Bioinspired Transparent Laminated Composite Film for Flexible Green Optoelectronics

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Supporting Information

ABSTRACT: Herein, we report a new version of a bioinspired chitin nanofiber (ChNF) transparent laminated composite film (HCLaminate) made of siloxane hybrid materials (hybrimers) reinforced with ChNFs, which mimics the nanofiber-matrix structure of hierarchical biocomposites. Our HCLaminate is produced via vacuum bag compressing and subsequent UV-curing of the matrix resin-impregnated ChNF transparent paper (ChNF paper). It is worthwhile to note that this new type of ChNF-based transparent substrate film retains the strengths of the original ChNF paper and compensates for ChNF paper’s drawbacks as a flexible transparent substrate. As a result, compared with high-performance synthetic plastic films, such as poly(ethylene terephthalate), poly(ether sulfone), poly(ethylene naphthalate), and polyimide, our HCLaminate is characterized to exhibit extremely smooth surface topography, outstanding optical clarity, high elastic modulus, high dimensional stability, etc. To prove our HCLaminate as a substrate film, we use it to fabricate flexible perovskite solar cells and a touch-screen panel. As far as we know, this work is the first to demonstrate flexible optoelectronics, such as flexible perovskite solar cells and a touch-screen panel, actually fabricated on a composite film made of ChNF. Given its desirable macroscopic properties, we envision our HCLaminate being utilized as a transparent substrate film for flexible green optoelectronics.

KEYWORDS: chitin, nanofiber, transparent substrate, perovskite solar cell, touch-screen panel, green optoelectronics

INTRODUCTION

The marvelous mechanical properties of the exo- and/or endoskeleton of some marine creatures are attributed to the complex hierarchical structures of the skeletons, which invokes inspiration for designing new composite materials.1−3 The stiffness of the arthropod exoskeleton,4 fracture toughness of nacre,5 and hardness of the squid beak6 are good examples. As the hierarchical complexity increases, the brilliant properties of such biostructures stem from the arrangement and interactions of the individual building blocks and not from each constituent on its own. For these marine creatures, particularly, the ingenious hierarchical assembly of chitin nanofibers (ChNFs) in a proteinaceous matrix plays a critical role in the remarkable performance of their skeletons.4−6 The nanofiber-matrix composite structure of these biological composites can serve as the design principle for the creation of novel man-made composite materials, exhibiting some unprecedented properties by combining both biogenic and synthetic materials.9−11

Herein, we report a bioinspired laminated composite film consisting of biogenic ChNFs and a synthetic siloxane hybrid material as the matrix; we use this material as a transparent substrate film to fabricate flexible green optoelectronics (Figure 1).12−15

As a natural polysaccharide, chitin [poly-β-(1,4)-N-acetyl-d-glucosamine] is the second abundant structural biopolymer on earth (Figure 1a) and is the main structural component of a number of marine creatures, such as the exoskeleton of arthropods, mollusk shells, and the endoskeleton of cephalopods.16 In these biocomposites, chitin exists as crystalline nanofibers17,18 (3−5 nm in diameter), in which the chitin macromolecules are tightly held by myriad hydrogen bonds, which are responsible for its mechanical stiffness.9 In the

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nanoﬁber-matrix structure of hierarchical biocomposites listed above, therefore, ChNFs function as a reinforcement of the proteinaceous matrix.19 Furthermore, in addition to excellent mechanical properties, the signiﬁcant property of ChNFs is superior optical transparency achieved by the nanoﬁbrillation of ﬁbrous building blocks.20−23 Taking inspiration from nature, accordingly, ChNFs have been utilized as reinforcement agents to create optically transparent composite ﬁlms that emulate the nanoﬁber-matrix structure of biological composites.24−27 In particular, Ifuku et al. reported optically transparent ChNFs/acrylic matrix resin composite ﬁlms.32 They obtained these composite ﬁlms from UV-curing of the acrylic matrix resin-impregnated ChNF transparent papers (ChNF papers). Compared to such conventional cross-linked polymers obtained by the photoradical polymerization of acrylates, siloxane hybrid materials (hybrimers), which are synthesized via the photocatonic polymerization of siloxane epoxide/oxetane blends, exhibit better thermal stability, chemical stability, and processability. These properties are attributed to the presence of living characters and lower oxygen sensitivity.31 With these enhanced properties, the hybrimers also show a high level of optical transparency.32

