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Monochromatic versus solar efficiencies of organic solar cells

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Abstract

In scientific papers on organic solar cells, all kinds of efficiencies are reported. The aim of this paper is to discuss some of the valuable as well as some of the less valuable efficiencies. However, the main aim of this discussion is to get a deeper insight in the efficiency limiting processes of state of the art molecular organic solar cells. As an example our three layer cell made from 20 nm N, N′-Dimethyl-3,4 : 9, 10-perylenbis (carboximid) (MPP), 30 nm Zinc-phthalocyanine (ZnPc) containing 50% C_{60} and 50 nm ZnPc is used. It is shown that here for the first time the efficiency of a purely organic solar cell is not limited anymore mainly by the achieved current efficiency but rather the obtained open-circuit voltage and the fill factor. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Molecular organic solar cells; Photovoltaics; Organic semiconductors, Solar efficiencies; Quantum yields

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1. Introduction

Encouraged by the successful development of sensitization solar cell [1,2] also pure organic solar cells [3] have been taken into closer scientific investigation. As in other fields of new photovoltaic devices, all scientists working with such cells have to deal with relatively poor power conversion and sometimes even small quantum efficiencies.

In order not to publish too discouraging small efficiency data, many ill-defined types of “efficiencies” were used to describe the cells. As examples, one finds monochromatic power conversion efficiencies in many cases even without any statement on

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the used light intensity, polychromatic efficiencies reached by using arbitrary light sources or calculated inner monochromatic quantum yields.

In the present paper we will discuss some well-defined polychromatic and monochromatic efficiencies that at least allow a comparison of the results published by different groups.

2. Experimental

Zinc phthalocyanine (ZnPc) from Kodak and the methyl substituted perylene pigment (MPP) N, N′-dimethyl-3,4 : 9, 10-perylene bis (carboximid) from Hoechst were purified by train sublimation. The C_{60} was obtained from Dr. Oleg Shevaleevsky, N.N. Semenov Institute, Moscow, with purity better than 99.9%. ZnPc, MPP and the contact metal gold were evaporated onto an ITO coated glass substrate from Balzers in an evaporation-chamber at 10^{-6} Torr. A ZnPc/C_{60}-composite layer was introduced between the MPP and ZnPc by co-evaporation of ZnPc and C_{60}. The mass concentration of the C_{60} in the mixed layer was chosen to 50%.

By using appropriate masks, sample structures as shown in Fig. 1 were obtained. The results presented in the following sections are obtained from a cell with the structure, substrate/ITO (30 nm)/MPP (20 nm)/ZnPc–C_{60} [1 : 1] (30 nm)/ZnPc (50 nm)/Au (40 nm).

The short-circuit photocurrent spectra were measured using a xenon arc lamp and a monochromator. For the I/V-characteristics under illumination an AM 1.5 solar simulator (K.H. Steuernagel Lichttechnik GmbH, Mörfelden) was used. The photocurrent spectra as well as the I/V-characteristics were monitored using a Keithley SMU 236.

3. Monochromatic efficiencies

3.1. Incident photon to current efficiency (IPCE)

A reliable monochromatic efficiency is the incident photon to current efficiency (IPCE), which is simply the number of electrons measured under short-circuit

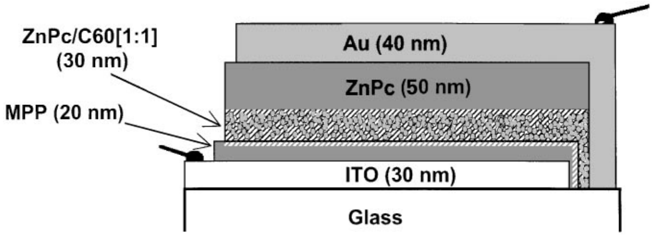

Fig. 1. Illustration of the sample structure.

