



In situ vapor-deposited parylene substrates for ultra-thin, lightweight organic solar cells



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ABSTRACT

We fabricate the thinnest (1.3 μm) and lightest (3.6 g/m^2) solar cells yet demonstrated, with weight-specific power exceeding 6 W/g , in order to illustrate the lower limits of substrate thickness and materials use achievable with a new processing paradigm. Our fabrication process uniquely starts with growth of an ultra-thin flexible polymer substrate in vacuum, followed by deposition of electrodes and photoactive layers in situ. With this process sequence, the entire cell—from transparent substrate to active layers to encapsulation—can be fabricated at room temperature without solvents and without breaking vacuum, avoiding exposure to dust and other contaminants, and minimizing damage risk associated with handling of thin substrates. We use in situ vapor-phase growth of smooth, transparent, and flexible parylene-C films to produce ultra-thin, lightweight molecular organic solar cells as thin as 2.3 μm including encapsulation with a second parylene-C film. These parylene-based devices exhibit power conversion efficiencies and fabrication yields comparable to glass-based cells. Flexible solar cells on parylene membranes can be seamlessly adhered to a variety of solid surfaces to provide additive solar power.

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1. Introduction

Solar photovoltaics (PV) are among the few low-carbon energy technologies capable of satisfying global electricity demand. Today's leading crystalline silicon (c-Si) and thin-film PV modules are low-cost, efficient, and reliable—but also rigid and heavy, up to 30 kg for a 300 W module. Restricted form factors exacerbate high balance-of-system (BOS) costs, which dominate PV system cost and hinder deployment [1,2]. Lightweight, flexible solar cells are possible with emerging PV technologies, but only if lightweight, flexible substrates are used. In this work, we introduce a processing paradigm for producing thin, lightweight, clean, nanoscale-smooth, laminable, and flexible PV substrates and encapsulation layers: in situ vapor-phase deposition of transparent polymer films.

The most common substrate material today is glass: It presents a flat, smooth, robust surface for cell processing and protects sensitive active materials from exposure to oxygen and water vapor. However, a rigid glass sheet dominates PV weight and thickness. For example, a typical organic, perovskite, or colloidal quantum dot

solar cell is 600–900 nm thick and weighs 3–5 g/m^2 , as shown in Fig. 1. In contrast, a typical glass substrate is 3 mm thick and weighs $\sim 8 \text{ kg}/\text{m}^2$, dwarfing the mass of the active layers and constraining specific power [W/g] for a given cell efficiency.

Plastics, textiles, and cellulosic materials are lightweight, flexible alternatives to glass. Organic solar cells have been demonstrated on polyethylene terephthalate (PET) [3], polyethylene naphthalate (PEN) [4], polyimide (PI) [5], paper [6–8], and cellulosic substrates [9,10]. In particular, PET and PEN allow scalable roll-to-roll processing and are produced commercially in high volumes. But thin PET and PEN substrates face several challenges intrinsic to their manufacture. Typically formed from bulk feedstock by extrusion and biaxial drawing, these films require additional packaging, transportation, cleaning, and surface preparation steps prior to device fabrication. Intrinsic and extrinsic surface defects are often unavoidable. Defect sizes range from below 200 nm–10 μm both laterally and vertically [11,12], presenting a major shorting risk for solar cells and other electronic devices with thin active layers. Planarizing overcoatings may help mitigate defects but add processing complexity [11]. Furthermore, thin PET and PEN films are difficult to handle and expensive on both a per-weight and per-area basis.