On the basis of these preceding researches, we report a novel ChNF transparent laminated composite ﬁlm made of the hybrimer reinforced with ChNFs (HCLaminate), which mimics the nanoﬁber-matrix structure of hierarchical biocomposites. The HCLaminate is prepared by vacuum bag compressing and subsequent UV-curing of the matrix resin-impregnated ChNF paper; a UV-curable matrix resin consists of siloxane epoxide/oxetane blends. The intimate assembly of the hybrimer and ChNFs maintains the advantages and compensates for the disadvantages of the original ChNF paper as a ﬂexible transparent substrate. As a consequence, our bioinspired laminated composite ﬁlm exhibits outstanding properties, including ﬂexibility, smooth surface topography, chemical stability, thermal stability, optical transparency, mechanical robustness, and dimensional stability. Given these desirable properties, the HCLaminate can be a promising candidate for the ﬂexible green optoelectronics substrate. We use our HCLaminate to demonstrate the fabrication of both ﬂexible perovskite solar cells and touch-screen panel, and, as far as we know, this work presents the ﬁrst demonstration of ﬂexible optoelectronics fabricated using the composite ﬁlm made of ChNF.

Figure 1. (a) Digital photograph of 0.4% (w/v) β-chitin/hexafluoroisopropanol (HFIP) solution and chemical formula for chitin. (b) A digital photograph showing the matrix resin and chemical structures of cycloaliphatic epoxy oligosiloxane (CAEO) and bis-[1-ethyl(3-oxetanyl)]methyl ether (DOX), which constitute the matrix resin. (c) Schematic illustration of the fabrication procedure of the HCLaminate. (d) A digital photograph of the transparent HCLaminate (scale bar = 2 cm). (e) An overlapped scanning electron microscopy-energy dispersive X-ray spectrometry (SEM-EDS) Si mapping image of the HCLaminate (scale bar = 10 μm). (f) A digital photograph showing the mandrel bend test of the HCLaminate (this test is conducted based on ASTM D522/D522M-13 standard).
RESULTS AND DISCUSSION

Figure 1a,b displays the starting materials for the preparation of the ChNF paper and the matrix resin, which serve as nanofiber and matrix component building blocks of the HCLaminate, respectively. As the preceding step for the fabrication process of the HCLaminate, the 40 μm thick ChNF paper is prepared via centrifugal casting of a 2.4% (w/v) squid-pen β-chitin/HFIP alcogel (20 mL). This alcogel is obtained from a homogeneous 0.4% (w/v) β-chitin/HFIP solution (120 mL) through evaporation of HFIP at ambient conditions (Figure 1a). Because HFIP breaks intermolecular hydrogen bonds leading to dissolution of ChNF, the evaporation of HFIP results in the regeneration of hydrogen bonds between adjacent chitin molecules. This evaporation induces the self-assembly of crystalline ChNF. From crystal structure analysis using X-ray diffraction (XRD) and Fourier-transform infrared (FT-IR) spectroscopy, the intersheet diffraction peak and absorption spectrum for the ChNF paper, which are in between both α- and β-polymorphs, indicate that the resultant ChNF paper is composed of α- and β-chitin crystals (dashed lines, Figure S2c,d). These results suggest that the β-chitin to α-chitin transformation occurs during the fabrication process of our ChNF paper. It should be noted that this crystalline phase transition between different chitin allomorphs is the result of the thermodynamic stability of α-chitin. The UV-curable matrix resin is comprised of CAEO/DOX blends (Figure 1b). As illustrated in Figure S1, a sol–gel reaction between 2-(3,4-epoxycyclohexyl)ethyltrimethoxysilane (ECTS) and diphenylsilanediol (DPSD) is used to prepare CAEO.

