Optically Transparent Wood Substrate for Perovskite Solar Cells
Yuanyuan Li,†,‡,*,†, Ming Cheng,∥,*, Erik Jungstedt,† Bo Xu,‡ Licheng Sun,*,‡ and Lars Berglund†
†Wallenberg Wood Science Center, Department of Fibre and Polymer Technology, School of Engineering Sciences in Chemistry, Biotechnology and Health (CBH), KTH Royal Institute of Technology, Teknikringen 56-58, SE-100 44 Stockholm, Sweden
∥Institute for Energy Research, Jiangsu University, 301 Xuefu Road, Zhenjiang 212013, P. R. China
‡Organic Chemistry, Centre of Molecular Devices, Department of Chemistry, School of Engineering Sciences in Chemistry, Biotechnology and Health (CBH), KTH Royal Institute of Technology, Teknikringen 42, SE-100 44 Stockholm, Sweden
*Supporting Information

ABSTRACT: Transparent wood is a candidate for use as an energy-saving building material due to its low density (ca. 1.2 g/cm³), high optical transmittance (over 85% at 1 mm thickness), low thermal conductivity (0.23 W m⁻¹ K⁻¹), and good load-bearing performance with tough failure behavior (no shattering). High optical transmittance also makes transparent wood a candidate for optoelectronic devices. In this work, for the first time, perovskite solar cells processed at low temperature (<150 °C) were successfully assembled directly on transparent wood substrates. A power conversion efficiency up to 16.8% was obtained. The technologies demonstrated may pave the way for integration of solar cells with light transmitting wood building structures for energy-saving purposes.

KEYWORDS: Biocomposite, Perovskite solar cell, Energy-Efficient, Building material, Transparent wood, Mechanical properties

INTRODUCTION
It has been predicted that the energy consumption in the world will increase by 48% and carbon dioxide emissions by 34% from 2012 to 2040.¹ The building sector accounts for over 30% of the total energy consumption and carbon dioxide emissions, leading to an urgent need for more energy-efficient buildings.² Integration of clean energy technologies with conventional building structures is a promising development. Photovoltaics, which convert solar energy into direct current electricity through semiconducting materials, are becoming increasingly attractive.³ Commercial technologies are dominated by crystalline silicon solar cells and thin film solar cells. They are based on high-purity, single-crystalline semiconductors and therefore rely on high-temperature manufacturing processes. Although the price of solar cell-based electricity is dropping, even lower cost and higher power conversion efficiency (PCE) are desirable. Perovskite solar cells (PSCs) have attracted great attention since the first work in 2009 due to the high PCE, easy processability, possible low processing cost, and so on.⁴,⁵ Even though with the rapid development of PSCs, some challenges still remain such as stability, toxicity, scale-up technologies, and sustainability.

The substrate is a key component for solar cells, which determines the end-use of the products and influences the sustainability of final solar cell products. Glass and plastics are commonly used substrates for solar cells. However, using low cost materials from renewable resources as the substrates is of great interest due to the goal of sustainability. In addition, as a building material, glass shows limitations because of the high brittleness and high thermal conductivity.

Wood is by far the most important structural material from renewable resources, and it is to a large extent used in construction for load-bearing applications.⁶ The potential of using wood as a substrate for functional materials has been discussed in the literature.⁷⁻⁹ One limitation for application of wood-based materials in photovoltaics is that wood is not transparent, although wood-based cellulose paper or nano-cellulose paper/films have been studied as substrates or functional light management layers in solar cell structures.¹⁰,¹¹ One reason for low optical transmittance of wood is the light scattering at the interfaces between the cell wall tissue and the
empty pore space ("lumen") in wood cells (e.g., cells such as tracheids, wood fibers, and vessels). In addition, the presence of strongly light absorbing polymers (mainly lignin) in the cell wall is a problem.\textsuperscript{12} Transparent wood was originally prepared in 1992 for wood morphology studies.\textsuperscript{13} Recently, efforts were developed to combine optical transparency with mechanical performance for light-transmitting, energy-efficient building applications.\textsuperscript{14−18} In recent reviews, the progress of transparent wood technology was discussed in detail.\textsuperscript{7,9,19} Transparent wood exhibits high optical transmittance and haze (over 70%). The high haze is interesting to be used for light directing for solar cells, which is demonstrated by the Hu group.\textsuperscript{20} However, studies of using transparent wood directly as the substrate for solar cell are rare.

