Supporting Information

Bifacial, Color-Tunable Semitransparent Perovskite Solar Cells for Building Integrated Photovoltaics

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Table S1. Summary of colourful opaque and semi-transparent (Semi-T) perovskite solar cells.

Opaque/ Semi-T	Structure	Color generation	Detail structure	Color tunability	PCE	Ref
Opaque	p-i-n	Reflective color from rear Al side, perovskite's domain grain structure generates vivid ring color	ITO glass/PTAA/CH3NH3PbI3/PCBM/C_{60}/BCP/Al	vivid color with ring patterns	12.2% (illumination from font side)	[1]
opaque	n-i-p	Reflective color from front FTO side, using porous photonic crystal	FTO glass/TiO2-SiO2 NPs alternated layers/$CH_3NH_3PbI_{3-x}Cl_x$/spiro-OMeTAD/Au	red, orange, green, green-blue, blue	4.5% (red) to 8.8% (blue)	[2]
opaque	n-i-p	Reflective color from front FTO side, using luminescent down-shifting (LDS) layers	LDS layer/FTO glass/TiO2/perovskite/spiro/Au	red (with efficiency), other colors on-going	9.4% (red)	[3]
opaque	p-i-n	reflective color from front ITO side, Localized resonances in ultrathin metal nano-strip optical resonators consisting of an array of metallic subwavelength nanowires on a transparent substrate	Ag nano figures patterned nanoresonators/ITO glass/NiOx/CH3NH3PbI_3/PCBM/ZnO/Al(80nm)	red, green, blue	7.72% (blue) to 10.12% (red)	[4]
Semi-T	n-i-p	Transmissive color, microstructured arrays of perovskite "islands"	FTO glass/TiO_2/perovskite/spiro-OMeTAD/thin Au (10nm)	Neutral color	5% to 11% for different AVT	[5]
Semi-T	n-i-p	Transmissive color, perovskite thickness tuning	ITO glass/PCBM/CH3NH3PbI3/spiro-OMeTAD/MoO3/Ag/MoO3	Brownish color	3.5% to 9.23%	[6]
Semi-T	p-i-n	transmissive color, tune perovskite thickness	ITO glass/PEDOT or CuSCN/$CH_3NH_3PbI_3$/PCBM/Bis-C60/Ag (20nm)	Brown-orange	7.53% to 10.73%	[7]
Semi-T	p-i-n	Transmissive color, optical cavity (Ag/WO_3/Ag, tune WO_3 thickness)	ITO glass/PEDOT:PSS/PCBM/PTCBI/Ag/WO_3/PTCBI/Ag	blue, green, red	3.18% (green) to 3.86% (red)	[8]

Semi-T	p-i-n	Transmissive color, optical cavity (Ag/ITO/Ag, tune ITO thickness)	ITO glass/PEDOT:PSS/Perovskite/PCBM/Ag/ITO/Ag	reddish-orange, yellow, yellow-green, yellowish-green, green, greenish-blue	5.7% (blue) to 7.2% (yellow, orange)	[9]
Semi-T	n-i-p	transmissive color, multilayer dielectric mirror (TiO2-SiO2 multilayers), tune incident angle	glass/TiO2-SiO2 multilayers/ITO(200 nm)/$CH_3NH_3PbI_3$/PCBM/ZnO NPs/ITO	cyan, violet, magenta, orange, red	10.12% (max)	[10]
Semi-T	p-i-n	transmissive color, based on phase-compensated optical microcavities (Ag/SiO2/ZnS/Ag/ZnS, tune middle ZnS cavity layer thickness)	ITO glass/NiOx/CH3NH3PbI_3/PCBM/BCP/Ag/SiO_2/ZnS/Ag/ZnS	red, green, blue	10.47% (red), 10.66% (green), 11.18% (blue)	[11]
Semi-T	n-i-p	Reflective color from PEDOT side, transfer-printed PEDOT:PSS layer thickness tuning	glass/FTO/c-TiO2/m-TiO2/$CH_3NH_3PbI_{3-x}Cl_x$/HTL(spiro-OMeTAD or P3HT)/PEDOT:PSS	Almost across entire visible spectrum	best 13.8 % (green-yellow) for PEDOT side	[12]
Semi-T	p-i-n	reflective color, via separated Dielectric Mirrors deposited on microscope glass	ITO glass/PEDOT:PSS/Perovskite/PCBM/ZnO/AgNW/dielectric mirror	red, dark blue, light blue, neutral transparent	3% to 3.6%	[13]