Following the preparation of the ChNF paper and matrix resin, the HCLaminate is fabricated according to the steps illustrated in Figure 1c: (I, II) the matrix resin-impregnated ChNF paper is placed between glass plates and subsequently compressed in a vacuum bag compressing instrument; (III) to cure the matrix resin, the sample is irradiated under UV-light (Figure S2a,b); (IV) finally, the transparent HCLaminate of 60 μm thickness is obtained by separating both glass plates (Figure 1d). SEM images in Figures 1e and S3a show the cross-sectional structure of the HCLaminate, in which the ChNF paper is laminated between two layers of the hybrimer. Upon further investigation using EDS, the homogeneous distribution of Si in the ChNF paper, even in the central region, indicates the infiltration of the matrix resin into the ChNF paper (Figures 1e and S3b). Furthermore, this result suggests that ChNFs are encrusted with the hybrimer while the matrix resin is cured and the hybrimer can be reinforced by such monolithically embedded ChNFs. As a candidate for the flexible green optoelectronics substrate, the HCLaminate is...
flexible enough to be bent over a cylindrical mandrel of 3.2 mm diameter without any cracks (Figure 1f).

As presented in Figures 2a and S4a, the atomic force microscopy (AFM) image obtained from the ChNF paper displays ultrafine ChNFs (ca. 3 nm in diameter), which are the building blocks of the ChNF paper. Despite the nanosized building blocks, however, the root-mean-square surface roughness ($R_{\text{rms}}$) of the ChNF paper is 2.65 nm because of the fibrous nature.\(^{35,36}\) Compared to that of the ChNF paper, the HCLaminate has an $R_{\text{rms}}$ value of 0.37 nm, which is attributed to the layers of the hybrimer covering the ChNF paper (Figures 1e, S3a, 2b, and S4b). Note that the $R_{\text{rms}}$ value of the HCLaminate is much smaller than that of conventional plastic substrates for flexible optoelectronics, including poly(ethylene terephthalate) (PET), poly(ether sulfone) (PES), poly(ethylene naphthalate) (PEN), and polyimide (PI) (Figure S5 and Table S1). This extremely smooth surface topography enables the HCLaminate to fabricate flexible devices on its surface without any additional planarization steps.

In addition, the layers of the hybrimer not only improve the surface smoothness, but also serve as barriers of the ChNF paper to chemicals.\(^{37}\) The ChNF paper becomes crumpled after soaking in DI water in contrast to the HCLaminate, which shows no dimensional change (Figure 2d,e). Furthermore, the HCLaminate clearly demonstrates its solution stability in a variety of solvents, including EtOH, IPA, and acetone (Figure 2f,g). This result indicates that the chemical stability of the hybrimer imparts a better manufacturing capability to the HCLaminate.\(^{38}\) Figure 2c displays the TGA profile of the hybrimer, the HCLaminate, and the ChNF paper, and their 5% weight loss temperature ($T_{5\%}$) values are 370, 289, and 236 °C, respectively. The onset of significant thermal degradation of the HCLaminate is observed at 255 °C, in comparison with that of the ChNF paper which is determined at 170 °C. Note that the TGA curve of the HCLaminate exhibits a bimodal decomposition ascribed to the decomposition of both ChNF paper and hybrimer (Figure S6). Furthermore, to determine the maximum process temperature for the HCLaminate, we conduct isothermal TGA on the HCLaminate at 150, 200, and 250 °C for 5 h. As shown in Figure S7, our HCLaminate shows noticeable weight loss (i.e., thermal degradation) after thermal aging at 200 and 250 °C for 5 h. However, at 150 °C, there is no obvious thermal degradation during the isothermal TGA. This hybrimer-assisted thermal stability\(^{39,40}\) of the HCLaminate permits the fabrication of high-temperature processed electronic devices on our HCLaminate.

Optical transparency of our HCLaminate is assessed by UV−visible spectroscopy. The total transmittance spectra of the ChNF paper, the HCLaminate, and hybrimer are shown in Figure 3a. The ChNF paper and hybrimer inherently exhibit superior optical transmittance (~91%) in the entire visible spectrum, and both have similar refractive indices of ca. 1.54 at 633 nm, which minimize the light scattering from the interface.\(^{41}\) Therefore, the HCLaminate shows an outstanding optical transmittance of 90.9% at 550 nm, with a limited transmission haze, which is comparable to that of the ChNF paper and the hybrimer (Table S2). In the wavelength of UVA light (315−400 nm), however, the presence of UV-absorbable
phenolic groups in the hybrimer results in slightly reduced transmittance of the HCLaminate (Figure S2a). It is also notable that conventional plastic substrates present either a lower optical transmittance or a higher transmission haze compared to our HCLaminate (Figure 3a and Table S2).

