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High-performance, robust, stretchable organic photovoltaics using commercially available tape as a deformable substrate

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ABSTRACT

Electronic skins and smart textiles are emerging applications integrating wearable displays, smart sensing systems, health-care monitors, and stretchable power systems. Although various deformable optoelectronic devices have been demonstrated, high-performance stretchable photovoltaic (PV) devices remain a significant challenge in device engineering and materials optimization. In this paper, we demonstrate how a ubiquitous material—3 M™ tape—can be used as a transparent substrate for highly efficient stretchable organic PV devices. Indeed, we constructed a stretchable OPV device displaying a power conversion efficiency (PCE) of 5.2% (under AM 1.5G 1000 W m^{-2})—the highest reported to date; in addition, this device retained 80% of its original PCE after 50 cycles of stretching at 20% strain. This study paves the way toward fully deformable OPVs for integration in wearable electronics.

1. Introduction

Organic bulk heterojunction (BHJ) photovoltaics (OPVs) have attracted extensive attention because they have a number of attractive features: amenability to roll-to-roll processing using large-scale flexible substrates; low energy consumption; proven stability for specific applications; and semi-transparency with vivid colors [1–6]. Furthermore, OPVs have the characteristics of light weight and attachable in deformable objects, are potentially mechanically robust toward stress and strain. Thus, they have a great potential—as new portable power generation systems—for using in electronic skins and smart textiles [7–11]. With the advances in materials development and device engineering, the power conversion efficiencies (PCEs) of OPVs have recently surpassed 11.5% (certified value) [12–16]. To date, most high-performance OPVs have been based on indium tin oxide (ITO) glass, or flexible substrates [e.g., polyethylene terephthalate (PET)–ITO or metal foil]. Nevertheless, these substrates and electrodes have exhibited an extremely low deformability. In addition to the substrates, the compliant electrodes and interfacial layers [electron transporting layer (ETL), hole transporting layer (HTL)] for OPV applications must also exhibit a suitable combination of mechanical and electrical properties as well as a high optical transparency [7]. To ensure an efficient high OPV device with a robust deformability, the quest remains for suitable transparent substrates, optimized active materials, highly conductive transparent electrodes, and excellent interfacial layers with high stretchability [17]. In this regard, these materials must simultaneously match the work functions (energy levels) and preferred interfacial properties for efficient charge extraction while also possessing well-defined active blend morphologies. Thus, it remains difficult to fabricate stretchable OPV devices that meet all the required points for high performance.

Several transparent electrodes—based on carbon nanotubes [18], graphene sheets [19], solution-processed metal nanowires (NWs), metal meshes [20], and conducting polymers [poly(3,4-ethylenedioxythiophene)/polystyrenesulfonate (PEDOT:PSS)] [21]—have been investigated for their applications in flexible or stretchable optoelectronics [7,21]. For stretchable OPVs, not only the electrode materials but, indeed, the whole structure—including interfacial layers (HTL, ETL) and active layers—must be highly mechanically stable. To the best of our knowledge, only PEDOT:PSS [on pre-strained polydimethylsiloxane (PDMS) substrates] has been used successfully as a mechanically compliant transparent electrode and HTL for stretchable P3HT-based OPV devices, providing a PCE of 1.2% [8,21]; the corresponding device maintained a PCE of 1.2% after stretching to 18.5% for 11 full cycles [8]. Recently, Lipomi et al. demonstrated wearable OPVs with the initial PCE of 1.16% having greater a mechanical compliance (withstanding up to 1000 cycles of compression with a little degradation in PCE(0.96%)) when using PEDOT:PSS as the electrodes and polyimide