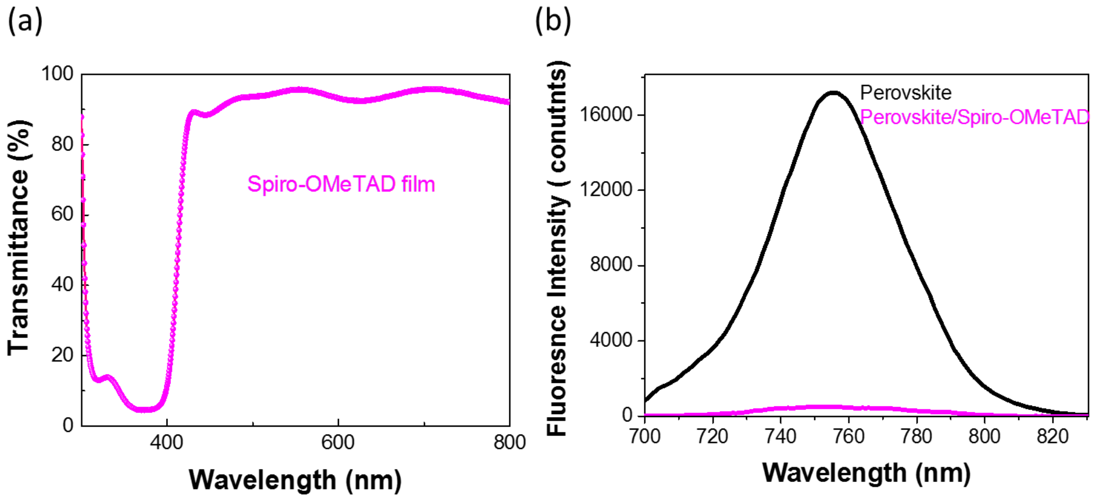

Figure S1: (a) Transmittance spectrum of Spiro-OMeTAD films, and (b) Steady-state photoluminescence spectra of perovskite films with and without HTM (Spiro-OMeTAD).

Table S2 Steady-state photoluminescence quenching efficiency of perovskite films with CuSCN or Spiro-OMeTAD as HTM.

Sample	PL Quenching Efficiency
Perovskite/CuSCN	0.90
Perovskite/Spiro-OMeTAD	0.97

