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Photovoltaic–thermal solar energy collectors based on optical tubes

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Abstract

In this work, we examine the use of oil filled tubular optical concentrators coupled with a model organic bulk heterojunction photovoltaic: poly-3-hexathiophene-[6,6]-phenyl-C61-butyric-acid methyl-ester (P3HT:PCBM) to create a photovoltaic–photothermal hybrid solar collector. The organic photovoltaic cells were fabricated onto one half of a tubular light pipe and then silicone oil was flowed inside the pipe. This allows solar energy in the visible wavelengths to be effectively converted into electricity by photocell while simultaneously; the silicone oil captures the infrared radiation (IR) part of the spectrum as heat energy. The VIS–IR power conversion efficiency for this model organic system, under normally incident AM1.5G illumination was found to be: PCE $\sim$ 28%, which is combined by the photovoltaic efficiency (PCE $\sim$ 2%) and the photothermal efficiency (PCE $\sim$ 26%). We further show that the oil filled tube, acts as a passive optical element that concentrates the light onto the photovoltaic and thereby increases its overall efficiency but also the range of incident angles in which the light is efficiently captured.

Keywords: Solar energy collector; Photovoltaic; Photothermal; Tube cell; Bulk heterojunction

1. Introduction

The total number of photons that can be captured by a photovoltaic, and thus its resulting power conversion efficiency (PCE) depends on the threshold photon energy below which electricity conversion does not take place, i.e. the bandgap of the photoabsorber. So long wavelength photons typically dissipate their energy as heat in photocells instead of generating power. This brings other undesirable consequences to the solar cells as well such as: a drop in the cell efficiency due to the added heat and even permanent structural damage of the cells (Garg et al., 1994). To better harness the solar energy, it is necessary to collect the solar energy in the long-wave band of the sun's spectrum. However, trying to use more and more narrow bandgap semiconductors to absorb longer and longer wavelength light results in diminishing voltage output for the solar cell. Thus, the most obvious way to harness this IR solar energy is to transform this part of the spectrum into heat and collect that heat, i.e. photo-thermal conversion (Davies and Luque, 1994). At present, there are a number of efforts which have demonstrated combined photovoltaic–thermal (PV/T) solar energy collectors, but these have been based primarily on planar geometries and silicon absorbers (Charalambous et al., 2007; Chow, 2010; Garg et al., 1994; Kumar and Tiwari, 2008; Singh and Othman, 2009; Davies and Luque, 1994).

These first generation hybrid photovoltaic–thermal solar energy collectors have resulted in some limited success, but their architectures have not been optimized for either solar or thermal collection of energy. That is, such PV/T devices

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are typically designed in a planar geometry, yielding relatively low combined photovoltaic/thermal conversion performance. In this work, we examine the use of optical tube concentrators, around which a photovoltaic cell has been added. The resulting hybrid photovoltaic–thermal solar energy collector geometry allows for optimized heating of a thermal fluid added to the tube and for concentration of the light onto the photovoltaic which yields great photovoltaic efficiencies. Our demonstration utilizes a solution-processed bulk heterojunction (BHJ) solar cell fabricated on one half of the tubes circumference and silicone oil contained inside the tubes as the photothermal collector. To fabricate these devices, we used a common absorber system: poly-3-hexyl-thiophene and phenyl-C61-butyric-acid methyl-ester (P3HT:PCBM) as a model absorber, which has been successfully applied to the fiber-based and tube-based solar cells recently (Liu et al., 2007; Li et al., 2010a,b). Thus, in these organic-PV/T (OPV/T) devices we utilize the advantages of organic photovoltaic (OPV) materials such as low cost, conformal flexibility, and abundant availability (Lewis, 2007). In order to better harness the utilization of the thermal fluid, we use a relatively smaller tube (1.5 mm I.D.) to get a higher ratio of cross-sectional area to volume. So in this case we build the OPV device directly onto the tube rather than adding a roll-to-roll (R2R) producible flexible OPV with an adhesive (Krebs, 2009; Krebs et al., 2009, 2010a,b). However, we find that this architecture further exhibits an increase in the performance of the P3HT:PCBM cell due to the concentrator effect of the tube acting as a focusing lens. Therefore, the combined power collection for this system; which is essentially an organic photovoltaic, is surprisingly high (PCE ~ 28%) compared to around 5% for the P3HT:PCBM system (Kim et al., 2007). We suggest that this approach may provide a more rapid approach to commercial viability of organic photovoltaics.