In the present study, transparent wood was for the first time used as the substrate for solar cells. PSCs with PCE up to 16.8% were prepared directly on transparent wood substrates using a low temperature process (<150 °C). Figure 1 shows a sketch of the transparent wood preparation procedure and the PSC assembly on a transparent wood substrate.

**RESULTS AND DISCUSSION**

The lack of transparency in wood is mainly due to the porous lumen space at the center of fibers, tracheids, and vessel cells, with diameters in the order of tens of micrometers. In addition, lignin, tannins, and other phenolic compounds absorb light through chromophoric groups. Lignin is the main component contributing to the brownish wood color.\textsuperscript{19} To make wood...
transparent, the wood was first delignified with NaClO₂ and then infiltrated with a refractive index matched polymer, poly(methyl methacrylate) (PMMA). Figure 2a shows the transparent wood microstructure in cross section, and the lumen pore space is filled by the polymer. In Figure 1, the photo of transparent wood specimens on top of a leaf is shown, demonstrating the optical transparency.

To validate that transparent wood is a suitable substrate for solar cell applications, materials and device characterization was performed. Optical properties were first studied. Figure 2b shows the optical transmittance and haze spectra of transparent wood. A high optical transmittance of 86% was demonstrated at a wavelength of 550 nm and a thickness of 1.0 mm, which met the requirements for a substrate for solar cells. At the same time, transient wood shows a haze of around 70% in the visible light range. Haze is the ratio between diffused light transmittance to total transmittance (diffused + direct). The haze of 70% means that diffused transmittance dominates despite high optical transmittance. The inset image in Figure 2b demonstrates the light diffusion pattern after the beam has passed through transparent wood. High haze should be favorable for solar cells since the light path in the active layer is increased. This was demonstrated by attaching transparent wood on top of a solar cell, with an improved energy conversion efficiency of 18%.²⁰

Mechanical property is important for solar cell substrates, since it influences the end performance of the device. Mechanical tests were performed in uniaxial tension by control of the displacement rate. Each specimens had 3 mm deep notches on each side of the specimen edge, double edge notched (DEN). The initial crack was generated by a sharp steel blade. Earlier work on elastic property characterization, rather than toughness, was carried out on transparent wood from balsa.¹² The fracture toughness has not been studied. The critical stress intensity factor $K_c$ (a measure of initiation of crack propagation) at the peak load is a measure of the fracture toughness of the composite.²¹

The critical stress intensity factor $K_c$ for DEN specimens was estimated according to eq 1:

