about $7\ \mathrm{mA/cm}^2$. The IPCE spectrum of the bottom cell in the concentrator device [Fig. 3(b)] reveals that the incoming light between 440 and 560 nm is absorbed by the dye and reemitted in random directions. Most of the emission is coupled into the waveguide and harvested by the side cell. Only some of the light is emitted inside the escape cone and leaves the concentrator towards the bottom cell, where it is converted with an efficiency of above 30%. Red light is passes through the concentrator plate with slight reflection losses and can be directly converted by the bottom cell.

If the responses of the bottom and side cells in the concentrator device are added together [Fig. 3(b), dotted line], a strong increase in the conversion of blue and green lights is apparent. This enhancement overcomes the reflection losses in the concentrator and leads to an increase of the J_{sc} from 8.5 to around $10\ \mathrm{mA/cm}^2$. The power conversion efficiency of the integrated concentrator device is around 1.25%, while a single solar cell with the same surface area yields about 1% under direct illumination.

In conclusion, this concept of combining organic solar cells and luminescent concentrators enhances the performance of organic solar cells with limited quantum efficiencies in the blue and green spectral ranges. As organic solar cells can be fabricated without substrate heating, the concentrator itself can be used as a support, leading to a better coupling of the side cell to the waveguide.

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