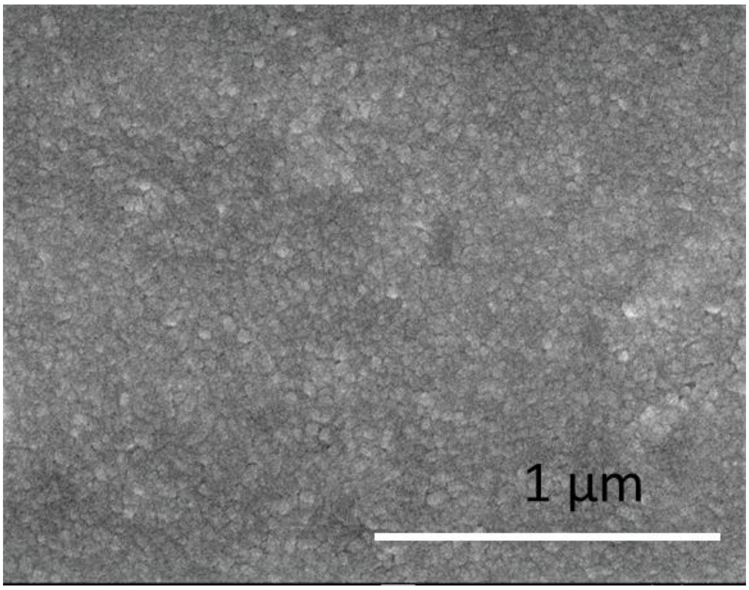

Figure S2: Top-view FESEM image of CuSCN film coated on top of perovskite layer

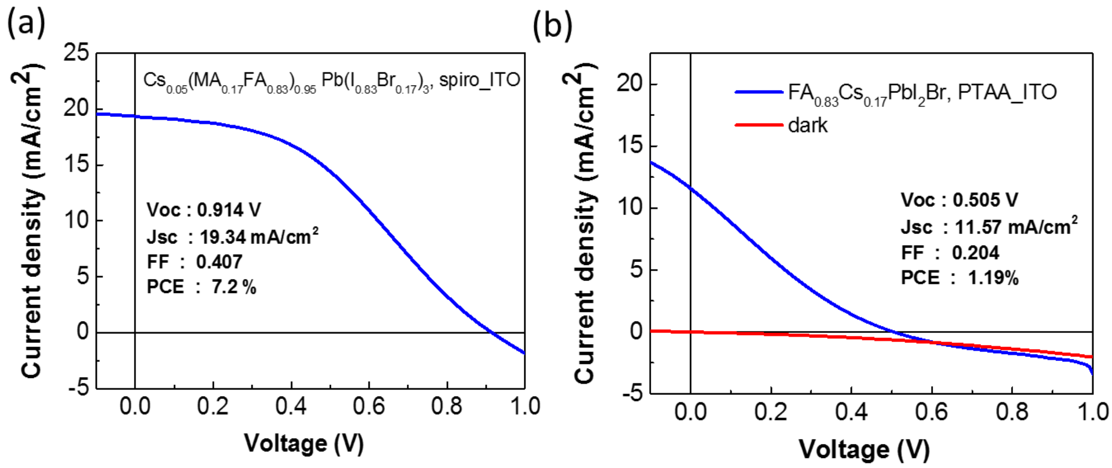

Figure S3: J-V characteristics of semi-transparent cells based on different perovskite absorber and HTMs using direct sputtered ITO as rear transparent electrode. (a) $Cs_{0.05}(MA_{0.17}FA_{0.83})_{0.95}$ $Pb(I_{0.83}Br_{0.17})_3$ as absorber, Spiro-OMeTAD as HTM, (b) $FA_{0.83}Cs_{0.17}PbI_2Br$ (Bandgap is ~1.72 eV) as absorber, PTAA as HTM.

