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Effect of incidence angle and polarization on the optimized layer structure of organic solar cells

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ABSTRACT

We theoretically and experimentally investigate the effect of the incidence angle and polarization of sunlight on the optimized layer structure of organic solar cells (OSCs) to obtain the best absorption efficiency in a realistic deployment situation. We use the generalized transfer matrix method with respect to the incidence angle and polarization, which can calculate the spatial distribution of the optical power dissipation in both the incoherent glass substrate and the coherent multilayer without using any indirect correction factor. The angular dependence of the short-circuit current, the open-circuit voltage, and the output electric power is calculated and compared with the experimental results. Using the simulation parameters matched with the experimental results, we calculate the generation energy density per day by considering the variation of the incidence angle during daytime and determine the optimized thickness of the active region for maximum absorption efficiency. We show that the optimized active-region thickness based on the generation energy density per day is different from that determined from the variation of the short-circuit current density in only normal incidence, which is generally used for optimizing device structure of OSCs.

1. Introduction

Organic solar cells (OSCs) have been intensively studied as one of the auspicious alternatives for traditional silicon-based solar cells due to their potential of easy manufacturing process, low cost, and versatile applications [1]. Because the absorption efficiency of thin-film OSCs depends on the thickness and the complex refractive index of each layer, the optical interference effect should be comprehensively understood to maximize the absorption efficiency of OSCs. In general, optimizing the layer structure to obtain the best absorption efficiency of OSCs is theoretically and experimentally performed for the normal incidence of sunlight [2–7]. However, most of OSCs, having the merit of low cost and flexibility, will not be used with a sunlight tracking system. Thus, the optimization process under normal incidence does not reflect the realistic deployment situation such as a rooftop application [8], where the incidence angle gradually varies during the daytime when the apparent path of the sun across the sky is considered. The current optimization process of OSCs should be further improved in terms of optical modeling and experimental characterization.

In the case of optical modeling, the transfer matrix method (TMM) has been widely used to calculate the spatial distribution of the optical field intensity within thin-film OSCs under normal incidence [2,3]. The effect of the incoherent light transmission through the thick glass substrate was indirectly included by summing the infinite Airy geometrical series for the optical field intensities inside the glass substrate at normal incidence [4,5]. One of the authors proposed to use the generalized transfer matrix method (GTMM), which can calculate the spatial distribution of the optical intensity in both the coherent multilayers and incoherent glass substrate only with a simple generalized 2×2 transfer matrix [7]. On the other hand, the TMM-based optical model for normal incidence has been adopted for oblique incidence to investigate the effect of incidence angle and polarization of sunlight on the efficiency of OSCs without providing a clear theoretical model [9–11]. Recently, we have presented a comprehensive TMM-based analytical model at oblique incidence for both s and p polarizations [12]. However, we have not yet found any literature to provide a comprehensive optical model for OSCs at oblique incidence with the inclusion of the incoherent light interaction between the thick glass substrate and coherent multilayers.

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Regarding experimental characterization, the efficiency of OSCs such as the short-circuit current density (J_{sc}) and the open-circuit voltage (V_{oc}) is generally measured at normal incidence in solar cell simulators. When the variation of the incidence angle of sunlight is considered, the actual solar cell efficiency should be obtained by accumulating the efficiency over the whole incidence angle during the daytime. Because the absorption efficiency of the OSC greatly depends on the incidence angle, one optimized layer structure for the best efficiency at normal incidence could be different from another optimized structure to give the maximum efficiency per day with the variation of incidence angle considered. There has been a numerical study based on the finite element method to maximize J_{sc} during the full day by adjusting the active layer thickness in V-shape OSCs with the consideration of the change of incident angle [13]. However, it has not yet been fully investigate to characterize the efficiency of OSCs by taking into account the variation of incidence angle during the daytime and compare with another efficiency obtained by considering only normal incidence.

