

Supporting information

Highly efficient and stable semi-transparent perovskite solar modules with a trilayer anode electrode

Kun-Mu Lee^{1,2,3*}, Kai-Shiang Chen¹, Jia-Ren Wu⁴, Yan-Duo Lin^{5*}, Sheng-Min Yu⁶ and Sheng Hsiung Chang^{4,*}

¹Department of Chemical and Materials Engineering, Chang Gung University, Taoyuan 33302, Taiwan, ROC

²Division of Neonatology, Department of Pediatrics, Chang Gung Memorial Hospital, Linkou, Taoyuan 33305, Taiwan, ROC

³Center for Reliability Sciences and Technologies, Chang Gung University, Taoyuan 33302, Taiwan, ROC

⁴Department of Physics, Chung Yuan Christian University, Taoyuan 32023, Taiwan, ROC

⁵Department of Applied Chemistry, National Chiayi University, 60004 Chiayi, Taiwan, ROC

⁶Material and Chemical Research Laboratory, Industrial Technology Research Institute, Hsinchu 31040, Taiwan ROC

Corresponding author:

Sheng Hsiung Chang, E-mail: shchang@cycu.edu.tw

Kun-Mu Lee, E-mail: kmlee@mail.cgu.edu.tw

Yan-Duo Lin, E-mail: ydlin@mail.ncyu.edu.tw

Telephone: +886-3-265-3208; Fax : 886-3-265-3299

Synthesis of CT

A heterogeneous mixture of 2 M K₂CO₃ (5 mL), THF (6 mL), **1** (1.00 g, 1.75 mmol), **2** (0.28 g, 0.83 mmol), and Pd(PPh₃)₄ (0.038 g, 4 mol%) under argon was heated at 80 °C for 18 h. The mixture was extracted with CH₂Cl₂. The organic layer was dried over anhydrous MgSO₄. Evaporation of the solvent gave a crude product, which was purified by silica gel column chromatography eluted with CH₂Cl₂/hexane (1/1) to

afford the desired product as a yellow solid in 70% yield. mp 100-102 °C; ¹H NMR (400 MHz, DMSO-*d*₆, δ): 7.45 (d, *J* = 8.4 Hz, 4H), 7.42 (s, 2H), 7.03 (d, *J* = 8.2 Hz, 8H), 6.91 (d, *J* = 8.2 Hz, 8H), 6.76 (d, *J* = 8.4 Hz, 4H), 3.95 (t, *J* = 6.4 Hz, 4H), 3.65 (s, 2H), 1.77-1.82 (m, 4H), 1.47-1.51 (m, 4H), 1.35-1.40 (m, 8H), 0.94 (t, *J* = 6.8 Hz, 6H) ppm; ¹³C NMR (100 MHz, DMSO-*d*₆, δ): 156.4, 150.8, 148.1, 144.1, 140.3, 136.22, 127.2, 126.2, 120.0, 118.8, 117.1, 115.5, 67.7, 33.8, 30.9, 28.6, 25.2, 22.0, 13.8 ppm; HRMS (FAB) *m/z* [M⁺] calcd for C₆₉H₈₀O₄N₂S₂: 1065.5166; found: 1065.5160.

Synthesis, optical and electrochemical properties

The synthetic route of **CT** is illustrated in **Fig. S1**, and the experimental details are provided in the Experiments section. The **CT** molecule was obtained following a simple synthetic route. *P*-hexthoxytriphenylamine pinacboronates (**1**) and 2,6-dibromo-4*H*-cyclopenta-[2,1-*b*:3,4-*b'*]dithiophene (**2**) were introduced by Suzuki coupling reaction to obtain di-substituted derivative **CT** in good yield. This compound was purified by column chromatography and characterized by ¹H/¹³C NMR spectroscopy and mass spectrometry.

