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Mechanical stability of roll-to-roll printed solar cells under cyclic bending and torsion

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ABSTRACT

The ability of printed organic solar cells (OSCs) to survive repeated mechanical deformation is critical to large-scale implementation. This paper reports an investigation into the mechanical stability of OSCs through bending and torsion testing of whole printed modules. Two types of modules are used that differ slightly in thickness as well as on the basis of the electrode materials: silver nanowires or carbon-based inks. Each type of module is subjected to two different mechanical modes of deformation, bending and torsion, of several thousand cycles per module using a purpose-built robotic device. Analysis of the distribution of stress in the devices performed by finite-element modeling predicts the locations of failure. Failure upon bending originates at the laser-cut edges of the modules from shear at the clamp/module interface leading to crazing of the plastic barrier encapsulant foils. This crazing leads to eventual delamination due first to decohesion of the active layer at the edge of the modules and later to deadhesion between the PEDOT:PSS (electrode) and P3HT:PCBM (semiconductor) layers. The torsion mode imposes greater stresses than the bending mode and thus leads to failure at fewer strain cycles. Failure during torsion occurs through crack propagation initiated at stress concentrations on the edges of the module that were imposed by their rectangular geometry and ultimately leads to bifurcation of the entire module. Rather than the differences in electrode materials, the differences in survivability between the two types of modules are attributed mostly to the thickness of the substrate materials used, with the thinner substrate used in the carbon-based modules (~160 μm) failing at fewer strain cycles than the substrate used in the silver-nanowire-based modules (~190 μm). Taken together, the results suggest ways in which the lifetimes of devices can be extended by the layouts of modules and choices of materials.

1. Introduction

Mechanical flexibility is the characteristic that enables most of the advantages of printed modules based on organic semiconductors [1]. In particular, organic solar cells (OSCs) must survive the rigors of roll-to-roll coating, use in the outdoor environment (e.g., exposure to the forces of wind, rain, and snow), and diurnal and seasonal changes and concomitant thermal expansion and contraction [2]. Portable applications in particular expose the modules to the most extreme modes of mechanical insult, including impact, shear, twisting, stretching, bending, and folding [3]. For modules to accommodate these types of deformations, the substrates, encapsulants, and active materials must act in concert to store or dissipate mechanical energy in ways that do not degrade the electronic performance. Despite considerable research into the understanding of the mechanical properties of their component materials and the adhesion between individual device layers [1,4–7], the stability of whole modules against cyclic (repeated) deformations has not been reported. This study investigates the decline in performance (and eventual failure) of packaged solar modules after thousands of repeated cycles with a stress amplitude below the yield stress of the component materials. In particular, two different types of devices were used and subjected to two different modes of deformation: bending and torsion. These modes were meant to mimic the types of deformations that might be encountered during the real-world operation of devices.

2. Background

Organic solar cells have been the subject of intense research over the last decade due to the low cost, low weight, mechanical compliance and scalability that comes with thin-film solution processing methods

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such as inkjet printing and roll-to-roll manufacturing [8]. Although OSCs employing a wide range of conjugated polymers as the active layer are less efficient than devices based on conventional inorganic semiconductors, lab scale devices with power conversion efficiencies (*PCE*) greater than 10% have been reported [9,10]. Such efficiencies are more than sufficient for use in an array of portable applications, such as power sources for wearable biosensors, consumer electronics, and LED lighting [11,12]. One can visualize a future in which ultrathin and inexpensive portable electronics are powered by flexible printed solar cells, provided such devices are mechanically compliant enough to withstand prolonged usage.

The majority of investigations into the mechanical stability of OSCs has focused on the elasticity of the conjugated polymer used as the active layer [13], as well as electrode materials such as poly(3,4-ethylenedioxythiophene): poly(styrene sulfonate) (PEDOT:PSS) [14]. Such investigations, however, have focused on determining mechanical properties (e.g., elastic modulus or crack onset strain) of single component films [15–17]. Other forms of micromechanical testing, such as the single cantilever beam method, have been employed to study the cohesion of individual module layers while the four-point bending method and double cantilever method have been employed to study the adhesion at the interface between device layers [18–20]. While mechanical characterization of materials in isolation is now well developed, work on whole devices has lagged behind, with few exceptions [6]. In particular, the long-term durability of whole OSC modules under repeated elastic strains has not been reported.