The reinforcement effect of ChNFs on the hybrimer is investigated by using tensile test, TMA, and DMA. ChNFs are promising candidates for the reinforcing element because of their excellent mechanical properties originated from the hydrogen-bond-driven crystal structure.8,42 In Figure 3b, the HCLaminate has a higher elastic modulus than that of the ChNF paper and hybrimer; note that the elastic modulus of the HCLaminate (6.2 GPa) has the highest value among the tensile-tested samples (Figure 3b and Table S3). These results confirm that ChNFs effectively improve the mechanical properties of the hybrimer. In combination with the crystal structure stabilized by strong hydrogen bonds between ChNFs, a morphology of randomly entangled ChNFs restricts its thermal relaxation motions (Figures 2a and S4a).20,43 Accordingly, the thermomechanical properties, including the coefficient of thermal expansion (CTE), storage modulus (E'), and glass-transition temperature (T_g) of the hybrimer, also can be enhanced by ChNF reinforcement. As presented in TMA curves of the hybrimer, HCLaminate, and ChNF paper, the incorporation of ChNFs leads to the reduction in the thermal expansion of the hybrimer (Figure 3c). Although the CTE of the hybrimer is 126 ppm K^{-1}, the HCLaminate exhibits an extremely decreased CTE of 22 ppm K^{-1}, which is slightly higher than that of the ChNF paper (18 ppm K^{-1}) and PI (17 ppm K^{-1}). Moreover, this CTE of our HCLaminate has the lowest value among commercial plastic films except that of PI (Figure 3c and Table S4). It should be emphasized that no noticeable glass-transition behavior is detected during the overall TMA test on the HCLaminate, whereas PEN and PET show clear glass-transition behaviors at their T_g.

Upon further investigation using DMA, these results can be elucidated. Ogura et al. concluded that chitin does not exhibit an obvious glass-transition behavior prior to its thermal decomposition because of the randomly entangled morphology of crystalline ChNFs.44,45 Even though the hybrimer shows the lowest level of E', with a weak and broad glass-transition behavior, ChNFs improve the E' and suppress such glass transition of the hybrimer. As shown in Figure 3d, therefore, the ChNF paper and HCLaminate possess the highest E' values, with a tiny increase in tanδ, in contrast to those of conventional plastic substrates except PI, which exhibit low E' and an obvious tanδ peak around their T_g. Given its low CTE without T_g, our HCLaminate can sustain its original dimensions when it is subjected to high-temperature processing.

As a proof-of-concept, we demonstrate both flexible perovskite solar cells and touch-screen panel using our HCLaminate as a substrate film (Figure 4). Figure 4a provides the device structure of the flexible perovskite solar cells fabricated on an indium zinc oxide (IZO)/HCLaminate (Figure S8), and also a reference device is fabricated on an indium tin oxide (ITO)/PET substrate. From the current-density–voltage (J–V) curves, the solar cells on the IZO/ HCLaminate exhibit a power conversion efficiency (PCE, η) of...
12.52%, with a short current density \( J_{sc} \) of 17.41 mA cm\(^{-2}\), an open circuit voltage \( V_{oc} \) of 0.98 V, and a fill factor of 0.74 (Figure 4b); note that the performance of the device on the IZO/HCLaminate is higher than that of the reference device showing a PCE of 11.68% (Table S5). Furthermore, a bending test on flexible perovskite solar cells on the IZO/HCLaminate and the ITO/PET confirms that the mechanical durability of the flexible device on the IZO/HCLaminate is better than that of the reference (Figure S9). This mechanical durability of the flexible solar cells on the IZO/HCLaminate originates from the mechanical robustness of the HCLaminate (Figure 3). In addition, the device structure of the fabricated touch-screen panel is schematically depicted in Figure 4c. The silver nanowires (AgNWs)-coated HCLaminate serves as both the top and bottom substrate (Figure S10), along with photoresist dot spacers and Au interconnects. Figure 4d and Movie S1 display the stable operation of the fabricated touch-screen panel device; it is amenable to write characters on its surface.