2. Experiments and measurements

Tube-based PV/T devices were fabricated on glass tubes with one end closed in a hemispherical cap (Chemglass, 1.5 mm I.D., 1.8 mm O.D.). Before building the devices, the tubes were cleaned in an ultrasonic bath. Firstly, the ITO films with a thickness of 100 nm were deposited on the tubes by radio frequency (rf) magnetron sputtering (BOSCH) from an ITO target. Then, these tubes were exposed to ozone for 90 min. Subsequently, by a dip coating procedure, poly(3,4-ethylenedioxythiophene)-poly (styrenesulfonate) (PEDOT: PSS, Clevios p, thickness ~200 nm), P3HT: PCBM (1:0.8 in WT, of 12 mg/ml in chlorobenzene, thickness ~150 nm) were deposited on the tubes. Al electrodes were deposited via thermal evaporation at the pressure of 10^{-6} torr. The length of the tube with active area was 1.8 cm. The resulting device structure is show in Fig. 1.

The photovoltaic characteristics of these devices were tested using an AM 1.5 g standard Newport #96000 solar simulator with an illumination intensity of 100 mW/cm^2. The device was illuminated laterally along the tube as shown in Fig. 1. Current voltage characteristics were collected using Keithley 236 source-measurement unit. The external quantum efficiency (EQE) was measured using a Newport Cornerstone 260 Monochromator in conjunction with a Newport 300 W Xenon light source. Apertures were used to ensure that side illumination did not occur. The photothermal characteristics of these devices were measured by a K-type thermocouple probe immersed in the inner silicone fluid and heating times of the silicone inner fluid was measured with a stopwatch. The angle of incidence of the light was varied by rotating the tube with respect to the light source IV and thermal data was collected for a variety of angles.

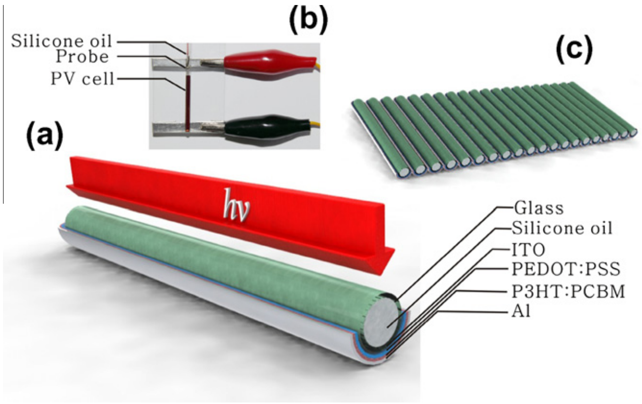

Fig. 1. (a) Schematic diagram of one tube-based solar energy collector. (b) The photographic image of the PV/T solar energy collector. (c) Schematic diagram of large area tube solar energy collectors.

3. Results and simulation

First we examined the effects of the addition of silicone oil into the tube on the angular response of the photocell on the back of the tube. From Fig. 2a, we observed that by injecting silicone oil inside the tube, the short current density (Jsc) of the photovoltaic was generally enhanced over tubes without silicone oil. This enhancement is seen across a 50° angular span, but is most pronounced when the device was under illumination that is normal to the center of the semi-cylinder of the tubular photovoltaic designated as 0° (~30% enhancement), whose current density–voltage (*J–V*) characteristics are shown in Fig. 2b. This enhanced performance was confirmed in the EQE measurements taken at 0°, which are shown in Fig. 2c. To understand the enhancement of the photovoltaic cell current response after injecting silicone oil, it's necessary to examine the differences in light distribution in the tube with and without silicone oil. To do this, devices were built without the photovoltaic absorber and back contact and they were illuminated from one side. It is apparent visually, from optical images, that the beam from the solar simulator has been strongly focused when the tube is filled with