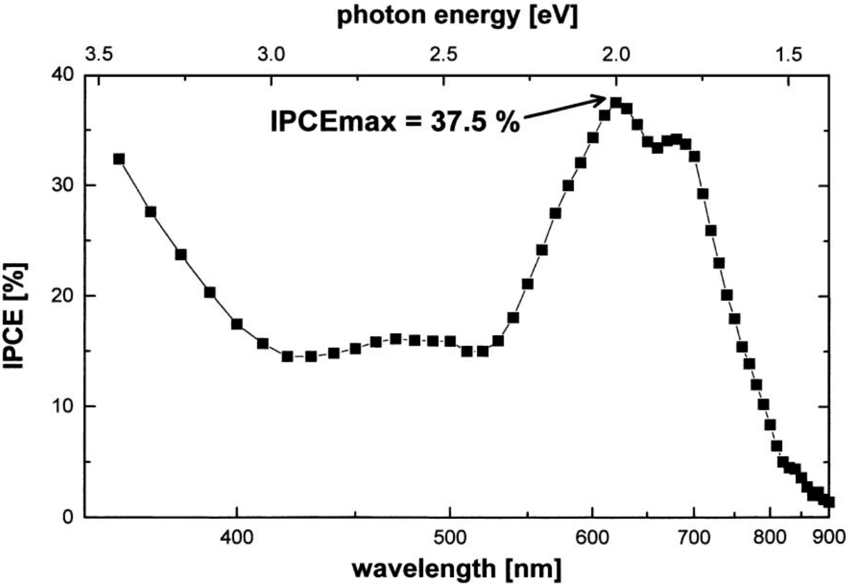

Fig. 2. Incident photon to current efficiency (IPCE) of an organic solar cell with a cell structure as depicted in Fig. 1.

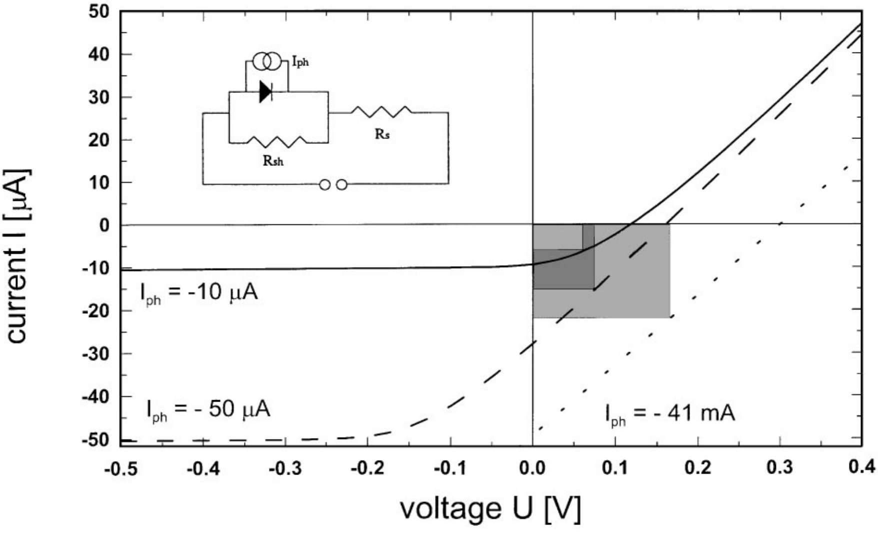

Fig. 3. Influence of the series and shunt resistances (R_{SH} and R_S) and the generated photocurrent (I_{ph}) on the fill factor (FF) and the power conversion efficiency. The inset shows a simple equivalent circuit of an organic solar cell.

conditions, no applied bias, divided by the number of incident photons. In order to normalize a measured photocurrent spectrum of the IPCE to the lamp spectrum one has to make sure that the short-circuit current is really directly proportional to the light intensity. In the case of molecular organic solar cells, this is the case only if the photoconductivity of the organic materials does not influence the measured photocurrent. The latter is found proportional to the square root of the photon flux [4]. A good test of an appropriate normalization of the photocurrent spectrum is provided by the relatively sharp emission maxima of a xenon lamp. They disappear completely in a normalized photocurrent spectrum only, if the correct intensity dependence is used.

The IPCE is defined as

$$\mathrm{IPCE} = \frac{I_{\mathrm{SC}}}{eN_0}, \tag{1}$$

where I_{SC} is the short-circuit photocurrent density, e the elementary charge, and N_0 the incident photons flux density.

In Fig. 2, we present the IPCE of an organic solar cell structured as depicted in Fig. 1 with a maximum of 37.5% at 600 nm.