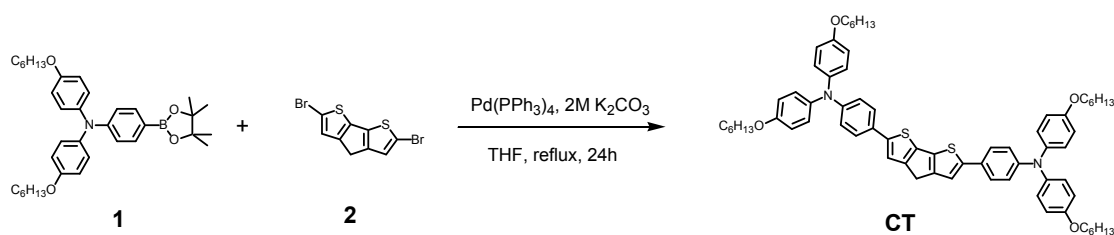


Fig. S1. Synthetic route for the **CT** molecule.

Figure S2 presents the absorption and photoluminescence (PL) spectra of **CT** molecules in a chlorobenzene solution (ca. 1x10⁻⁵ M). The absorption spectrum of **CT**

has two prominent peaks at 303 nm and 445 nm. The emission peak of CT locates at 509 nm. The optical band gap (E_{0-0}) was estimated from the intersection of the corresponding normalized absorbance and PL spectra. The intersection wavelength of CT is 482 nm, which corresponds to an optical bandgap of 2.57 eV.

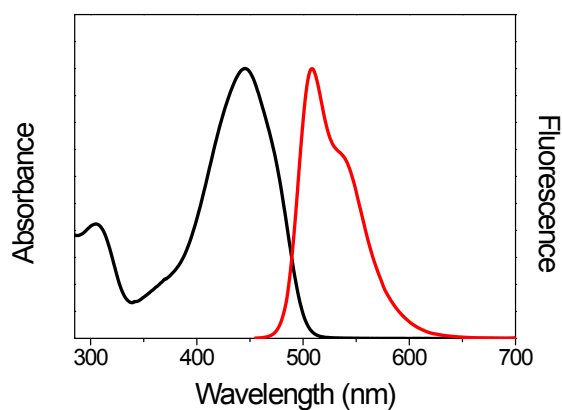


Fig. S2 Absorption (black line) and emission (red line) spectra of the CT molecules in a chlorobenzene solution (1×10^{-5} M).

Cyclic voltammetry (CV) and differential pulse voltammetry (DPV) analyses were carried out to identify the electrochemical behaviors of CT molecules. As shown in Figure S3, CT displays reversible multi-oxidative behavior. The HOMO energy level is obtained at -5.17 eV for CT, which is slightly larger than the E_{VBM} (-5.43 eV) of $\text{CH}_3\text{NH}_3\text{PbI}_3$, as shown in Figure S4.

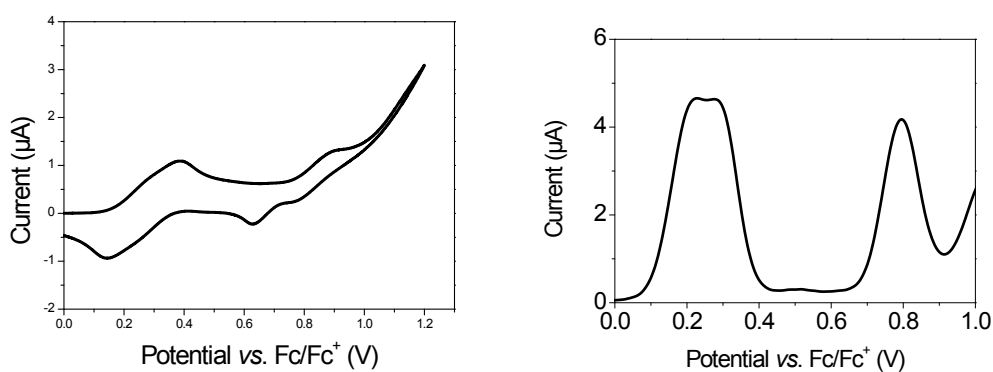


Fig. S3. Cyclic voltammograms and differential pulse voltammetry of CT measured at a sweep rate of 100 mV/s in THF solution.

