Simulation of semi-transparent organic tandem solar cells for solar shading

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***Abstract*—We present design considerations for semi-transparent organic tandem solar cells that exhibit both good visible transparency and good power conversion efficiencies. The tandem solar cells show excellent color properties, such as the corresponding transparency color temperature and the color rendering index (CRI), that prevail for high angles of incidence of the incoming sunlight. Up to an angle of light incidence of 70°, the devices exhibit a convenient CCT which implies a neutral white and a CRI which is above 96.**

I. Introduction

Organic solar cells are promising candidates for cost-efficient renewable power conversion. The large variety of compounds offered by organic chemistry enables the design of semi-transparent devices with tailored optical properties. Semi-transparent organic solar cells are of interest for building integration and for automotive applications in order to combine window shading and power harvesting. For this purpose, other device properties beyond the power conversion efficiency (PCE) are of pivotal importance: The transparency color perception, the color rendering index (CRI) and the corresponding color temperature (CCT) are important criteria to ensure comfortable illumination through the solar cells. For convenient lighting, the CCT should range between $3300\,\mathrm{K}$ and $5000\,\mathrm{K}$ and the CRI should approach 100. Both parameters are only considered valid if the distance of the chromaticity of the transmission spectrum to the Planckian locus does not exceed $\Delta_0 = 5.4 \cdot 10^{-3}$.

Semi-transparent cells with single absorber layers do not offer enough flexibility to optimize all parameters at the same time whereas tandem solar cells allow more degrees of freedom. The latter allow for the fabrication of devices exhibiting excellent transparency color properties and a freely adjustable level of transparency [1], enabling the integration into building façades, overhead glazing or automotive windows. Still, real-life lighting situations require a much more advanced transparency color design as the direction of the incident sunlight varies over time. In the following, we investigate the influence of the angle of incidence of the incoming sunlight on the color properties of the semi-transparent devices in organic tandem solar cells.

II. Simulation Model

We use an in-house developed simulation tool which is capable of optical and electrical device modelling. The optical simulation is used to calculate the spectrally resolved optical properties of the devices as well as the optical field distribution and thus the spatial absorption profile within the organic solar cell under illumination. This is used as an input parameter for the electrical simulation. The chromaticities and all other color properties of semi-transparent devices were derived from the transmission spectrum. The optical model employs the transfer-matrix method, where each layer and each layer interface is described by an interface and a propagation matrix, respectively, hence taking into account the interference effects within the stacked thin-films.

The electric field is split into forward and backward propagating components and combined into a two-row vector. As a mandatory boundary condition, the backward propagating electric field behind the thin film stack, i.e. the side facing away from the sun, is set to zero.

Usually, organic solar cells are fabricated on comparably thick transparent substrates through which they are illuminated (front illumination). In these thick layers, effectively, no interference effects appear and therefore our model was extended to treat the multiple reflections in the substrate layer incoherently [2]. In case of semi-transparent organic solar cells, devices can also be illuminated through the top electrode (back illumination). Although this does not affect the transparency perception of the device, the absorption within the active layers and thus the PCE can change. For this purpose we further extended the optical model, because the backward propagating electric field behind the thin film stack is not zero and therefore is not a valid boundary condition.

The electrical simulation model was used to calculate the current density-voltage (J-V) curves and hence the PCE. This model is based on a drift diffusion approximation [2]. It is extended by a multiple-trapping model to account for the specific charge carrier transport phenomena in organic bulk heterojunction solar cells [3], [4].

III. Results and discussion

We simulate a parallel connected organic tandem solar cell comprising poly(3-hexylthiophene-2,5-diyl) and [6,6]-phenyl C_{61}-butyric acid methyl ester (P3HT:PC_{61}BM) as front absorber and poly{[4,40-bis(2-ethylhexyl)dithieno(3,2-b;20,30-d)silole]-2,6-diyl-alt-(2,1,3-benzothidiazole)-4,7-diyl} and [6,6]-phenyl C_{71}-butyric acid methyl ester

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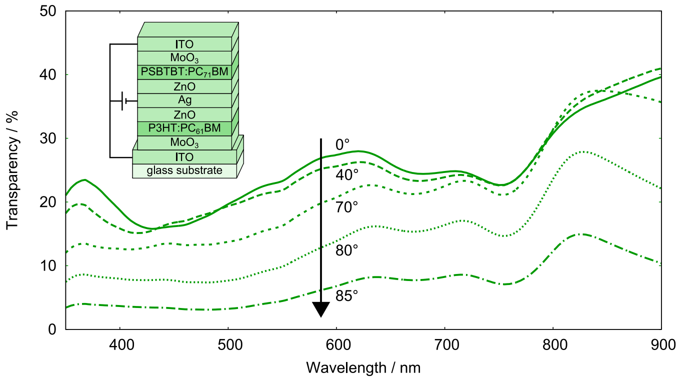

Figure 1. Spectral transparency of the tandem solar cell versus the angle of incidence of the incoming light. The inset shows a schematic representation of the simulated device architecture.