### CONCLUSIONS

In summary, we introduced a bioinspired ChNF transparent laminated composite film made of the hybrimer reinforced with ChNFs (HCLaminate), which emulated the nanofiber-matrix structure of biological composite materials. The HCLaminate was obtained from vacuum bag compressing and subsequent UV-curing of the matrix resin-impregnated ChNF paper. The ingenious hierarchical assembly between the hybrimer and ChNFs allowed the new material to retain the strength of the original ChNF paper and compensated for its weakness as a flexible substrate film. Consequently, our HCLaminate showed outstanding properties, including flexibility, an extremely smooth surface topography \( R_{rms} = 0.37 \) nm, chemical stability, thermal stability \( T_{d5\%} = 289 \) °C, optical transparency \((\sim 91\%\) at 550 nm), elastic modulus of 6.2 GPa, and CTE of 22 ppm K\(^{-1}\) without \( T_g \). To prove its possibility as a flexible transparent substrate film, we fabricated both flexible perovskite solar cells and touch-screen panel using our HCLaminate. The flexible perovskite solar cells on the HCLaminate showed higher performance compared to that of the reference device on PET, and the touch-screen panel fabricated using the HCLaminate exhibited a stable operation. Given its advantageous macroscopic properties, we envision our HCLaminate being utilized as a transparent substrate film for flexible green optoelectronics.

### EXPERIMENTAL SECTION

#### Materials.

\( \beta \)-Chitin extracted from squid pen, \( ^{46} \) HFIP (Halocarbon), ECTS, DPSD (Shin-Etsu, Japan), DOX (Teagosei, Japan), barium hydroxide monohydrate, triarylsulfonium hexafluoroantimonate salts, prawn shell \( \alpha \)-chitin, trichloro(octadecyl)silane (OTS), lead(II) iodide (Pbl\(_2\)), dimethyl sulfoxide (DMSO), toluene anhydrous, chlorobenzene anhydrous (Sigma-Aldrich), chloroform (Samchun Pure Chemicals, Korea), poly(3,4-ethylenedioxythiophene)-poly(styrenesulfonate) (PEDOT:PSS) (H.C. Starck, Germany), methylammonium iodide (CH\(_3\)NH\(_3\)I) (1-material, Canada), \( \gamma \)-butyrolactone (GBL) (TCI, Japan), \( [6,6] \)-phenyl-C\(_{61}\)-butyric acid methyl ester (PC\(_{60}\)BM) (Nano-C), silver nanowires (AgNWs) (Nanopyxus, Korea), and SU-8 photoresist (MicroChem) were used without further purification.

#### Fabrication of ChNF Paper via Centrifugal Casting.

\( \beta \)-Chitin powder was dissolved in HFIP to prepare the 0.4% (w/v) \( \beta \)-chitin\//HFIP solution. Undissolved impurities in the chitin\//HFIP solution were filtered using a syringe filter to obtain the homogeneous chitin\//HFIP solution. A 120 mL homogeneous chitin\//HFIP solution (0.4% w/v) was poured into a rectangular plastic container, and then this solution-containing container was covered with an aluminum foil. To prepare 20 mL of chitin\//HFIP alcool (2.4% w/v), the covered plastic container was placed in a fume hood for 3 days. The resultant alcool-containing container was centrifugal-casted using a centrifuge Combifluor 514R (Hanil Science, Korea) at an optimized rotation speed (2100 rpm), time (3 h), and temperature (20 °C). As the calendering process for the as-casted ChNF paper, it was placed between OTS-treated glasses and compressed in a vacuum hot press instrument.

#### Preparation of Matrix Resin and HCLaminate.

A sol–gel reaction between ECTS and DPSD was used to synthesize the CAEO. ECTS and DPSD were blended according to the Si/phenyl molar ratio of 1:1:2 in a two-neck flask with a condenser and a stirrer. Then, 1 mol % of barium hydroxide monohydrate catalyst was added to the mixture. The reaction was performed at 80 °C for 6 h. After the reaction, the residual solvent and H\(_2\)O were removed by vacuum-pumping at 80 °C. After evaporation, clear and viscous CAEO was obtained. The CAEO was then mixed with 50 wt % of DOX and 2 wt % of triaryl sulfonium hexafluoroantimonate photocatalyst to prepare the matrix resin. The matrix resin-impregnated ChNF paper was placed between OTS-treated glasses and compressed in a vacuum bag compressing instrument for 1 min. After UV-curing of the sample for 8 min, the HCLaminate was acquired after removal of the glass plates.

