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Application of optical coherence tomography (OCT) as a 3-dimensional imaging technique for roll-to-roll coated polymer solar cells

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ABSTRACT

The 3-dimensional imaging of complete polymer solar cells prepared by roll-to-roll coating was carried out using high-resolution 1322 nm optical coherence tomography (OCT) system. We found it possible to image the 3-dimensional structure of the entire solar cell that comprises UV-barrier, barrier material, adhesive, substrate and active solar cell multilayer structure. The achievable resolution was 12 μm in the lateral plane and 4.5 μm in the depth. We found that the OCT technique could be readily employed to identify coating defects in the functional layers. We finally identify the limitations of the technique, and future developments that would strengthen the use of the technique are described.

1. Introduction

The polymer solar cell presents a potentially very low cost photovoltaic (PV) technology that can be prepared as thin films by coating and printing techniques [1,2]. The performance in terms of power conversion efficiency and stability has increased steadily to levels that begin to compete with other thin film PV technologies. Currently, record power conversion efficiencies in the 8–9.5% range [3] and lifetimes of many thousands of hours [4–6] have been claimed. In terms of the OPV technology in the form available to the public, the corresponding values are much smaller and there have been only a few studies where many independent groups agree on performance/stability [7,8] and the methods suitable for studies and reporting [9]. This far, most of the characterization techniques employed have addressed the structure and morphology of the individual layers in the polymer solar cell at the nanoscale using scanning probe and electron microscopy techniques [10]. The only techniques that have been used to provide 3-dimensional imaging of the polymer solar cell stack have this far been chemical probes such as time of flight secondary ion mass spectrometry (TOF-SIMS) and X-ray photoelectron spectroscopy (XPS) coupled with depth profiling by destructively sputtering through the material [11–14]. Only recently have 3-dimensional imaging been reported at the nanoscale using coherent X-ray or electron tomography [15]. Common to all these techniques is that they are destructive and only enable mapping of small regions of the polymer solar cell. The destructive nature of these techniques is due to the extraction of the sample for the experiment where only the probed layer can be present. New developments include 2-dimensional imaging techniques such as light beam induced current (LBIC), dark lock-in thermography (DLIT), electroluminescence imaging (ELI), photoluminescence imaging (PLI) and optical imaging using dark field, transmission or reflection techniques, which have proven very useful in identifying shorts, open circuit, poorly performing areas and defects [16–20]. All those techniques cover the macroscopic regime (from microns to millimeters) and are expected to become very useful in the context of manufacture and production of polymer solar cells as information can be collected and processed while performing the roll-to-roll coating and printing of the polymer solar cell thus enabling process control by real time adjustment to the process.

In this report, we describe the use of optical coherence tomography [21] as a 3-dimensional imaging technique for polymer solar cells, and describe how the layered structure can be analyzed and coating errors can be identified. We also describe the limitations of the technique and identify future developments that would strengthen the use of the technique.

2. Experimental

2.1. The polymer solar cell module

The polymer solar cell was prepared according to the well known ProcessOne [22] as a module having 16 serially connected solar cells with dimensions 15 × 225 mm each. The entire module had an active area of 360 cm^2. Briefly, the module was prepared

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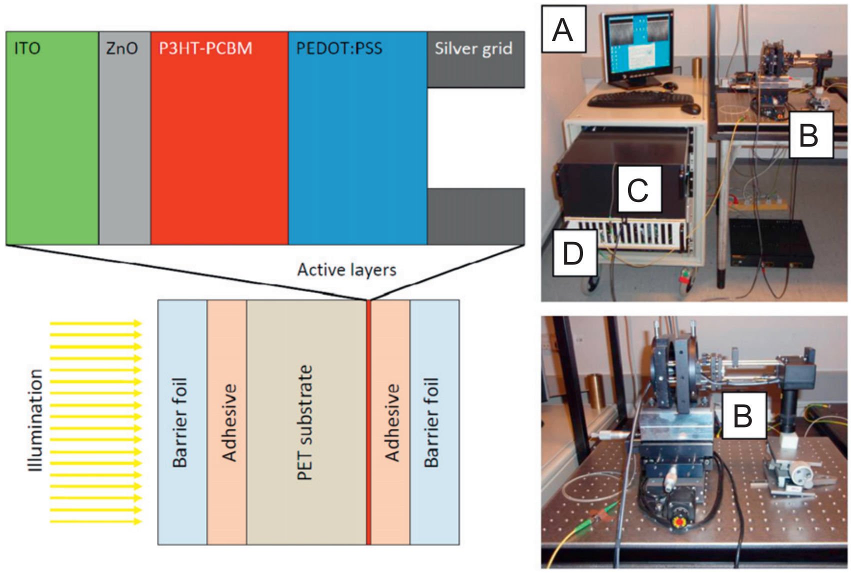