In this paper, we present theoretical and experimental results of OSCs at oblique incidence. We use the GTMM with a simple matrix form to calculate the spatial distribution of the optical power dissipation in both the incoherent glass substrate and the coherent multilayer with respect to the incidence angle and polarization of sunlight. The angular dependence of J_{sc} and V_{oc} under the solar spectrum (AM 1.5) is measured and compared with the theoretical results. Based on the simulation parameters matched with the experimental results, we calculate the generation energy density per day as a function of the active layer thickness by considering the variation of the incidence angle during daytime. We show that the optimized thickness of the active region based on the generation energy density per day is different from that determined from the variation of the short-circuit current density in only normal incidence.

2. Theory

The multilayer structure shown in Fig. 1(a) is composed of a stack of m layers, which has the mixed incoherent and coherent thin layers between the semi-infinite transparent ambient (usually air) on the left ($j=0$) and on the right ($j=m+1$). A plane wave with an incidence angle of θ and a wavelength of λ is incident from the semi-infinite transparent ambient on the left ($j=0$). We assume that each layer j ($j=1, 2,\ldots, m$) has a thickness of d_j and a complex refractive index of $\tilde{n}_j = n_j + i\kappa_j$, where n_j and κ_j are the refractive index and extinction coefficient. The orientation of the electromagnetic field oscillations is composed of s and p polarizations that are orthogonal to or parallel to the incident plane, respectively. The first layer ($j=1$) of the thick glass substrate should be considered as incoherent because it has the larger thickness (~2 mm) in reference to the coherence length of sunlight (~1 μm) [14]. As shown in Fig. 1(b), the remaining $m-1$ layers with the small total thickness (~100 nm) are considered as coherent.

2.1. Definition of 2 × 2 matrixes in the generalized transfer matrix method

The multilayer structure in Fig. 1 is considered as homogeneous and isotropic layers with plane and parallel interfaces. We assign a positive (negative) direction to the light propagating from left (right) to right (left), designating the $+(-)$ superscripts. We expand the GTMM theory for normal incidence into that for oblique incidence, referring to our previous work [7]. In the case of coherent multilayers in Fig. 1(b), the electric field amplitudes on the interface between the layers j and k ($j<k$) are related with an interface matrix $\mathbf{I}^{j/k}$ [15]

$$\begin{bmatrix} E_{jR}^{+} \\ E_{jR}^{-} \end{bmatrix} = \mathbf{I}^{j/k} \begin{bmatrix} E_{kL}^{+} \\ E_{kL}^{-} \end{bmatrix} = \frac{1}{t_{j,k}} \begin{bmatrix} 1 & -r_{k,j} \\ r_{j,k} & t_{j,k}t_{k,j} - r_{j,k}r_{k,j} \end{bmatrix} \begin{bmatrix} E_{kL}^{+} \\ E_{kL}^{-} \end{bmatrix}, \tag{1}$$

where E_{jR}^{+} and E_{kL}^{+} are the forward-propagating electric field amplitudes at the right boundary of the layer j and the left boundary of the layer k, respectively. The terms r_{jk} and t_{jk} are the complex Fresnel reflection and transmission coefficients at the interface from layer j to layer k. For s polarization, they are defined as [16]

$$r_{j,k}^{s} = \frac{\tilde{n}_j \cos\theta_j - \tilde{n}_k \cos\theta_k}{\tilde{n}_j \cos\theta_j + \tilde{n}_k \cos\theta_k}, \tag{2a}$$

$$t_{j,k}^{s} = \frac{2\tilde{n}_j \cos\theta_j}{\tilde{n}_j \cos\theta_j + \tilde{n}_k \cos\theta_k}, \tag{2b}$$

and for p polarization as

$$r_{j,k}^{p} = \frac{\tilde{n}_j \cos\theta_k - \tilde{n}_k \cos\theta_j}{\tilde{n}_j \cos\theta_k + \tilde{n}_k \cos\theta_j}, \tag{3a}$$

$$t_{j,k}^{p} = \frac{2\tilde{n}_j \cos\theta_j}{\tilde{n}_j \cos\theta_k + \tilde{n}_k \cos\theta_j}. \tag{3b}$$