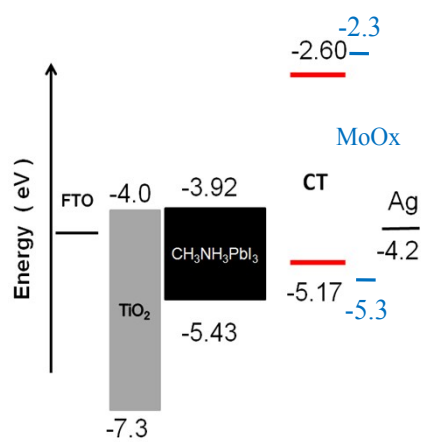


Fig. S4. Energy level diagram of the hole-transporting materials used in perovskite solar cells.

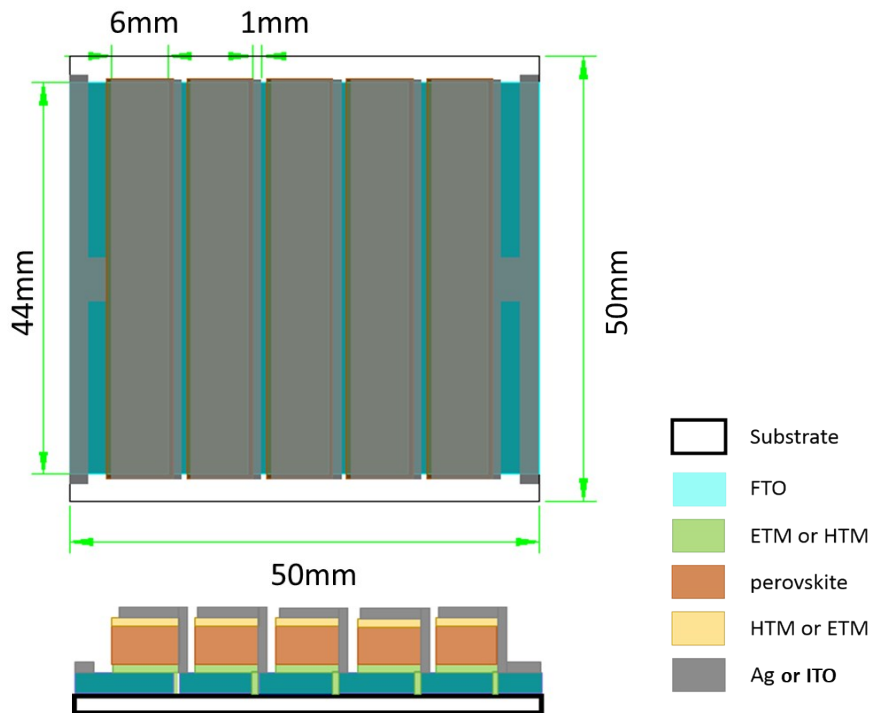


Fig. S5. Schematic of perovskite solar module.