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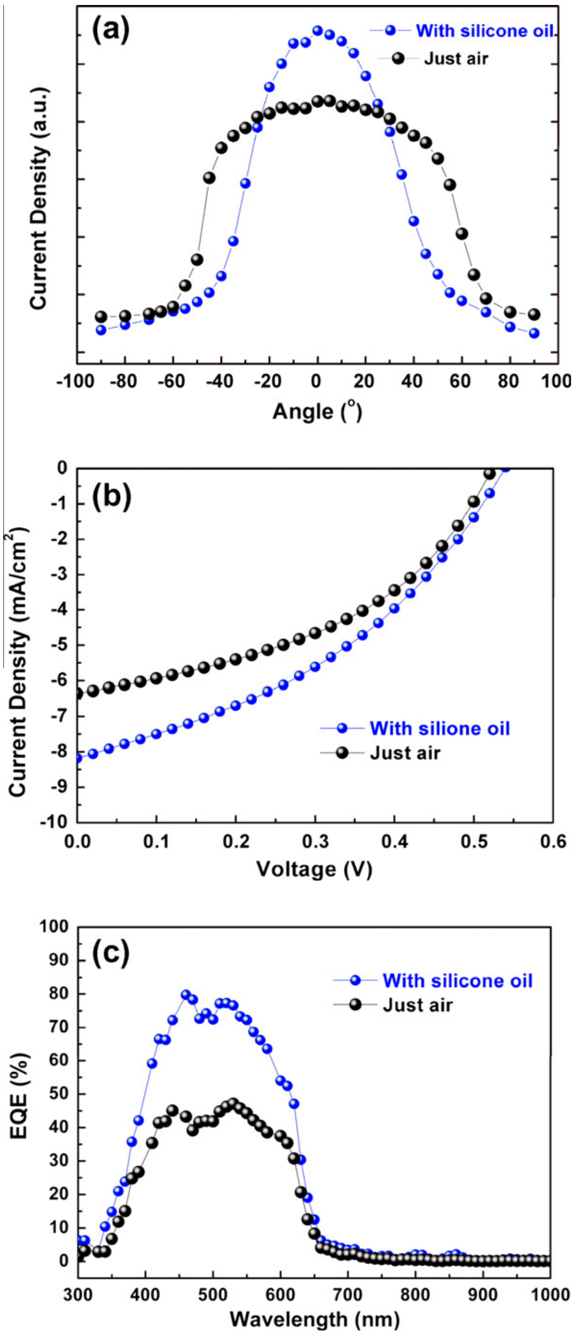

Fig. 2. (a) The behavior of Jsc vs. illumination angles. (b) *J*–*V* characteristics of the photovoltaic cells under normal (0°) illumination. (c) The EQE of the devices with and without silicone oil.

silicone oil, which is shown in the inset of Fig. 3b. This is easily understood with the schematic diagram of the light paths of one light ray in the tube with and without silicone oil, which is shown in Fig. 3a. So the beam is better focused by injecting higher refraction index materials into the tube, in our case silicone oil.

