



Polarizing polymer solar cells based on the self-organization of a liquid crystalline polymer



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ARTICLE INFO

Article history:

Received 4 May 2015

Received in revised form 11 July 2015

Accepted 15 July 2015

Keywords:

Optical anisotropy

Polarizing PSCs

Liquid crystalline polymer

Self-organization

ABSTRACT

We manufactured polarizing polymer solar cells (PSCs) utilizing a liquid crystalline polymer (i.e., poly(2,5-bis(3-dodecylthiophen-2-yl)thieno[3,2-b]thiophene) (PBTTT)) as an electron donor material and a material that selectively absorbs polarized light. The oriented PBTTT films prepared using a self-organization process exhibited a high dichroic ratio of ca. 6.35 at the absorption peak. The polarizing PSCs based on oriented PBTTT-PC₇₁BM photoactive layers exhibit an anisotropic photovoltaic effect under polarized illumination along the two orthogonal axes. The polarizing PSCs have a larger power conversion efficiency under parallel-polarized illumination than that of isotropic PV devices under unpolarized illumination. Based on picosecond fluorescent spectra, the parallel excitation produces a slower ground state recovery and a longer exciton lifetime than perpendicular excitation for PBTTT molecules in a uniaxially oriented arrangement.

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1. Introduction

Liquid crystal displays (LCDs) have become the most popular flat panel display (FPD) technology [1]. Unfortunately, more than 75% of the backlight energy is absorbed by the orthogonal polarizers because the operating principle of the LCD involves using a combination of two orthogonal polarizers with liquid crystal molecules to form a light valve, which can be modulated by a driving voltage. Fig. 1(a) shows the schematic construction of a LCD lighting pixel. Taking an example of twisted nematic (TN) mode LCD, the backlight becomes polarized after transmitting the back polarizer. In the absence of applied electric field, the LC molecules twist 90° due to two orthogonal orientation patterns between the polarizers. This TN arrangement generates roto-optic effect, which allows rotational variation of linearly polarization continuously from 0° to 90° [2]. Under this condition, linearly polarization provided by the back polarizer can pass through the front polarizer without any absorption. However, when a high enough voltage is applied on, the alignment of liquid crystal molecules in the bulk will be practically parallel to the electric field. Hence, the polarized light will be absolutely absorbed by the front polarizer. Since the pixel is on the off state more than half of the time, 50% backlight

energy is lost due to the back polarizer, and about another 25% backlight energy is wasted in the front one. Therefore, the polarizing polymer solar cells (polarizing PSCs) were recently introduced, and this approach suggests integrating the function of polarizers and photovoltaic devices to recycle the lost energy and harvest the ambient light energy (Fig. 1(b)). The polarizing PSCs must satisfy the characteristics of optical transmission of linearly polarized light and the conversion of absorbed photons to electrical energy. Previous experiments have suggest that π -conjugated polymers oriented with a preferred direction only absorb light polarized parallel to its molecular chain [3], which means that the light polarized perpendicular to the aligned direction can propagate through photoactive polymers with a uniaxial orientation without absorption. Early studies [4–6] of polarizing PSCs have primarily focused on mechanical friction to obtain oriented poly(3-hexylthiophene) (P3HT) for polarized absorption. However, direct rubbing on the photoactive layer may result in large size defects and impurities, which can form quenching areas that degrade the photovoltaic conversion efficiency.

In this study, we utilized a method based on liquid crystalline self-organization to manufacture polarizing PSCs, which employed PEDOT:PSS as an alignment layer inducing the polymer chains of poly(2,5-bis(3-dodecylthiophen-2-yl)thieno[3,2-b]thiophene) (PBTTT) to spontaneously orient in a specific direction via annealing. The liquid crystalline self-organization method has the following advantages: damage-free, optically anisotropic and available in

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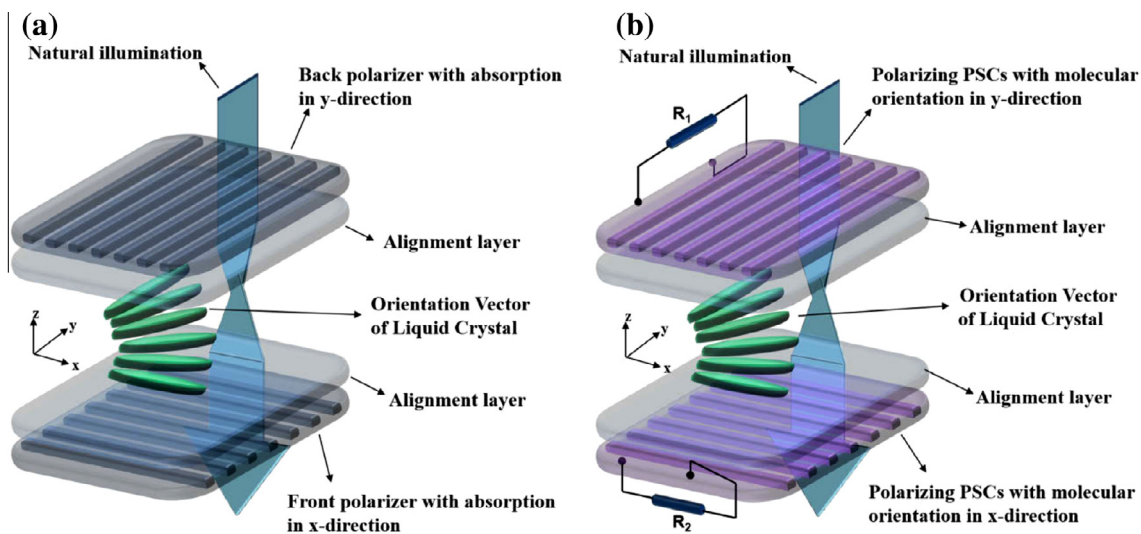