Fig. 1. The layered structure of the polymer solar cell module is illustrated (left) and photographs of the OCT setup shown (right) with a close-up of the OCT imaging probe (right; bottom). The system components are A: Complete system, B: OCT probe, C: Fourier-domain rapid scanning optical delay line and D: Optical balanced detector and control electronics.

on a 175 μm PET substrate carrying a patterned layer of indium tin oxide (ITO) that formed the transparent bottom electrode. On top of the ITO, the layers in the active stack were subsequently coated, i.e. zinc oxide (electron transport layer), P3HT:PCBM (active layer), PEDOT:PSS (hole transport layer and semitransparent electrode) and finally a silver grid as the back electrode. The layered structure of the device is shown in Fig. 1 along with photographs of the experimental OCT setup.

2.2. The OCT setup

The basic time domain OCT technique employs low coherence light from a super luminescent diode (SLD) to illuminate a fiber optic Michelson interferometer. The solar cell is placed at one of the interferometer arms and a reference mirror is placed at the other arm. Reflections from the solar cell film (amplitudes and delays) are measured by scanning the reference mirror position and recording the amplitude of the interferometric signal. A signal is recorded only when the group delay of the sample and reference signal are matched because a low coherent light source is employed and this implies that the time-of-flight for the reflections can be determined with great accuracy. Photographs of the OCT setup used are shown in Fig. 1 (right). This OCT system has previously been described in detail [23]. It is a mobile fiber-based, 4 kHz (A-scan rate) time-domain, real-time OCT system. The lateral resolution has been increased to 12 μm. Furthermore, the light source used is now a superluminescent diode with 1322 nm center wavelength, a power of 19 mW (ex fiber), and a 3 dB-bandwidth of 108 nm corresponding to an axial or depth resolution of 7.1 μm in air. Assuming an average refractive index (RI) of 1.575 for the solar cell (RI for PET [24]), the depth resolution in the solar cell is 4.5 μm. The OCT probe shown in Fig. 1 (close-up: right; bottom) is placed on a computer-controlled micrometer-precision translation stage such that 3D OCT scanning can be automatically performed. This is done by the recording of a series of 2D cross-sectional OCT images of the solar cell each image separated by 5 μm. Each saved 2D cross-sectional image has a width of 2 mm and is an average of four images (recording time: 0.5 s) in order to reduce the noise. The recorded 3D OCT data were processed and visualized using a combination of the ImageJ [25] and MeVisLab [26] software packages. Image enhancement included histogram adjustment of the gray level histograms of the pixel data for better contrast. It was carried out using MeVisLab together with the volume rendering.

2.3. LBIC

The LBIC images were obtained using a setup described earlier consisting of a 410 nm laser diode that was scanned in a raster pattern over the solar cell device [17]. The current at each pixel was translated into a bitmap with a blue–yellow color scale (yellow: high current).

3. Results and discussion

3.1. Imaging techniques for polymer solar cells

The imaging of polymer solar cells can be carried out at several levels for several different purposes. Various techniques have been available for many years while they have not been applied for polymer solar cells. Up until recently the typical polymer solar cell comprised single laboratory devices with small outlines and imaging rarely provided useful information. With the recent upscaling and roll-to-roll manufacture of polymer solar cell modules the need for efficient imaging techniques has become important. The main purpose of the imaging techniques is to confirm correct assembly and function of the polymer solar cell module and in the event of malfunction identify the reason and enable remedying the problem. Since the polymer solar cell is a thin multilayer structure that is packaged in barrier film with a complex make-up there is often a need for several complementary techniques. It should be noted that most imaging techniques are inherently 2-dimensional imaging techniques and there are currently no available 3-dimensional imaging techniques that enable full scale imaging of the entire device.

3.2. The optical coherence tomography technique

Optical coherence tomography is an emerging and powerful optical imaging technique enabling depth-resolved, non-invasive