To further confirm this, we also constructed a mathematical model to calculate the light absorption of the photovoltaic cells with and without silicone oil, where the refractive indexes of silicone oil and glass are 1.4 and 1.5, respectively. This simulation is based on two models for two scale calculations: Optical path model of the behaviors of reflection and of refraction in tube architecture (Li et al., 2009, (www.OPVAP.inwake.com)). Details of the calculation methods used to determine the optical field distribution in thin films are given in the references (Pettersson et al., 1999; Sievers et al., 2006). Briefly, because the optical paths in tube and silicone oil are of the order of millimeters in our case, we first use Ray Tracing methods with the Fresnel equations to calculate where the light would occur in reflection and refraction, along with its corresponding angle and intensity. Then, in the thin film (∼100 nm), it is necessary to use a Transfer Matrix, to simulate the optical field distribution and account for interference. Also, the incident angle dependence was simulated in the software package OPVAP, developed by us (www.OPVAP.inwake.com). The results are shown in Fig. 3b, and the simulation is in excellent agreement with the Jsc enhancement observed when the devices are under normal (0°) illumination. Further study is underway to explain the Jsc observed for the oil filled and the air filled tubes when they are under different beam angles, however, we note that the back contacts of the device are added by thermal evaporation and are therefore not continuous at their edges. We therefore expect that little current will be collected there.

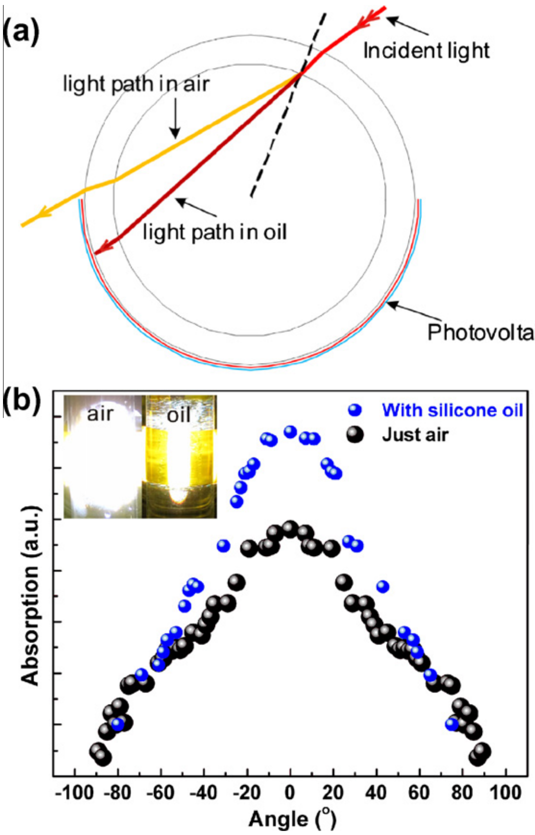

Fig. 3. (a) Ray diagram in the tube with and without silicone oil. (b) Simulation of the absorption of the photovoltaic cell with and without silicone oil. The inset shows the optical images of the tubes with and without silicone oil.

Turning to the conversion and collection of heat energy; the temperature of the oil within the tube was measured under static conditions, it is without flowing the oil. The K-type thermocouple was placed outside of the illuminated area of the device and the temperature was measured at certain time intervals. Again, since the oil was static within the tube, this is an accumulated temperature rise of the silicone oil and is shown in Fig. 4a.

After about 40 s this rate of heat collection "rolls off" as radiative and convective cooling dominates. Under normal operating conditions, this liquid would be shunted into a heat exchanger to maintain a temperature gradient and be replaced by a constant flow of cooled oil. The solar thermal efficiency (η_{th}) could be calculated as (Charalambous et al., 2007):

$$\eta_{th} = \frac{W_u}{G \cdot A_C} = \frac{\Delta Q_u/\Delta t}{G \cdot A_C} = \frac{m \cdot C_p \cdot \Delta T/\Delta t}{G \cdot A_C} = \frac{m \cdot C_p}{G \cdot A_C} \cdot T'(t) \tag{1}$$

where W_u is the heat collected, G is solar irradiance, C_p is the specific heat of the silicone oil (2.49 kJ/(kg°C)), A_C is the collector area (=0.27 cm^2 for one tube cell). When the silicon oil is a circular flow with speed v, its efficiency could be described by following:

$$\eta_{th} = \frac{v \cdot \pi \cdot r^2 \cdot \rho \cdot C_p}{G \cdot A_C} \cdot T'(1/v) \tag{2}$$