#### Characterizations of HCLaminate.

SEM images were collected from a Nova 230 (FEI). FT-IR and XRD spectra were collected using an FT-IR 460 plus (Jasco, Japan) and a D/Max2500 (Rigaku, Japan), respectively. Phase and topographic AFM images were obtained using a Dimension 3100 (Veeco). Optical transparency was evaluated by both total and parallel transmittance spectra recorded with a UV 3101PC (Shimadzu, Japan) and a UV 2550 (Shimadzu, Japan), respectively. The stress–strain curves were measured on the basis of the ASTM-D882-12 standard with an AGS-X (Shimadzu, Japan) at the rate of 0.1 mm/min. The tensile test was performed five times on rectangular samples with a size of 6 × 50 mm\(^2\). TGA, TMA, and DMA profiles were obtained from a TGA Q50 (TA Instruments), a TMA/SS 6100 (Seiko Instruments, Japan), and a DMA 2980 (TA Instruments), respectively, with a temperature ramp rate of 5 °C min\(^{-1}\) in N\(_2\) atmosphere.

#### Fabrication and Characterization of Flexible Perovskite Solar Cells.

As a transparent electrode, IZO (160 nm) was deposited on the HCLaminate by radio frequency (RF) sputtering (RF power = 120 W) in vacuum (5 × 10\(^{-3}\) Torr) for 15 min. Fabricated flexible perovskite solar cells had the device structure of PEDOT:PSS (40 nm)/perovskite (270 nm)/PC\(_{60}\)BM (20 nm)/Ag (150 nm). Spin-coating of PEDOT:PSS onto the IZO/HCLaminate substrate was performed at a rotation speed of 4000 rpm for 30 s, and then the sample was dried at 140 °C for 15 min. Perovskite (CH\(_3\)NH\(_3\)I/Pbl\(_2\)) solution was obtained by dissolving CH\(_3\)NH\(_3\)I and Pbl\(_2\) according to a molar ratio of 1:1 in a blend of GBL/DMSO (7:3 v/v) at 70 °C for 12 h. The perovskite solution was consecutively spin-coated onto the as-coated PEDOT:PSS on the IZO/HCLaminate by a three-step process at 500, 1000, and 3000 rpm for 5, 10, and 40 s, respectively. Through the third coating step, a toluene droplet of ∼70 μL was dropped onto the prepared perovskite layer, and then the specimen was immediately annealed at 100 °C for 10 min. The 1 wt % PC\(_{60}\)BM/chlorobenzene solution was spin-coated on the perovskite layer at 3000 rpm for 45 s. Ag layer was deposited on the shadow mask-covered PC\(_{60}\)BM layer by thermal evaporation in vacuum (10\(^{-7}\) Torr). A reference device was fabricated on the ITO (75 nm)/PET substrate. The \( J–V \) curves of the fabricated flexible solar cells were collected in the range of 1.0 to −0.2 V by a solar simulator K201 LAB55 (McScience, Korea) under irradiance of 100 mW cm\(^{-2}\) from a 150 W Xe short-arc lamp filtered by an attenuation of 1.5 G filter. Calibration of light intensity was performed by using a Si reference cell K801S-K302 (McScience, Korea). The illuminated area was clearly defined by attaching an aperture mask of 8.75 mm\(^2\) onto the device.

#### Fabrication of the Touch-Screen Panel.

To prepare the transparent electrodes of substrate layers, the AgNWs dispersed in distilled water were spin-coated onto the HCLaminate. After coating the electrodes, the SU-8 photoresist was spin-coated at a rotation speed of 3000 rpm for 30 s on the AgNWs-coated HCLaminate.
Deposition of Au interconnects (50 nm) were performed by using thermal evaporation in vacuum (10⁻⁶ Torr) on the AgNWs-coated HCLaminates (bottom and top substrates), which were covered by a shadow mask. The top and bottom substrates were assembled and connected to an integrated circuit board (Touch Display, Korea) and a desktop computer.

**ASSOCIATED CONTENT**

## Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acsami.7b03126.

Reaction mechanisms, FT-IR and XRD spectra, additional cross-sectional SEM and SEM-EDS Si mapping images; additional AFM images, derivative weight loss profile, isothermal TGA results, total transmittance spectra for the IZO-deposited HCLaminate and bending test results; a digital photograph, SEM image, and total transmittance spectra for the AgNWs-coated HCLaminate; summary tables of critical and elastic moduli, CTE, and photovoltaic parameters (PDF)

Stable operation of the fabricated touch-screen panel device (AVI)

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**Notes**

The authors declare no competing financial interest.

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