If light is only incident from the transparent ambient on the left, the interface matrix $\mathbf{I}^{j/k}$ in Eq. (1) becomes

$$\begin{bmatrix} E_{jR}^{+} \\ E_{jR}^{-} \end{bmatrix} = \mathbf{I}^{j/k} \begin{bmatrix} E_{kL}^{+} \\ E_{kL}^{-} \end{bmatrix} = \frac{1}{t_{j,k}^{s(p)}} \begin{bmatrix} 1 & r_{j,k}^{s(p)} \\ r_{j,k}^{s(p)} & 1 \end{bmatrix} \begin{bmatrix} E_{kL}^{+} \\ E_{kL}^{-} \end{bmatrix}, \tag{4}$$

which is the generally used form in the TMM [2,16]. The electric field amplitude at the left and right boundaries of the j-th layer is related with a layer matrix $\mathbf{L}^{j}$:

$$\begin{bmatrix} E_{jR}^{+} \\ E_{jR}^{-} \end{bmatrix} = \mathbf{L}^{j}(d_j) \begin{bmatrix} E_{jL}^{+} \\ E_{jL}^{-} \end{bmatrix} = \begin{bmatrix} e^{-ik_{z,j}d_j} & 0 \\ 0 & e^{ik_{z,j}d_j} \end{bmatrix} \begin{bmatrix} E_{jL}^{+} \\ E_{jL}^{-} \end{bmatrix}, \tag{5}$$

where we assume the time dependence of e^{iwt}.

The light propagation in the incoherent layer can be treated by means of modified matrix formalism analogous to that of coherent layers. The electric field intensities $U=|E|^2$ on the interface between the layer j and k ($j<k$) are described with a modified interface intensity matrix $\bar{\mathbf{I}}^{j/k}$ [15]

$$\begin{bmatrix} U_{jR}^{+} \\ U_{jR}^{-} \end{bmatrix} = \bar{\mathbf{I}}^{j/k} \begin{bmatrix} U_{kL}^{+} \\ U_{kL}^{-} \end{bmatrix} = \frac{1}{|t_{k,j}^{s(p)}|^2} \begin{bmatrix} 1 & -|r_{k,j}^{s(p)}|^2 \\ |r_{k,j}^{s(p)}|^2 & |t_{k,j}^{s(p)} t_{k,j}^{s(p)}|^2 - |r_{k,j}^{s(p)} r_{k,j}^{s(p)}|^2 \end{bmatrix} \begin{bmatrix} U_{kL}^{+} \\ U_{kL}^{-} \end{bmatrix}, \tag{6}$$

where U_{jR}^{+} and U_{kL}^{+} are the forward-propagating electric field intensities at the right boundary of the layer j and the left boundary of the layer k, respectively. The propagation of the electric field intensities from the left to right boundaries of the layer j are treated with a layer intensity matrix $\bar{\mathbf{L}}^{j}$:

$$\begin{bmatrix} U_{jR}^{+} \\ U_{jR}^{-} \end{bmatrix} = \bar{\mathbf{L}}^{j}(d_j) \begin{bmatrix} U_{jL}^{+} \\ U_{jL}^{-} \end{bmatrix} = \begin{bmatrix} |e^{-ik_{z,j}d_j}|^2 & 0 \\ 0 & |e^{ik_{z,j}d_j}|^2 \end{bmatrix} \begin{bmatrix} U_{jL}^{+} \\ U_{jL}^{-} \end{bmatrix}. \tag{7}$$

2.2. Description of total reflectance and transmittance

In Fig. 1(b), the electric field amplitude passing from incoherent layer (layer 1) to the ambient on the right (layer m+1) through all the coherent packets can be expressed as

$$\begin{bmatrix} E_{1R}^{+} \\ E_{1R}^{-} \end{bmatrix} = \mathbf{S}^{1/(m+1)} \begin{bmatrix} E_{(m+1)L}^{+} \\ E_{(m+1)L}^{-} \end{bmatrix}, \tag{8}$$

where the amplitude scattering matrix $\mathbf{S}^{1/(m+1)}$, relating the electric field amplitude between the layer 1 and m+1, is given