From this, we could calculate the solar thermal efficiency of the device at different mass flow rates, as Fig. 4a shown. Along with the increase of flow speed, its efficiency would be enhanced rapidly, approaching a maximum value. However, for a real industrialized device, the mechanical energy loss, and thermal energy dissipation also needs to be taken into account. If neglecting thermal energy dissipation in transport can be assumed, and only considering the mechanical energy loss of the flowing liquid, that is proportional to the square of flow speed ($\varepsilon \propto v^2$), i.e. this loss is proportional to kinetic energy of flow, we obtain the trend in Fig. 4b, which shows a optimum flow velocity to the efficiency peak. It is worth noting that during this operation the photovoltaic part of this device shows good stability since the temperature increase of this tube is relatively very small (3.5 °C) (Jørgensen et al., 2008).

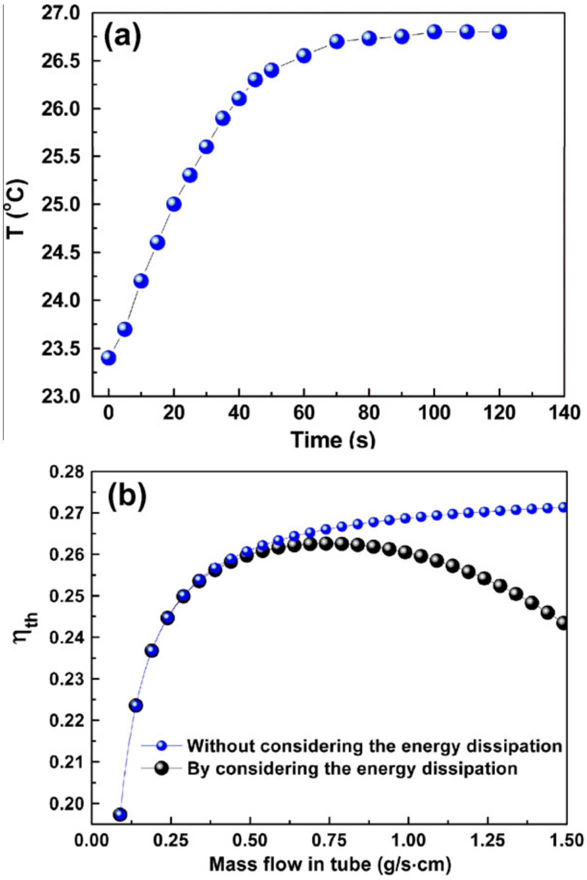

Fig. 4. (a) Solar thermal characteristics of the device. The temperature rise is measured under AM1.5 g illumination applied normal to the tube surface and is roughly equal for all angles inside of ±25° from 0°. (b) The calculated variation in thermal efficiency with silicone oil mass flow rate at the tube.

Naturally, we recognized that there are numerous better choices for the thermal fluid (oil) the silicone model system we have chosen provides a nice compromise between heat collection and refractive index for use with the photovoltaic. Alternatively we anticipate that the oil could be loaded with IR collecting dyes to enhance its properties.

To get the total power converted we add the power from photoelectric conversion (η_{el}) to that of photo-thermal conversion (η_{th}):

$$\eta = \eta_{th} + \eta_{el} \tag{3}$$

The result is ~28%, though admitted the power is in two different forms and thus the heat energy must be extracted using heat exchangers.

4. Summary

In summary, we have demonstrated a PV/T hybrid system based on organic photovoltaics. The tubular geometry coupled with a high optical index thermal fluid can be used to concentrate the light on the back photovoltaic providing enhanced efficiency of photovoltaic conversion and greater daily power generation. The model system we used with P3HT:PCBM coupled to a silicone oil thermal collector provides 28% conversion efficiency across a wide spectrum of the suns radiation. When optimized using the new low bandgap polymers available (Chen et al., 2009; Coffin et al., 2009; Gong et al., 2009; Huo et al., 2009; Park et al., 2009) and a better thermal fluid, it is reasonable to expect such devices to exceed 40%, potentially making them a cost effective approach to OPV in general.

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