



Fully solution-processed indium tin oxide-free textile-based flexible solar cells made of an organic–inorganic perovskite absorber: Toward a wearable power source



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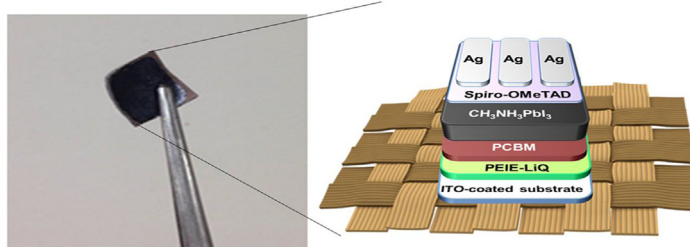
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HIGHLIGHTS

- Prototype of perovskite solar cells fabricated on textile substrates was shown.
- Textile-based perovskite solar cells achieved an efficiency of 5.72%.
- All-solution-processed, printable, ITO free device is promising in real world.

GRAPHICAL ABSTRACT

Textile-based Flexible Perovskite Solar Cells



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ABSTRACT

Practical textile-based perovskite solar cells are prepared via low-temperature solution-processing, adopting a planar heterojunction architecture on a textile substrate. Polyurethane-coating of the textile enables low-temperature solution-processing, providing a robust substrate for forming polymeric anode, hole transport layer, perovskite layer, and electron transport layer. The prototype of planar perovskite solar cells on the textile substrate exhibits a power conversion efficiency of 5.72%, with good flexibility and durability in ambient conditions. This work shows the advantages of using textile substrates in flexible and practical solar cell fabrication, which can be applied to wearable electronics.

1. Introduction

Wearable electronics offer great potential for portable device applications [1–5]. In recent years, a variety of wearable electronic devices embedded in clothes, watches, and glasses have attracted considerable attention as human-friendly functional technologies [6–8]. Lightweight and wearable power supply modules are desirable for practical portable electronics; thus, energy conversion devices fabricated on flexible substrates have been thoroughly investigated [9–14].

Different types of flexible solar cells have been extensively studied, including amorphous Si, organic, hybrid, dye-sensitized, and copper-indium-gallium-selenide (CIGS) photovoltaic devices [15,16]. Notably, methylammonium-lead-trihalide perovskites (e.g., $\text{CH}_3\text{NH}_3\text{PbX}_3$, $\text{X} = \text{Cl}, \text{Br}, \text{I}$) have emerged as promising next-generation efficient photoactive materials for solar cell applications. The unique electronic properties of perovskite semiconductors with small exciton binding energies ($\sim kT$ at room temperature) and long charge carrier diffusion lengths with lifetimes exceeding 100 ns have boosted the power

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conversion efficiencies (PCEs) of perovskite solar cells up to > 22% on rigid substrates [17–22].

Another advantage of the perovskite semiconductor is its solution-processability. Perovskite semiconductor is excellent in coating various substrate such as plastics and paper. It can be readily applied to practical flexible solar cells due to its superior optoelectronic properties (long exciton-diffusion length, high extinction coefficient in UV–Vis region and low-lying energy bands) as well as physical properties such as flexibility, light weight, and high crystallinity [23]. In developing such flexible perovskite solar cells, several groups have demonstrated high-efficiency solar cell devices fabricated on plastic substrates via molecular or device engineering [24–27]. Although state-of-the-art flexible solar cells have reached high power conversion efficiencies exceeding 15%, the plastic substrates such as poly(ethylene terephthalate) or poly(ethylene naphthalene) are not the ideal platforms for wearable electronic devices because the thin-film devices on a flat substrate cannot be widely applied in clothes due to limited mechanical flexibility. Unlike plastic substrates, fabrics or textiles can be readily used to develop actual substrates for wearable electronics because of physical softness and flexible property. There have been many recent studies on textile-based flexible electronic devices, including sensors, nanogenerators, batteries, and photovoltaic devices [28–31]. However, textile substrates still have many problems hindering their use in electronic devices, including rough surface morphology, chemical vulnerability, low physical strength, and high thermal expansion. These obstacles have made it difficult to develop textile-based flexible perovskite solar cells [32–35].

In this work, we demonstrate fully solution-processed perovskite solar cells fabricated on textile substrates. The typical woven texture of the textile allows it to be infiltrative or swell due to solvent, restricting its solution-processing for the fabrication of textile-based devices. In this work, to solve the problems of textile substrates such as their rough and porous surface, a thin layer of polyurethane (PU) was introduced onto the bare textile as a planarization layer (Fig. 1a). The PU layer effectively improved the wettability, processability, and surface morphology of the textile substrate, allowing subsequent solution-processing for each layer in solar cell devices. The textile-based perovskite solar cells were successfully fabricated and showed a PCE of 5.72% using solution-processed anode, hole transport layer (HTL), and electron transport layer (ETL) materials. This result is the first demonstration of printable perovskite solar cells using woven textile substrates.

