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Thermal analysis of organic solar cells using an enhanced opto-thermal model

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ABSTRACT

In this paper, an opto-thermal model is presented in order to specify the dominant thermal phenomena in organic solar cells (OSCs), as rather low efficiency photovoltaic devices. This model is capable of predicting the amount of optical heat generation (Q_{th_opt}), also the transient and steady state thermal behavior of an organic photovoltaic cell combining both the optical and thermal models. In a typical organic solar cell, Q_{th_opt} plays a significant role in heating up the device while the electric heat generation (Q_{th_elec}) does not effectively have such a role. Developing an optical model for a solar cell, Q_{th_opt} can be determined in every position of the device; also, the contribution of each layer in heat generation is precisely specified. The device thermal behavior is predicted by feeding the thermal model with Q_{th_opt}. This is done for an organic solar cell with a typical architecture and it is shown that thermal convection and radiation are two determinative thermal phenomena while conduction plays a minor role; furthermore, the electrodes, Aluminum (Al) cathode and Indium Tin Oxide (ITO) anode, are two strong light absorbers which contribute to more than 80% of optical heat generation. Assuming Stefan–Boltzman radiation loss, the temperature rise for a typical single junction OSC is estimated under different conditions. The device temperature rise might be even larger for other architectures consisting of several layers depending on their thicknesses and absorption coefficients. This temperature increase enhances the OSCs' efficiency while degrading the lifetime. The model can be applied to thermal analysis of other types of photovoltaic cells and optoelectronic devices with minor modification.

1. Introduction

During the past few years, extensive researches have been conducted towards improving the applicability of novel photovoltaic technologies. The key advantage of these technologies is that they are fed by solar energy as a clean and abundant source of energy [1,2]. The main challenge which prevents widespread commercial applications of these technologies all around the world is their relatively high total electricity price; therefore, great efforts have be made to develop low cost thin film solar cells, one of the most promising types of which is organic based cell. Organic photovoltaic cells also offer several interesting advantages over other types of photovoltaic devices, such as full mechanical flexibility, semi-transparency, light weight, compatibility with other organic electronic devices and simple production methods in large scale (screen printing, inkjet printing, etc) [1,3–12].

So far, there have been numerous works on electric and optical modeling of organic solar cells (OSCs) using numerical and analytical methods [13–24]. Some works also tried to clarify how temperature variation correlates with OSC performance in terms of short circuit current, open circuit voltage, fill factor, efficiency and lifetime [25–27].

In this paper, we aim to answer the question that how OSC temperature changes when it works continuously under sunlight illumination and in different ambient conditions, also what factors may influence the device temperature. We first propose two thermal models that are both useful in predicting the device temperature, depending on what is looked for. The first model is the steady state (SS) thermal model, which is more straightforward and calculates the device temperature in steady state. It also provides more intuition about the device internal condition in comparison with the other model. The second model is the transfer matrix based (TM) thermal model which specifies the transient and steady state device temperature at the expense of more complexity and algebraic labor. Coupling the appropriate thermal model with 1-D TM optical model, a comprehensive opto-thermal model is

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developed, which can specify the amount of optical heat generation and heat flow mechanism in photovoltaic devices. So far, there have not been a thorough research on thermal analysis of organic solar cells; therefore, we have applied this model to understand the thermal mechanism of these devices in detail; however, the model can be extended to be used in other opto-electronic devices, as well.

The paper is organized in four sections: firstly, the thermal models (TM and SS) and the mathematical concepts behind them are presented; also, they are verified using experimental data of an organic light emitting diode (OLED); then, these two models are compared to each other. Secondly, the 1-D optical model is briefly presented and verified for a typical OSC. Thirdly, the thermal and optical models are combined to specify the thermal phenomena in an organic photovoltaic device under different sunlight illuminations. Finally, the whole idea and results are summed up and other potential applications of the model are discussed.

2. Thermal model

The mathematical duality of heat flow and electric current propagation is of significant help in understanding the thermal analysis problems. Several mathematical techniques, which have been already developed to solve electric circuits, are also applicable in the case of thermal analysis. In order to solve the heat flow in a one-dimensional (1-D) slab of material, one needs to consider two basic equations: Fourier's law and continuity equation [28]. Fourier's law states how temperature (T) changes spatially with heat flux (Q),

$$-\frac{\partial T(x,t)}{\partial x}=\frac{1}{K}Q(x,t) \tag{1}$$

where K is the material thermal conductivity (W/km). This is electrically analogous to Ohm's law and can be used to predict the SS temperature in a system. The continuity equation implies how T changes temporally with spatial variation of Q and it is shown below:

$$-\frac{\partial T(x,t)}{\partial t}=\frac{1}{C}\frac{\partial Q(x,t)}{\partial x} \tag{2}$$

where C is the volumetric heat capacity (J/m^3 K). The full (transient and steady state) thermal response of the slab is determined by combining (1) and (2) which yields:

$$\frac{\partial^2 T(x,t)}{\partial x^2}=RC\frac{\partial T(x,t)}{\partial t} \tag{3}$$

where R is $1/K$ [28,29]. In order to get rid of solving complex differential equations, also incorporating the effect of internal heat generation, the SS and TM thermal models are presented, verified and discussed in the following sections.