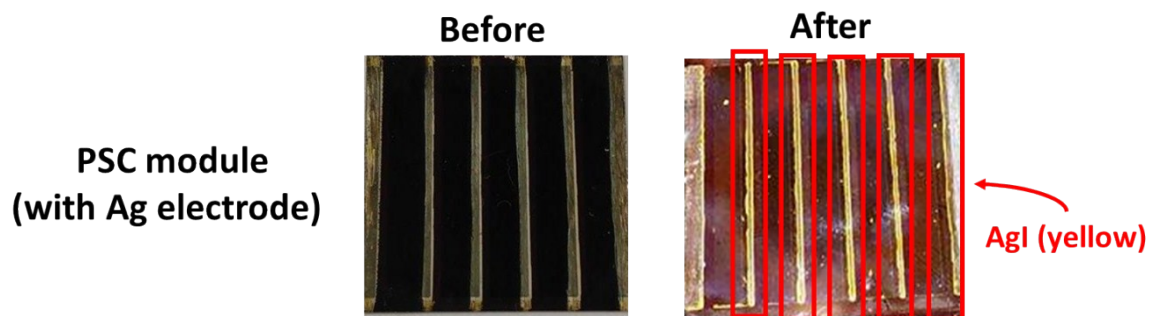


Fig. S6. Photo images of perovskite solar module with Ag electrode under a wet environment ($26^{\circ}\text{C}\pm 2^{\circ}\text{C}$ and 70 ± 5 RH%) when $t=0$ (before) and $t=250$ hours (after) .

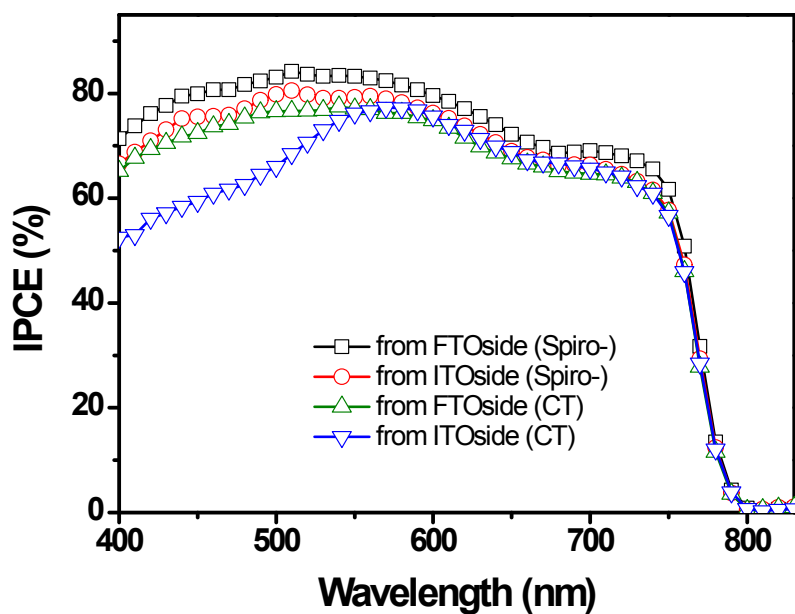


Fig. S7. The IPCE of perovskite solar cells measured from FTO side and ITO side.

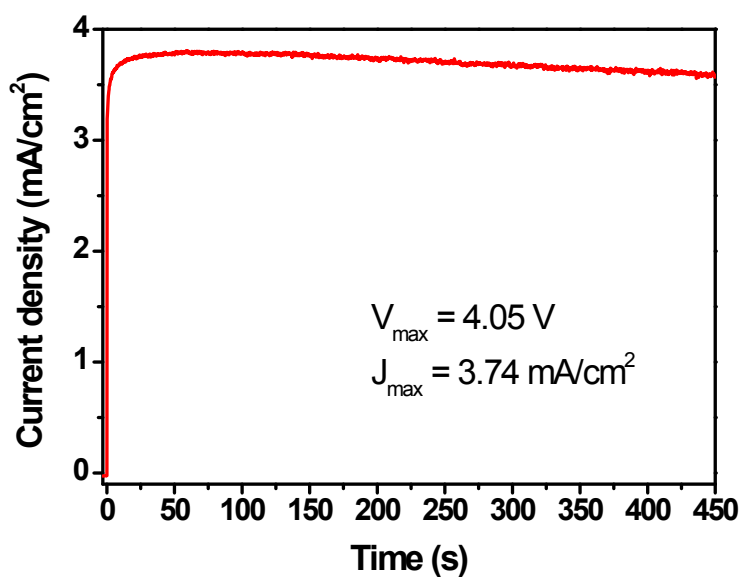


Fig. S8. The maximum power point tracking of an ITO/MoO_x/CT based perovskite solar module under one sun illumination.