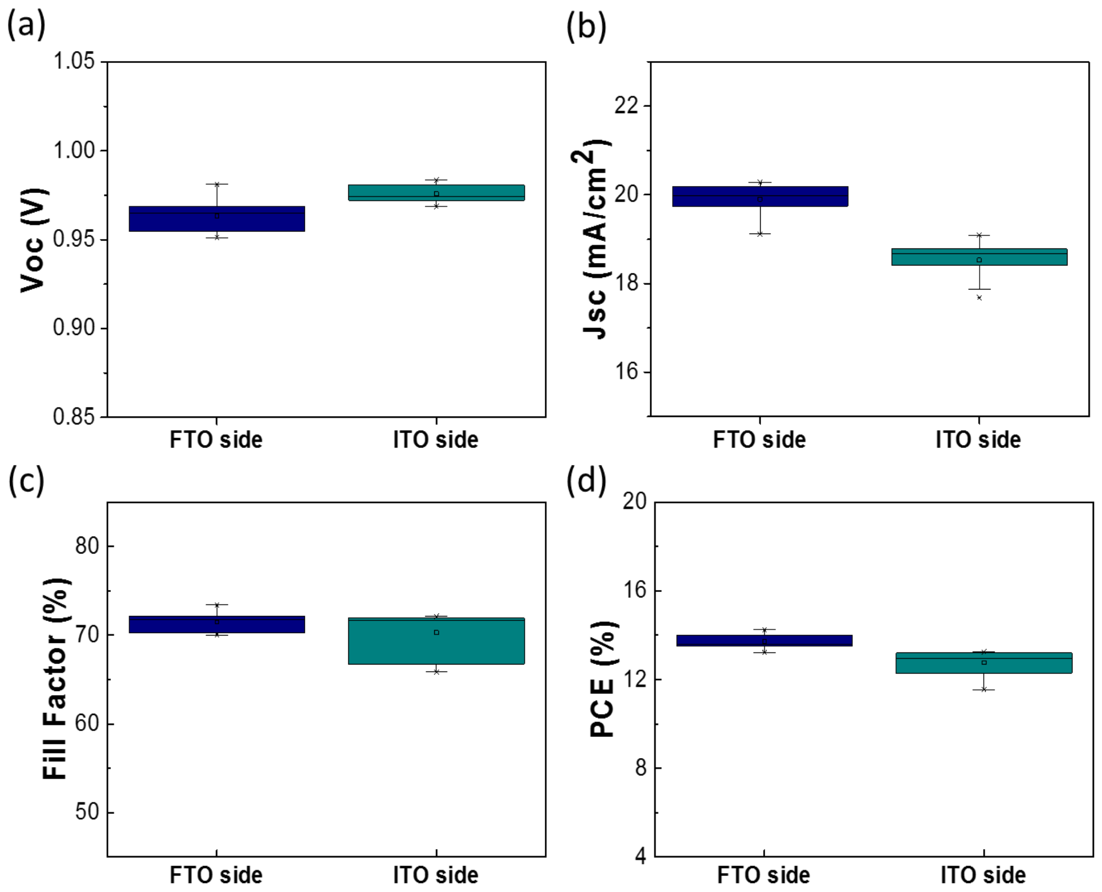

Figure S4: Statistics of photovoltaic characteristics of bifacial ST-PSCs using CuSCN as HTM. (a) Voc, (b) Jsc, (c) fill factor, (d) PCE. (FTO side: ST-PSCs tested with light illumination from front FTO side; ITO side: ST-PSCs tested with light illumination from rear ITO (back) side.

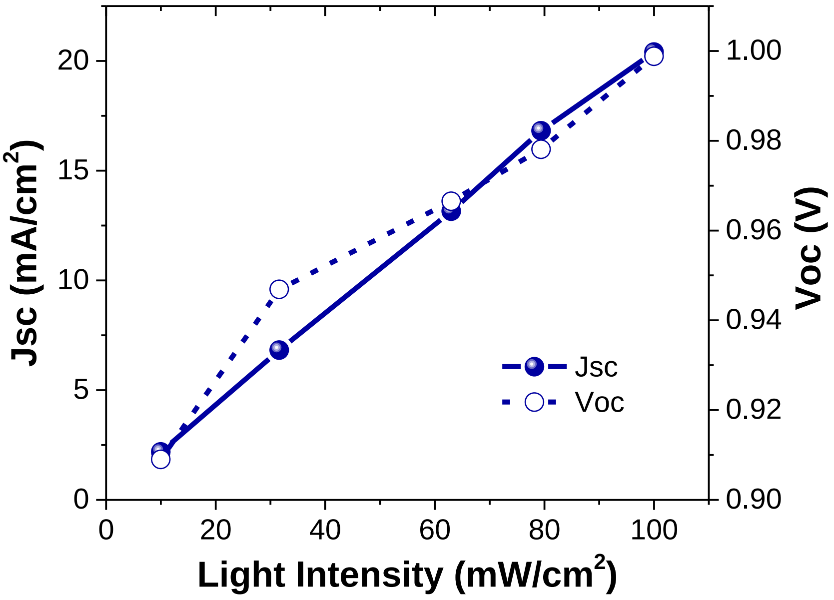

Figure S5: Photocurrent density (solid line and symbol) and Photovoltage (dashed line and open symbol) as a function of light intensity of CuSCN based PSC.

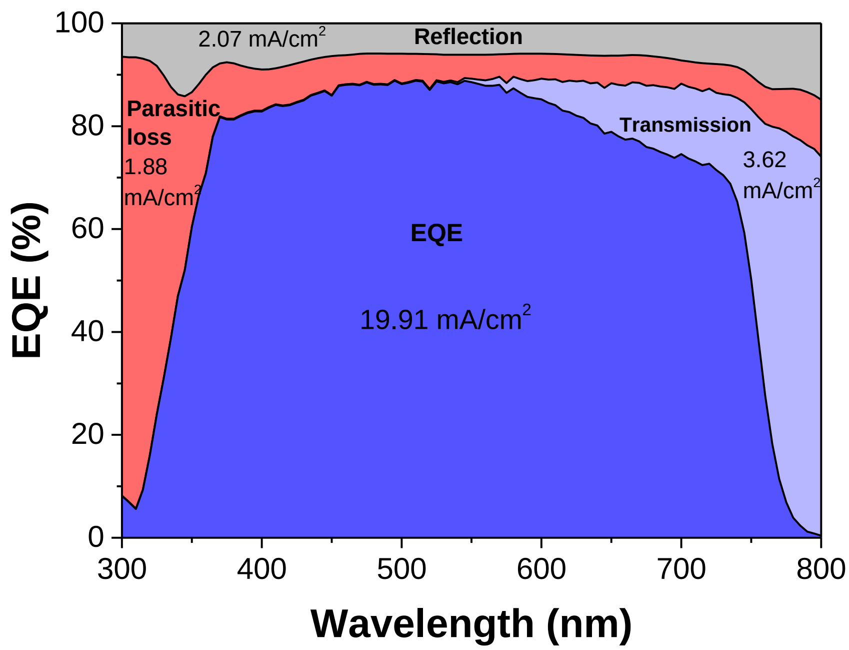

Figure S6: Optical analysis of the CuSCN ST-PSCs: EQE spectra, reflection, transmission and parasitic losses in CuSCN based ST-PSC illuminated from front FTO side. No anti-reflection coating (ARC) is applied on FTO substrate. There is about 6 % reflection loss in the visible region for the bifacial ST-PSCs, giving rise to a photocurrent loss of 2.07 mA/cm2 for 300-800nm.