2.1. Steady state thermal equivalent circuit

A 3-D steady state model is a resistor network that specifies the device temperature in steady state. Considering heat flow in three dimensions makes the result much reliable since it takes the heat flow in parallel paths into account. Each slab of material with no internal heat generation can be thermally modeled as in Fig. 1 in steady state. Since $R_{th}=t/K$ (where R_{th} is the thermal resistance (K m^2/W) and t is the thickness in heat flow direction), the thermal model would be realized knowing device materials and dimensions (L and W stand for thickness and width, respectively).

The architecture of an encapsulated OLED is shown in Fig. 2(a). In case of optoelectronic devices such as OLEDs and OSCs, the internal heat generation should also be taken into account. To minimize the mathematical complexity, it is assumed that the internal heat source injects heat at a single point of device (ITO–organic interface) (Fig. 2(b)). In the following sections, it will be shown why such an assumption is valid. The heat conduction occurs in three dimensions and heat convection is described by considering an air layer with an effective thickness ($t_{air\text{-}z}$ and t_{air_xy}). To consider the radiation losses, Stefan–Boltzman law may be employed:

$$Q_{rad}=\varepsilon\sigma(T_{src}^4-T_0^4)\cong h_{rad}(T_{src}-T_0) \tag{4}$$

where σ is Stefan–Boltzman constant and ε represents the OLED emissivity (in this case 0.5) [28]. Using the above approximation, the three dimensional radiation losses can be modeled as an effective resistive path. This is interesting to note that some works claim that heat radiation does not follow Stefan–Boltzman law in very small scales (less than thermal wavelength) [30]. In fact, it has been

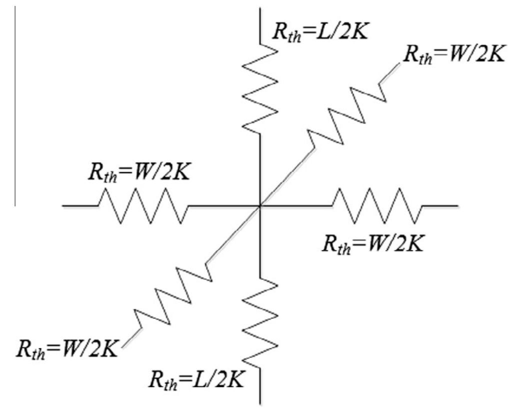

Fig. 1. Thermal resistor network for a slab of material with no internal heat generation.

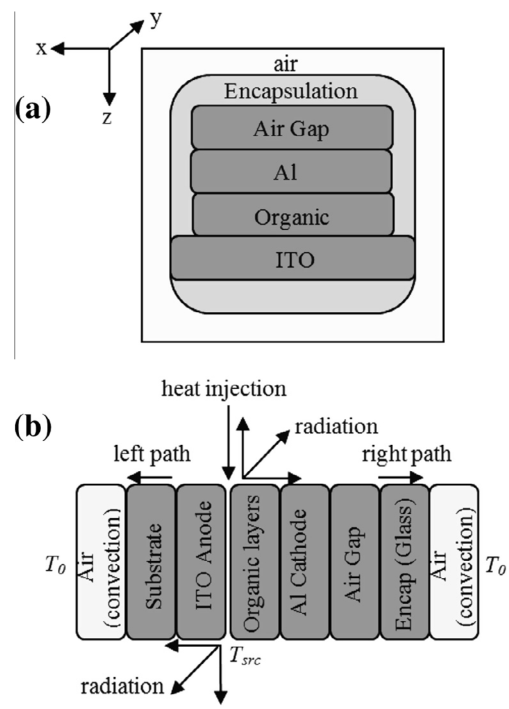

Fig. 2. (a) General OLED architecture consisting of series of layers surrounded by glass encapsulation and air with an effective thickness. (b) Schematic showing how thermal mechanisms (conduction, convection and radiation) occur in an OLED [28].