$$K_c = \sigma_0 \sqrt{\pi a f_4 \left( \frac{a}{w} \right)}$$

where $f_4 \left( \frac{a}{w} \right)$ is a geometry dependent function.²¹ $\sigma_0$ is determined at peak load. Since transparent wood is anisotropic, two different cases are studied as shown in Figure 2c. Loading is applied either parallel to the fiber direction (longitudinal tangential, LT) or perpendicular to fiber direction (tangential longitudinal, TL). Tensile stress–strain curves of notched transparent wood DEN specimens and PMMA are shown in Figure 2d. The $K_c$ value for PMMA is 1.48 MPa m⁻¹/², which is comparable with the literature (around 0.9−1.70 MPa m⁻¹/²).²² Transparent wood LT shows a higher $K_c$ value of 3.2 MPa m⁻¹/². This is due to the orientation of the reinforcing wood template skeleton in the composite. Fibers are oriented perpendicular to the plane of the initial crack notch. The wood-PMMA bond integrity appears favorable at the sub-micrometer scale (Figure 2e), which leads to good microscale load transfer in the composites. In addition, the softer bio composite structure with nanocellulosic cell walls and a polymer matrix phase leads to tougher failure mode compared with glass, which may show brittle fracture (shattering) leading to potential safety problems. Transparent wood TL demonstrates lower initiation $K_c$ value of 0.67 MPa m⁻¹/², even lower than that of the neat polymer phase. Figure 2f shows the crack propagation pattern in transparent wood.
samples. In transparent wood TL, the crack is progressing straight between the notches following the weakest plane in the biocomposite. For transparent wood LT, the crack most likely started at the notch on the right-hand side and then deviated from the plane perpendicular to the loading direction. The reason is the lower toughness for cracks growing along the fiber direction. Although the fracture toughness $K$ is lower in the TL direction, the problem can be addressed by lamination of transparent wood layers as in a plywood structure.23 In comparison with glass ($K$ is $0.7−0.85$ MPa m$^{1/2}$ for soda-lime glass),24,25 transparent wood shows higher fracture toughness. Even in the weakest direction, the fracture toughness of transparent wood is comparable to that of glass.

The toughness criterion provides an argument for transparent wood as a replacement for glass as solar cell substrate. In addition, transparent wood shows much better thermal insulation properties than glass. Transparent wood has a lower thermal conductivity (0.23 W m$^{-1}$ K$^{-1}$) than glass (1.0 W m$^{-1}$ K$^{-1}$).26 Low thermal conductivity contributes to the energy requirements reduction for air-conditioning systems and lower thermal energy exchange between indoor and outdoor environments. Another strong argument is that wood is from renewable resources and may substantially reduce the carbon footprint associated with building structures. Overall, transparent wood is potentially suitable as a load-bearing substrate for solar cells and shows advantages over glass in energy-efficient buildings.

Transparent wood is nonconductive. Therefore, in order to assemble a solar cell on transparent wood, a transparent conductive layer with sufficient conductivity is required.27,28 In this work, an indium tin oxide (ITO) film was deposited by pulsed laser deposition. Optical transmittance data showed a decrease due to the deposition of the ITO layer, although there was little in optical haze before and after ITO deposition (Figure 3a). Figure 3a inset image shows that a light green color appears after ITO deposition on transparent wood. The surface roughness of the substrate is important for solar cell assembly. Low surface roughness will increase the conductivity of the coated ITO layer and decrease the risk for pin-holes. The transparent wood substrate described here demonstrated a surface roughness of 30 nm within the scanning area of 5 $\mu$m $\times$ 5 $\mu$m. After ITO deposition, the surface roughness changed to a nominal value of 9 nm (Figure 3b), which is comparable with fluorine doped tin oxide (FIO)-glass that is commonly used for solar cell assembly. A perovskite solar cell was then successfully assembled on the ITO-coated transparent wood. The detailed device structure is transparent wood substrate/ITO/compact TiO$_2$/(FAPbI$_3$)$_{0.85}$(MAPbBr$_3$)$_{0.15}$/Spiro-OMeTAD/Au as shown in Figure 1. In fabricated devices, the compact TiO$_2$ layer (40−50 nm thick) functions as electron transport material (ETM), and Spiro-OMeTAD (around 150 nm thick) functions as hole transport material (HTM). A mixed perovskite (FAPbI$_3$)$_{0.85}$(MAPbBr$_3$)$_{0.15}$ (around 450 nm thick) was used as the light harvesting material. The morphologies of the compact TiO$_2$ perovskite layer, and Spiro-OMeTAD are shown in Figure 3c−e. A flat dense perovskite film is observed from Figure 3d. The perovskite film is fully covered by a uniform Spiro-OMeTAD layer (Figure 3e), which is very important for restricting the charge recombination in PSCs. It should be noted that low temperature processing was adapted in order to avoid thermal degradation of the transparent wood substrate.29