3.2. Monochromatic power conversion efficiency

A monochromatic power conversion efficiency (Eq. (2)) by its own is useless without quoting the monochromatic light intensity.

$$\eta = \frac{I_{\mathrm{SC}} U_{\mathrm{OC}} \mathrm{FF}}{I_{\mathrm{light}}(\lambda)}, \tag{2}$$

where U_{OC} is the open-circuit voltage, FF the fill factor, and I_{light} (λ) the incident light intensity.

Especially, a light independent series resistance as explained in Fig. 3 in connection with a shunt resistance will lead to a saturation of the power output for higher light intensities. In the example shown in this figure a series resistance of 5 kΩ and a shunt

Table 1
Important quantities in Fig. 3 showing the strong influence of the resistances and the generated photocurrent on the fill factor (FF) and the power conversion efficiency (η) of organic solar cells

Illumination	I_{ph}	I_{SC} (μA)	U_{OC} (mV)	FF (%)	η (%)
Monochromatic e.g. 7.3×10^{13} Photons/cm^2 600 nm	– 10 μA	– 10	110	33	1.4
Monochromatic e.g. $5 \times 7.3 \times 10^{13}$ Photons/cm^2 600 nm	– 50 μA	– 30	150	25	0.4
Solar AM 1.5 100 mW/cm^2	– 41 mA	– 66	330	25	5×10^{-3}

resistance of 1 MΩ will lead to saturation at about 10^{-3} of 1 sun. Thereby, an assumed monochromatic power efficiency of 1.4% corresponds to a solar efficiency of only 1.6×10^{-3}% only as an effect of the higher current density under solar irradiation.

The important quantities of Fig. 3 are summarized in Table 1.

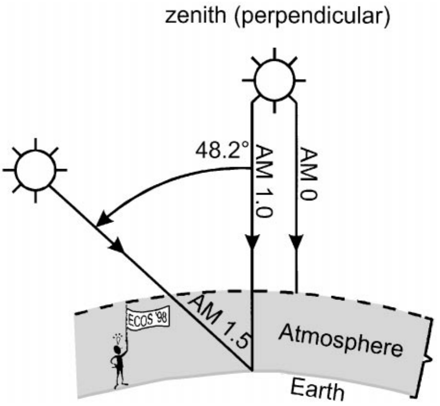

Fig. 4. Schematic explanation of the different AM sun light spectra.

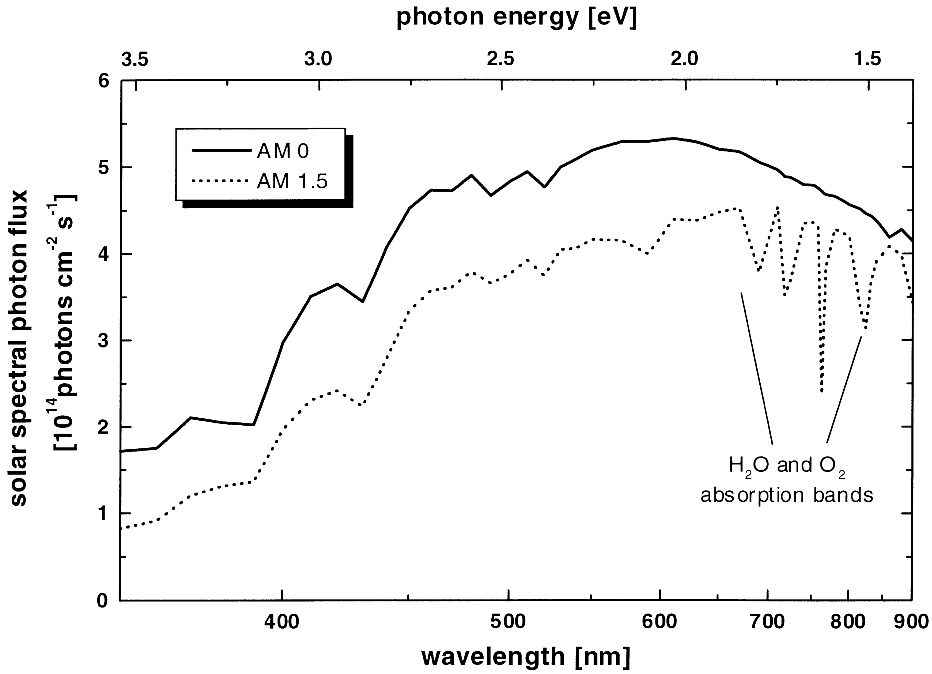

Fig. 5. Solar spectral photon flux for AM 0 and AM 1.5 sunlight.