3. Experimental design

3.1. Selection of OSC modules

The modules tested in this study (Fig. 1) were roll-to-roll printed in open air by the group of Frederick Krebs at the Danish Technical University and are described in great detail elsewhere [21,22]. We chose two types of modules. The primary differences between the two types were the use of carbon-based inks versus silver nanoparticle ink for the serial electrode links between the individual photocells that make up the modules. In the carbon electrode (C-type) module, the device stack had the configuration PEDOT:PSS/ZnO/P3HT:PCBM/PEDOT:PSS. In this configuration, the ZnO is a hole-blocking layer that permitted the use of PEDOT:PSS as both the cathode and anode. In the silver electrode (Ag-type) modules, the PEDOT:PSS used as a cathode was replaced by a hybrid blend of ZnO and silver nanowires (AgNW) to form the configuration AgNW:ZnO/P3HT:PCBM/PEDOT:PSS. Aside from these differences in the selection of materials, an important additional difference was the use of a UV filter in addition to the barrier foil for the Ag-type module [22,23]. Encapsulation in both cases was provided by Amcor Ceramis, a commercially available multilaminate barrier foil consisting

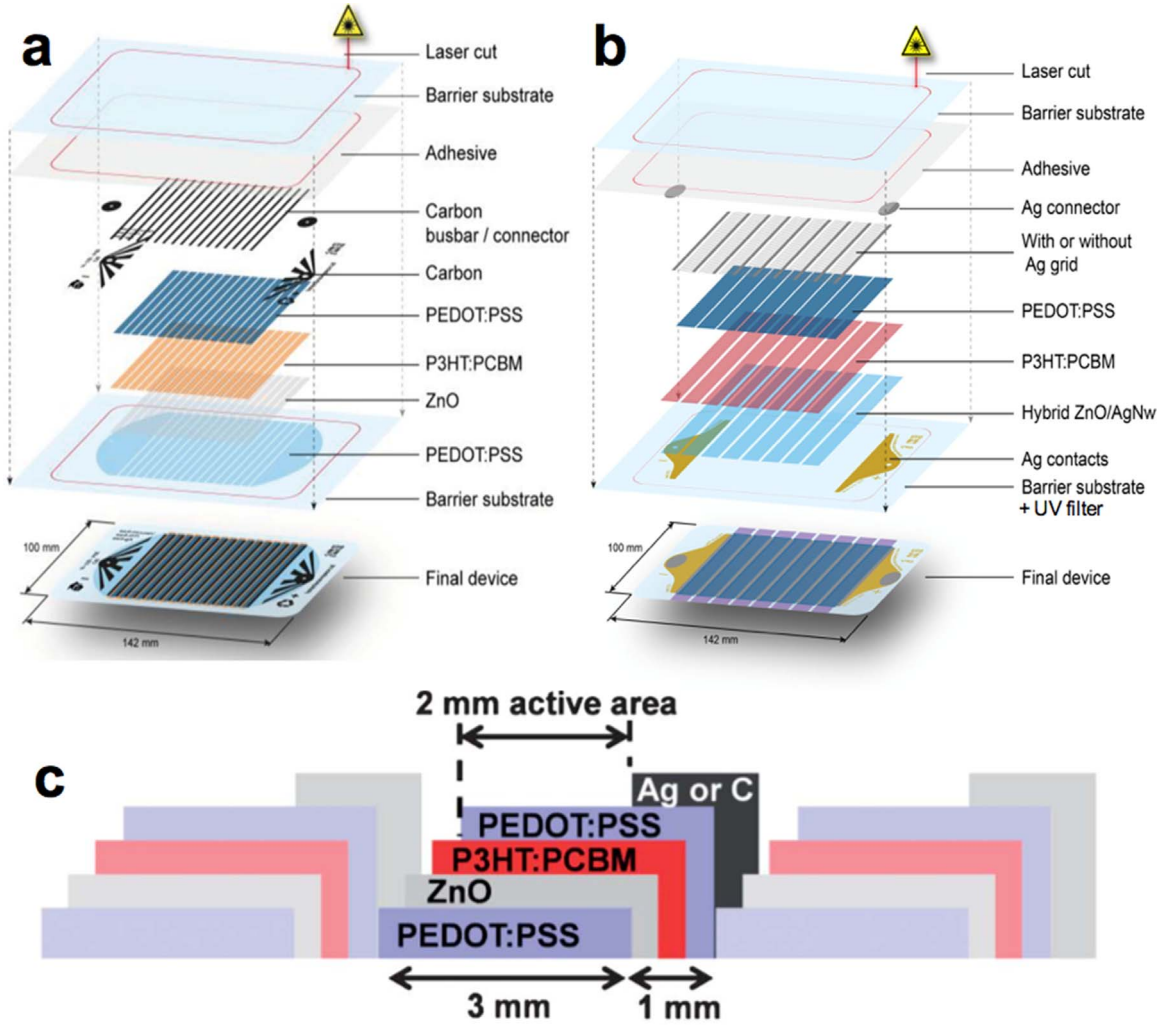

Fig. 1. Schematic diagrams of (a) C-type and (b) Ag-type module. (c) Cross sectional schematic diagram of the module stack illustrating the serial electrical connectivity within the module. (a) And (b) reproduced with permission from Ref. [24]. Copyright 2015, Wiley-VCH Verlag, GmbH & Co., KGaA. (c) reproduced with permission from Ref. [25]. Copyright 2012, Royal Society of Chemistry.