2. Experimental section

2.1. Preparation of materials

Polyester/satin textile (The One Solution, 75d, scoured), polyurethane resins (Daewon Polymer & Chemicals and VIX), CH_3NH_2 (Junsei Chemical), HI (Duksan Chemical), and PbI_2 (Acros) were used as received. $\text{CH}_3\text{NH}_3\text{I}$ was synthesized and purified according to a

method reported elsewhere [34]. Perovskite precursor solution was prepared by dissolving PbI_2 (461 mg, 1.0 M) and $\text{CH}_3\text{NH}_3\text{I}$ (159 mg, 1.0 M) in a mixture of dimethyl sulfoxide (DMSO) and N,N-Dimethylformamide (DMF) (1.0 mL, 3:7 in volume), and the solution was stirred at 70 °C for 90 min [6,6].-phenyl-C61-butyric acid methyl ester (PCBM, Nano-C) was dissolved in anhydrous chlorobenzene (1 wt%) and the solution was stirred at 70 °C for 1 h before use.

2.2. Fabrication of devices

A thin layer of PU was coated on the prepared polyester textile using a paper transfer method (R/P lamination) to ensure an even textile substrate surface suitable for solution-processing. Textile-based solar cell devices were fabricated with an inverted architecture: poly(3,4-ethylenedioxythiophene):polystyrene sulfonate (PEDOT:PSS, PH1000, Heraeus Clevios):0.5 wt% single-walled carbon nanotubes (SWCNTs, Iljin Chemicals)/PEDOT:PSS (AI4083, Heraeus Clevios)/ $\text{CH}_3\text{NH}_3\text{PbI}_3$ /PCBM/Ag. In order to fabricate the anode, a mixture of PEDOT:PSS and SWCNT was vigorously stirred for 2 h under ultrasonication. The mixture was coated using a bar-coating on PU-coated textile at 80 °C and then annealed for 10 min at 100 °C. To prevent direct contact between the anode and the perovskite layer, a layer of low-conductivity PEDOT:PSS (AI4083) diluted with isopropyl alcohol (0.5 wt%) was coated using a bar coating method. The perovskite layer was formed by bar coating using a 30 wt% precursor solution (1:1 molar ratio of PbI_2 and MAI in a 3:7 vol ratio mixture of DMSO and DMF) at 80 °C. After 80 μL of the precursor solution was dropped on top of the hot-plate, the blade was moved smoothly with a gap of $\sim 35 \mu\text{m}$. The bar-coating speed was critical to control the thickness of the perovskite layer. The coating speed of 0.5 cm/s and 0.8 cm/s resulted in 400 nm and 600 nm thick films, respectively. The film was dried at 100 °C for 10 min after the bar-coating was completed. The PCBM layer was then printed by bar coating using a 1 wt% solution in chlorobenzene at the coating speed of 0.5 cm/s. Finally, the transparent electrode was formed by deposition of Ag (8 nm) through a shadow mask under high vacuum ($\sim 10^{-6}$ Torr) to complete the device. The active area (6.00 mm^2) was defined using shadow masks.

2.3. Characterization

The field emission scanning electron microscopy (FE-SEM) and the optical microscopy images showing the layered structure of the coated textile were acquired using SU-8010 (Hitachi) and IMS-345 (SOMETECH) microscopes, respectively. X-ray diffraction patterns of the perovskite layer on the textile were investigated using an X-ray diffractometer (D8 Advance, Bruker). The sheet resistance of the electrode was measured using a four-point probe system (Ossila). The current density–voltage (J–V) curves of device response under AM 1.5 G (100 mW/cm^2) illumination were collected using a semiconductor analyzer (4200-SCS, Keithley), which was calibrated using an NREL-

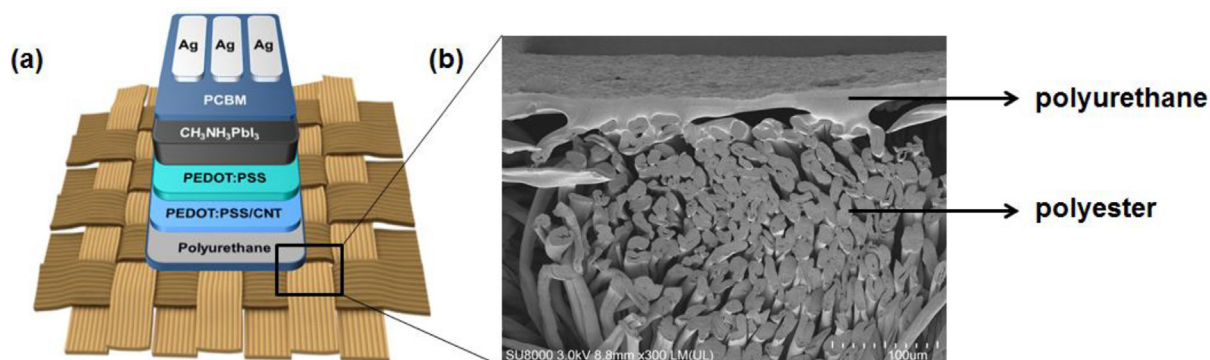


Fig. 1. (a) Schematic illustration of textile-based perovskite solar cells, (b) SEM image of the polyurethane-coated textile substrate.

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