4. Solar efficiencies

In the case of polychromatic efficiencies like the power conversion efficiency and the current efficiency, it is very crucial to use a well-defined and reproducible light spectrum. The AM-solar spectra are certainly the standard light spectra to use for outdoor photovoltaic applications.

The differences between the solar spectra AMO, AM 1 and AM 1.5 are illustrated in Fig. 4. The spectral photon distributions of the AM 0 and the global AM 1.5 spectra are shown in Fig. 5. The global AM 1.5-spectrum combines a direct AM 1.5 spectrum and a standard spectrum of scattered light (Fig. 6) [5].

For photovoltaic applications, the global AM 1.5 spectrum as defined in Table 2 is used as the reference spectrum [6,7].

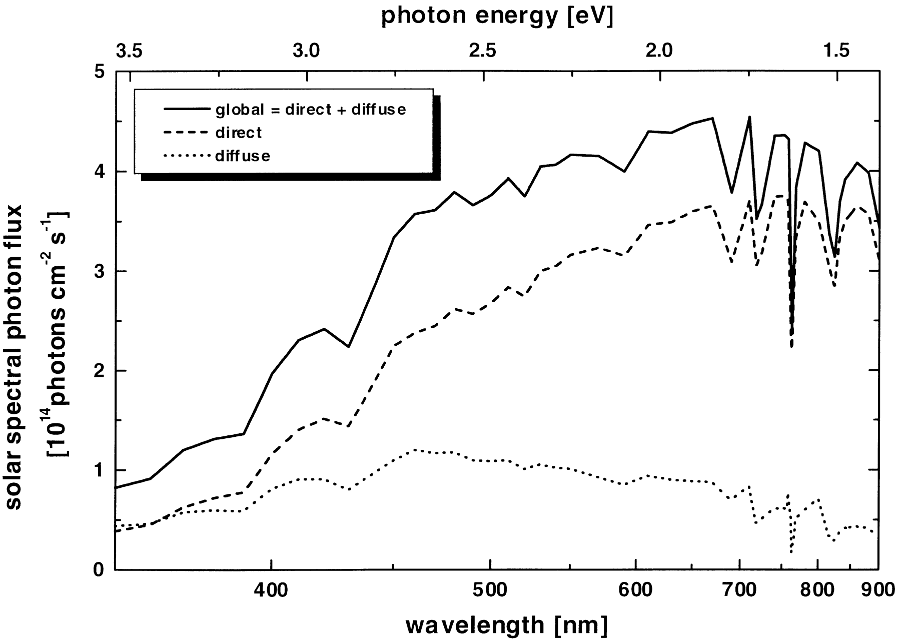

Fig. 6. Global AM 1.5, direct AM 1.5 and scattered light (global AM 1.5 = direct AM 1.5 + scattered light).

Table 2
Standard reporting conditions (SRC) for solar light as reference spectrum

Criteria	Value
Light intensity	1000 W/m^2
Sun spectrum	AM 1.5 (IEC 904-3 [1,2])
Sample temperature	25°C

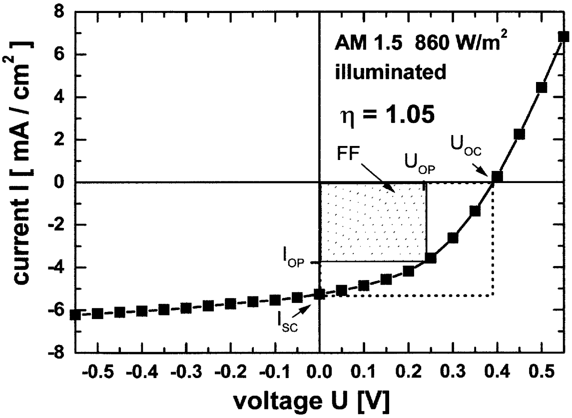

Fig. 7. I/V-characteristic for an organic solar cell (sample structure in Fig. 1) under illumination with a solar simulator: (I_{SC}) short-circuit photocurrent, (U_{OC}) open-circuit voltage, (FF) fill factor, (I_{OP}) photocurrent at the maximum power point, (U_{OP}) photovoltage at the maximum power point.