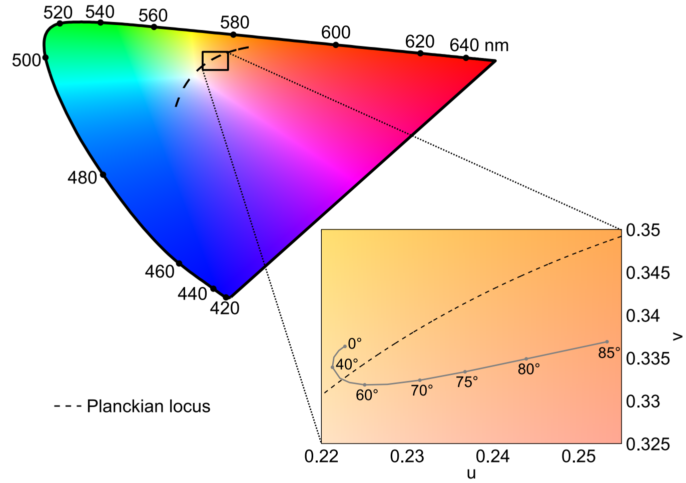

Figure 2. Chromaticities of the tandem solar cell in the CIE 1960 UCS color space versus the angle of incidence of the incoming light. In the lower part of the figure, an enlargement of the relevant part is shown.

($PSBTBT:PC_{71}BM$) as back absorber. The inset of Fig. 1 depicts the device architecture. The active layer thicknesses are 40 nm and 70 nm for the front and back absorber layer, respectively. The device is virtually illuminated with an ASTM AM1.5 global standard spectrum. Under normal light incidence, the calculated visible transparency T_{vis} of this device is 24.2 % and the PCE obtained by the electrical simulation is 2.4 % for illumination through the glass substrate (front illumination) and 4.0 % for illumination from the back, showing a good trade-off between transparency and PCE. The distance Δ of the chromaticity of the transmission spectrum from the Planckian locus is smaller than $\Delta_0 = 5.4 \cdot 10^{-3}$, the CCT and the CRI were determined to 4037 K and 96.5, respectively. In short, all parameters are well within the required range as defined before and therefore the investigated device exhibits excellent color properties for normal incidence.

To investigate the dependency of the transparency color perception on the angle of incidence, the spectral transparency of the tandem device was simulated as depicted in Fig. 1. The transparency decreases with an increasing angle of incidence Θ. We found that the transparency remains about unaffected up to $\Theta = 40°$. Even at $\Theta = 70°$, the transparency is reduced only marginally in the visible regime of the solar spectrum.

Also, the cromaticities in the CIE 1960 UCS color space remain about the same upon changing the angle of incidence as depicted in Fig. 2.

The most relevant part of the CIE 1960 UCS diagram is enlarged in the lower part of the figure. The chromaticity shows only a very small shift in the color space upon tilted illumination but rather remains close to the Planckian locus. This implies a small angle dependency of the transparency color perception of the device. For a more detailed assessment of the angle dependent color perception the distance between chromaticity and Planckian locus Δ, the CCT, the CRI and the visible transparency are shown in Table I. The distance Δ and the CCT are well within the required range up to an angle of incidence of $\Theta = 70°$. Even at an angle of $\Theta = 85°$, the chromaticity remains close to the Planckian locus and the corresponding color temperature turns into warm white (CCT $\approx$ 3000 K). Up to an angle of incidence of $\Theta = 85°$ the CRI stays above 94 implying excellent color rendering properties of the semi-transparent organic tandem solar cell.

Table I
COLOR PROPERTIES OF THE TANDEM SOLAR CELL VERSUS THE ANGLE OF INCIDENCE OF THE INCOMING LIGHT.

Angle	Δ	CCT	CRI	T_{vis}
0°	$3.0 \cdot 10^{-3}$	4037 K	96.5	24.2 %
40°	$1.8 \cdot 10^{-3}$	4159 K	97.3	22.8 %
70°	$5.2 \cdot 10^{-3}$	3811 K	97.2	17.6 %
80°	$9.0 \cdot 10^{-3}$	3339 K	95.6	11.1 %
85°	$11.0 \cdot 10^{-3}$	3036 K	94.7	5.2 %

IV. Conclusions

We presented design consideration for semi-transparent organic tandem solar cells with both good transparency and PCE that exhibit excellent color properties. These color properties are preserved for high angles of light incidence. Up to an angle of $\Theta = 70°$, the devices exhibit a convenient CCT which implies a neutral white and a CRI which is above 96.

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