Fig. 1. (a) Conceptive structure of a pixel unit in a LCD. (b) Orthogonal polarizers are replaced by polarizing PCs in a LCD unit.

large-area device. PBTTT was selected as a photoactive material for selectively absorbing polarized light because it is a thermotropic liquid crystalline polymer. Based on the rotational invariance of two symmetrically fused thiophene rings in the polymer backbone (Fig. 2(a)) and the tail-to-tail arrangement of the alkyl side chains (Fig. 2(b)), PBTTT is favorable for forming highly ordered crystalline domains and self-organization [7–9]. In addition, PBTTT has a high hole mobility of $0.2\text{--}0.6\text{ cm}^2/\text{Vs}$ in thin film transistors [10–12] and exhibits photoelectric conversion characteristics [13,14]. Therefore, PBTTT is an ideal material for preparing an oriented photoactive layer for polarizing PSCs. In this study, the oriented PBTTT films exhibited a high dichroic ratio of ca. 6.35 at the absorption peak, indicating that most of the polymer backbones were perfectly aligned in the same direction. In addition, these optical anisotropic photoactive layers were fabricated as polarizing PSCs with dichroic photovoltaic performance. In comparison to the photovoltaic (PV) devices based on isotropic PBTTT, the polarizing PSCs typically exhibit analogous PCE under unpolarized illumination and were even more efficient under parallel polarized illumination. This improvement is due to the ordered arrangement of molecules in the uniaxially oriented PBTTT films. Because the ordered orientation of polymer chains destroys the isotropic aggregation, the aligned arrangement may have a substantial influence on the behavior of excitons. Therefore, it is necessary to extend the investigation to the ultrafast time scale to gain insight into the impact of the anisotropic exciton behavior on the photoelectric conversion process. In this study, the picosecond fluorescent

spectra were used to investigate the initial photophysics on an extremely short time scale after the oriented PBTTT layer was excited by different polarized light, and we demonstrated that the parallel excitation produces a slower ground state recovery and a longer exciton lifetime than the perpendicular excitation for PBTTT molecules in the uniaxially oriented aggregation, which is beneficial to more efficient exciton dissociation.

2. Experimental details

The PBTTT was purchased from Solarmer Tech Inc. PC₇₁BM (the acceptor) was purchased from American Dye Source Inc. All of the materials were used as received. The polarizing photovoltaic devices were fabricated with a conventional PSC structure consisting of FTO/PEDOT:PSS/PBTTT/PC₇₁BM/LiF/Al, as shown in Fig. 3. The FTO-coated glass substrates ($14\ \Omega/\square$) were pretreated with ultraviolet ozone for 15 min after being cleaned stepwise in detergent, water, acetone and ethanol under ultrasonication for 30 min each. A thin layer ($\sim 40\text{ nm}$) of PEDOT:PSS was deposited onto the FTO surface by spin coating a 1:3 vol% solution of PEDOT:PSS (Clevios P VP Al 4083): isopropanol (HPLC, Fisher Chemicals) at 2000 rpm. for 60 s. Then, this layer was baked at $150\text{ }^\circ\text{C}$ for

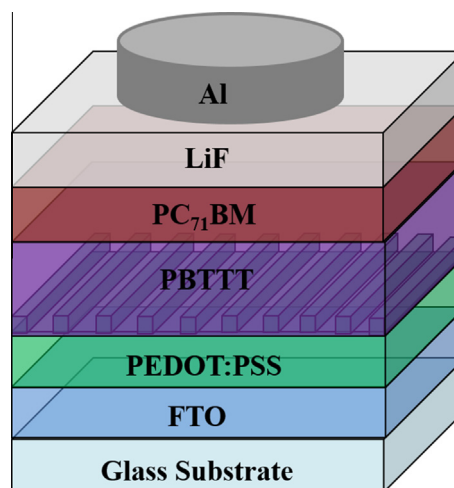


Fig. 3. Schematic structure of the quasi-bilayer polarizing polymer solar cell.

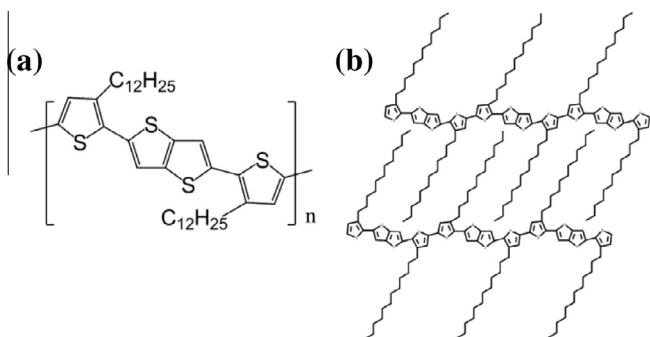


Fig. 2. (a) Molecular structure of PBTTT. (b) Schematic representation of possible structures for pristine PBTTT crystal.

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