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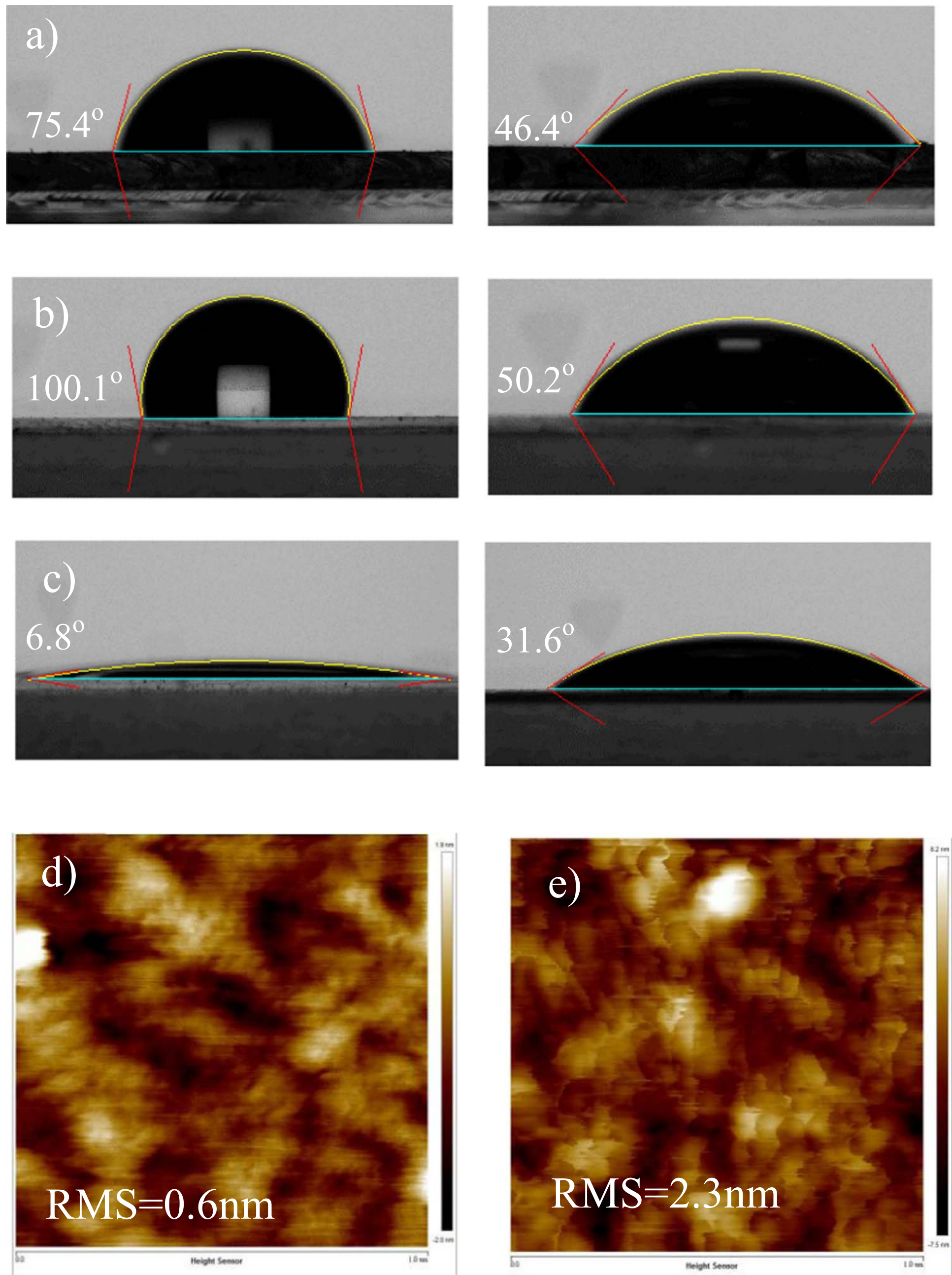

Fig. 1. (a)–(c) Contact angles (θ) of various substrates: a) 3M elastomer, b) PDMS and c) PDMS after the O_2 plasma treatment (right: H_2O as probe solvent; left: DIM as probe solvent); d–e) AFM topographical images (1 µm ×1 µm) of PEDOT:PSS on d) elastomer and e) PDMS after surface plasma treatment.

as the substrate [22]. However, the stretchable OPV devices with the PCE higher than 5% have not been demonstrated, to the best of our knowledge.

In this study, we employed two transparent elastomeric substrates [PDMS and 3M VHB 4905 tape (3M elastomer)] to fabricate stretchable OPV devices. Note that PDMS is the most common transparent elastomer in stretchable electronics [18]. We investigated the effects of the substrates, electrodes, and interfacial layers on the blend film morphology and performance of OPVs based on poly[[4,8-bis[(2-ethylhexyl)oxy]benzo[1,2-*b*:4,5-*b′*]dithiophene-2,6-diyl][3-fluoro-2-[(2-ethylhexyl)carbonyl]thieno[3,4-*b*]thiophenediyl]] (PTB7):$PC_{71}BM$ blend films. Notably, we demonstrate that 3M type can be used as a transparent substrate for stretchable electronic applications. The 3M VHB tape is a commercially available material that is viscoelastic and has excellent solvent- and moisture-resistance. The resulting 3M elastomer–based OPV devices exhibited an average PCE of 3.82 ± 0.65%. We obtained a remarkable best performance—a PCE of 5.2%—under AM 1.5G irradiation (1000 W m^{-2}) with a short-circuit current density (J_{sc}) of 12.7 mA cm^{-2}, an open-circuit voltage (V_{oc}) of 0.75 V, and a fill factor (FF) of 54.4%. To best of our knowledge, this value is the highest performance ever reported for a stretchable OPV device. Moreover, the 3M based stretchable device retained 80% of its original PCE after 50 cycles of stretching at 20% strain.

2. Results and discussion

2.1. Optoelectronic properties of substrates

The first criterion of selecting a substrate for the OPV application is the materials with a high optical transmittance. We examined the UV–vis transmittance spectra after attaching PDMS and 3M films onto glass substrates, which was used as the background. As shown in Fig. S1