The AM 1.5 global sun light spectrum of a solar simulator should be employed to determine the solar power conversion efficiency, because it defines a precise spectrum. All other light sources make it impossible to compare efficiencies obtained by different groups. By e.g. using metal grids, in such a simulator one can decrease the light intensity without changing the spectral distribution significantly.

Fig. 7 shows a power plot of our organic solar cell, again structured as sketched in Fig. 1, under the illumination of our solar simulator. The power conversion efficiency as defined by Eq. (2) was such determined to 1.05%.

5. From monochromatic to solar efficiencies

IPCE spectra can be used to estimate solar efficiencies if the series resistance under solar illumination is small enough (for a few percent efficient cells at least below 100 Ω for a cell area of 1 cm^2). Using a solar photon flux spectrum, a simple multiplication with the IPCE spectrum and the elementary charge will lead to a calculated short-circuit current spectrum (Fig. 8, left axis). By integration from a lower limit (here 360 nm) up to an assumed cut off value (here 900 nm), one can calculate a short-circuit current (here 6.3 mA/cm^2 at 1000 W/m^2). This corresponds to 5.4 mA/cm^2 at 860 W/m^2, which is in good agreement with a directly measured value of 5.2 mA/cm^2 at 860 W/m^2. In the same range of the solar spectrum, a maximum current of 39 mA/cm^2 (Fig. 8 right axis) would be possible. Therefore, a solar current efficiency of around 16% was obtained. However, assuming an open-circuit voltage of 0.5 V and a fill factor of 0.5, we can estimate a maximum power conversion efficiency of 1.2% with 1.05% being the directly determined value (for 860 W/m^2).

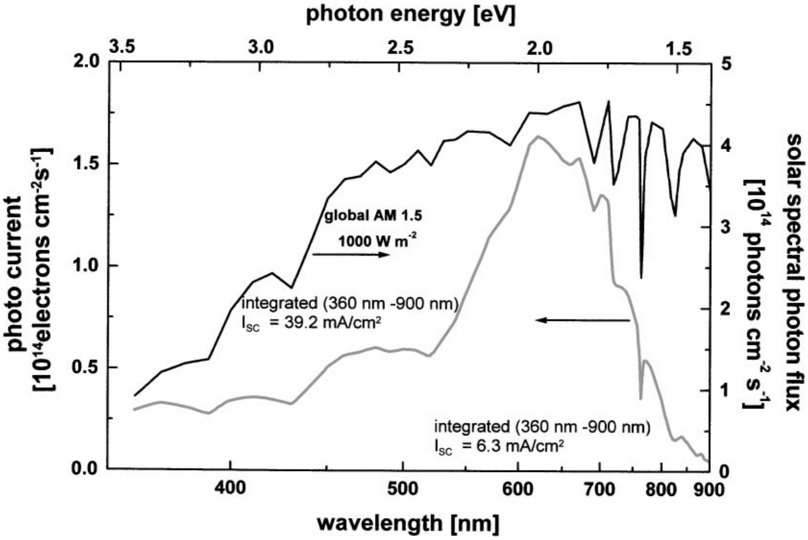

Fig. 8. From monochromatic to polychromatic efficiencies, for explanation see text.

However, this calculation proves, that the key problem of the here investigated organic solar is not the small current efficiency anymore, but rather the low output voltage together with the small fill factor.

6. Summary

Our best organic solar cell (MPP/ZnPc) exhibits a solar AM 1.5 (860 mW/cm^2) efficiency of 1.05%. Already the IPCE spectrum with a maximum of nearly 40% measured under monochromatic low light intensity conditions indicates that the photocurrent generation in this type of device is not too bad anymore at least for the C_{60}-doped ZnPc. Using this IPCE spectrum and typical values for the open-circuit voltage and the fill factor, a solar efficiency can be calculated. This turns out to be in satisfying agreement with the directly measured value. However, this is only because the series resistance at high light intensities is decreased to values below 100 Ω as determined by fitting the I/V-characteristic from Fig. 7. These calculations show, that in state of the art molecular organic solar cells already sufficiently high currents can be produced to reach solar efficiency of practical interest if the cell voltage and the fill factor could be improved.

Acknowledgements

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