![Image of Current density–voltage properties of PSCs](image-a)

**Figure 4.** (a) Current density–voltage properties of PSCs (scan rate: 20 mV/s). (b) IPCE spectra of PSC. (c) Steady-state current density and PCE at max power output points (0.82 V). (d) The PCE histogram chart of the devices (a batch of 20 cells).
The photovoltaic performance of transparent wood substrate-based PSC is presented in Figure 4, and the relevant data are collected in Table 1. The perovskite-based solar cells on transparent wood substrates exhibited the highest PCE of 16.8% at 100 mW/cm² AM 1.5 G simulated irradiation with a short current density ($J_{sc}$) of 21.9 mA·cm⁻², an open circuit voltage ($V_{oc}$) of 1.09 V, and a fill factor (FF) of 70.2% (Figure 4a), which are slightly lower than that of FTO-glass based PSCs (PCE of 18.9%, $J_{sc}$ of 24.2 mA·cm⁻², $V_{oc}$ of 1.10 V, FF of 71.1%) (Figure S1 in Supporting Information). The lower $J_{sc}$ of transparent wood substrate-based PSC can be mainly ascribed to the lower transmittance of conductive transparent wood substrate than that of FTO-glass. The above results indicate that transparent wood could be an interesting candidate for ecofriendly solar cell substrates with a reduced carbon footprint.

From the incident-photon-to-current conversion efficiency (IPCE) spectrum (Figure 4b), it can be concluded that PSCs display a very wide photoelectric response to the solar spectrum with a long wavelength limit at around 800 nm, consistent with the band gap of the (FAPbI₃)₀.₈₅(MAPbBr₃)₀.₁₅ well. The steady-state power output characteristic at the maximum power point was further investigated, and the results are shown in Figure 4c. The transparent wood substrate-based PSC showed a steady-state current density of 20.3 mA·cm⁻² and a PCE of 16.6% under 0.82 V bias, respectively, matching well with the photocurrent–voltage ($J$–$V$) measurement. The histogram chart (Figure 4d) demonstrates a high reproducibility of the devices (a batch of 20 cells). Over 50% of the manufactured devices obtained a PCE exceeding 15.5%.

Long-term stability is a crucial concern for practical applications of perovskite solar cells. Figure 5 shows the $J_{sc}$, $V_{oc}$, FF, and PCE as a function of time for the transparent wood-based PSCs, in which the devices were kept under air conditions in the dark. It was found that the devices could retain 77% of its initial performance after 720 h of aging, showing a good long-term stability.

**CONCLUSION**

Transparent wood shows high optical transmittance and haze, good mechanical properties, a smooth surface, and a low thermal conductivity. This makes it suitable as a substrate for solar cell assembly with potential in energy-efficient building applications. For the first time, perovskite solar cells with a power conversion efficiency up to 16.8% were successfully assembled on optically transparent wood substrates, using a low temperature process below 150 °C. The devices also showed good long-term stability. Our results suggest that transparent wood is a substrate candidate for assembly of sustainable solar cells to replace glass and lower the carbon footprint for the device. Through molecular and nanoscale materials design of the transparent wood substrate, transmittance and haze can be optimized, so that higher solar cell efficiency can be anticipated.
EXPERIMENTAL SECTION

All the experimental information is present in the Supporting Information.

ASSOCIATED CONTENT

Supporting Information

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AUTHOR INFORMATION

Corresponding Authors

*(L.S.) E-mail: lichengs@kth.se.
*(Y.L.) E-mail: yua@kth.se.

ORCID

Yuanyuany Li: 0000-0002-1591-5815
Ming Cheng: 0000-0003-0793-0326
Licheng Sun: 0000-0002-4521-2870
Lars Berglund: 0000-0001-5818-2378

Author Contributions

*(L.S.) and *(Y.L.) contributed equally to this work.

Notes

The authors declare no competing financial interest.

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