Here we demonstrate an in situ, solvent-free, all-room-

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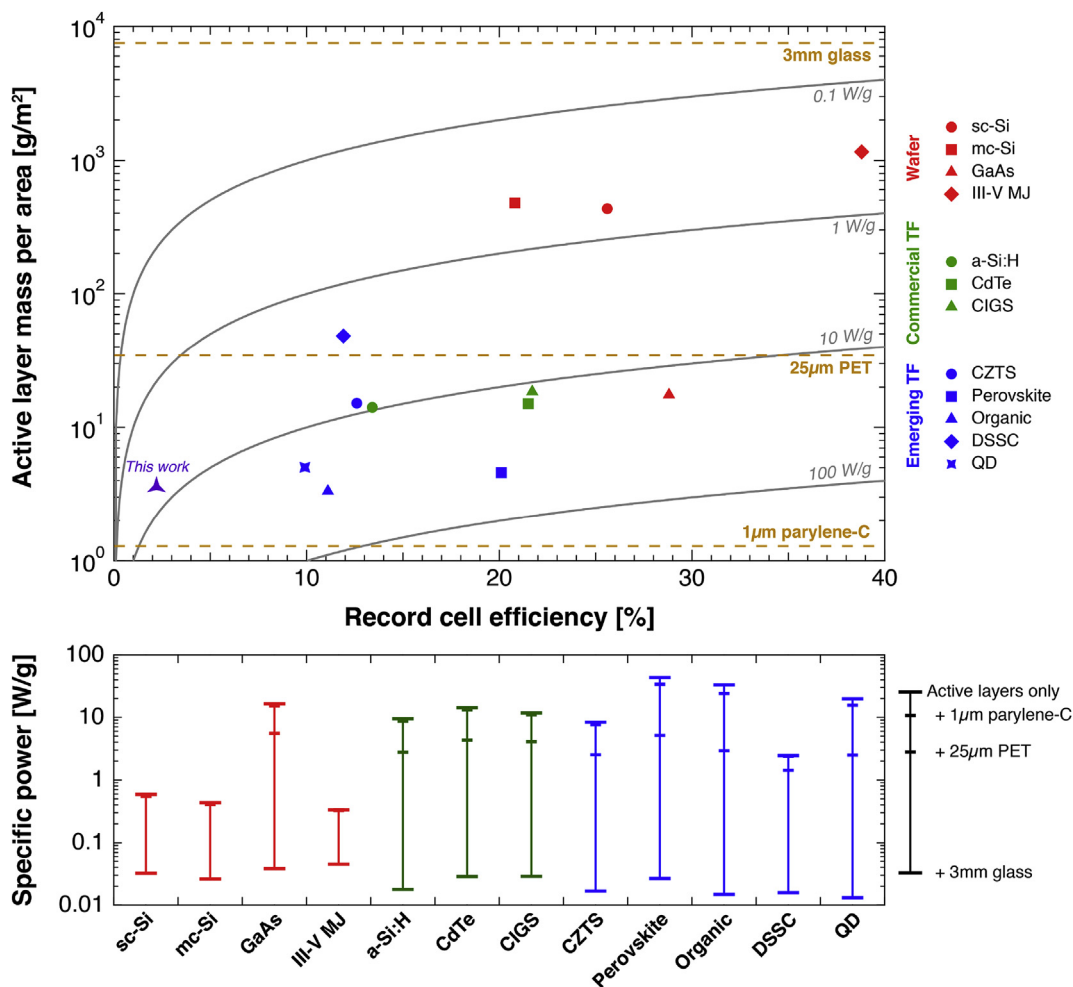


Fig. 1. Effect of substrates and active layers on PV power-to-weight performance. In the top plot, typical mass per area (active layers including electrodes) vs. record power conversion efficiency is shown for all PV technologies. Dashed gold lines represent substrates: 3 mm-thick glass, 25 μm PET, and 1 μm parylene-C. Typical thick glass and plastic substrates dominate the weight of thin-film (TF) cells. Specific power contours show that power-to-weight ratios are more sensitive to total cell weight per area than to power conversion efficiency. Emerging TF technologies are 2–3 \times less efficient but use 10–100 \times less active material than deployed technologies, allowing them to achieve higher specific powers by employing lightweight substrates. The purple marker represents the parylene-based cells from this work. In the bottom plot, specific power is shown for active layers alone and with various substrates. Device structures are described in Ref. [1]. Wafer-based PV technologies include single-crystalline silicon (sc-Si), multicrystalline silicon (mc-Si), gallium arsenide (GaAs), and III–V multijunction (III–V MJ) PV. Commercial thin-film technologies include hydrogenated amorphous silicon (a-Si:H), cadmium telluride (CdTe), and copper indium gallium diselenide (CIGS). Emerging thin-film technologies include copper zinc tin sulfide (CZTS), perovskites, organic PV, dye-sensitized solar cells (DSSC), and colloidal quantum dot (QD) PV. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

temperature process for fabricating organic solar cells on vapor-deposited parylene-C, which forms smooth, transparent films on a variety of surfaces. From substrate to active layers to encapsulation, solar cells are fabricated without breaking vacuum, thus minimizing contamination and damage risk associated with the transport and handling of ultra-thin substrates. Complete parylene-based devices released from a carrier wafer are the thinnest and lightest solar cells demonstrated to date (Fig. S14, SI).

2. Materials and methods

2.1. Materials

Parylene-C dimer (dichloro-[2,2]paracyclophane, diX-C) was purchased from Uniglobe Kisco. An indium zinc oxide (IZO; In_2O_3 with 10 wt.% ZnO) sputter target (99.99% purity) was purchased from Idemitsu Corp. MoO_3 (Alfa Aesar, 99.9995%), tetraphenyl-dibenzoperiflanthene (DBP; Lumtec, >99%), bathocuproine (BCP; Lumtec, >99%), and Ag (Alfa Aesar, 99.999%) were used as received.

C_{60} (99.9%, Sigma–Aldrich) was purified once by thermal gradient sublimation [13]. Commercial PET and PEN films of varying thickness were obtained from Goodfellow.

2.2. Parylene substrate formation

Parylene-C films of varying thickness were deposited on borosilicate glass and on complete OPV devices in a custom-designed chamber. Glass and silicon substrates were cleaned by sonication in detergent, DI water, and acetone (5 min each), followed by boiling in isopropanol twice for 5 min and O_2 plasma treatment for 1 min. Prior to parylene deposition, 1% Micro-90 in DI water was spin-coated on glass at 2000 RPM for 60 s to form a release layer. Parylene deposition was carried out at a base pressure of 5 mTorr. diX-C dimer was sublimed at 90–120 $^\circ\text{C}$ and cleaved in a pyrolysis furnace at 750 $^\circ\text{C}$. Parylene-C films with thicknesses from 200 nm to 3 μm were deposited at rates of up to 5 $\text{\AA}/\text{s}$ and monitored with a quartz crystal microbalance.

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