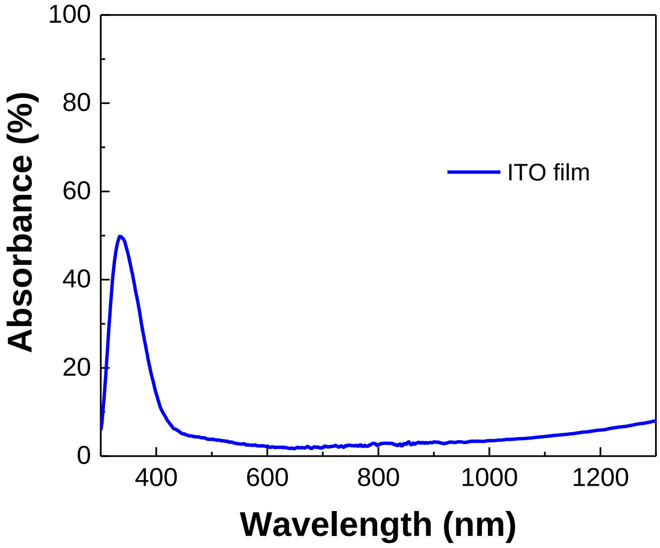

Figure S7: Absorbance of ITO film deposited on glass excluding the glass absorption.

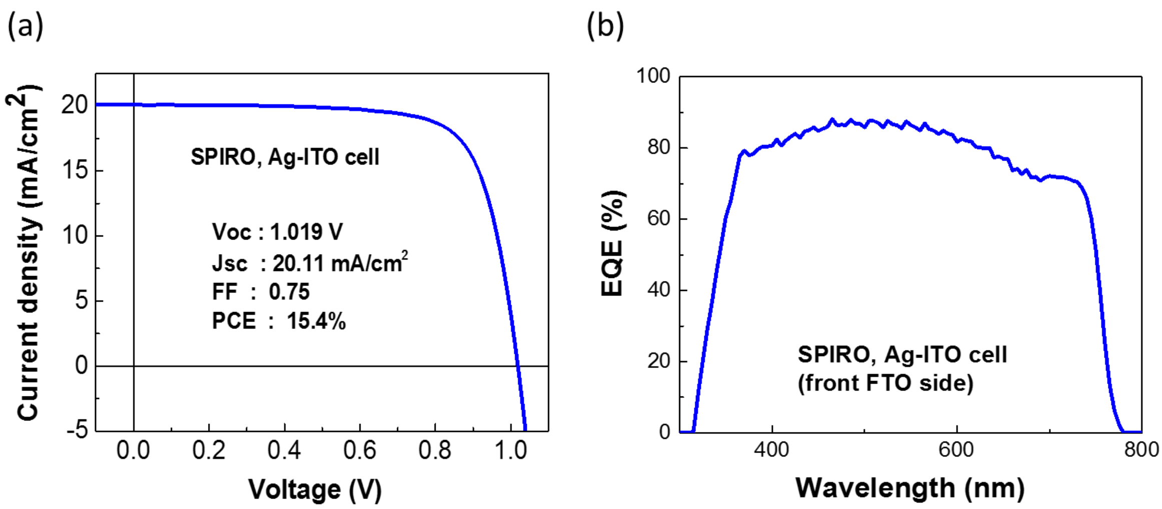

Figure S8: (a) Current-voltage (J-V) curves under 1-sun illumination and (b) EQE spectra of bifacial ST-PSC based on Spiro-OMeTAD. A thin Ag layer (1nm) was used as buffer layer prior to ITO sputtering deposition to protect the underlying layers from the sputter damage.

Table S3 Testing details of bifacial performance measurement of ST-PSCs. The background reflection with White Paper as back reflector is evaluated by using a power meter to measure the reflected light intensity from backside. The reflection albedo (RA) was obtained as the ratio between the background reflection and the standard 1 SUN illumination.

	Power (@550nm), using power meter	Calculated Reflection Albedo(RA), using white paper
1 SUN, calibration	103.0 mW	
With white paper, D =1.5 cm	34.7 mW	33.7%
With white paper, D =3cm	56.0 mW	54.4%

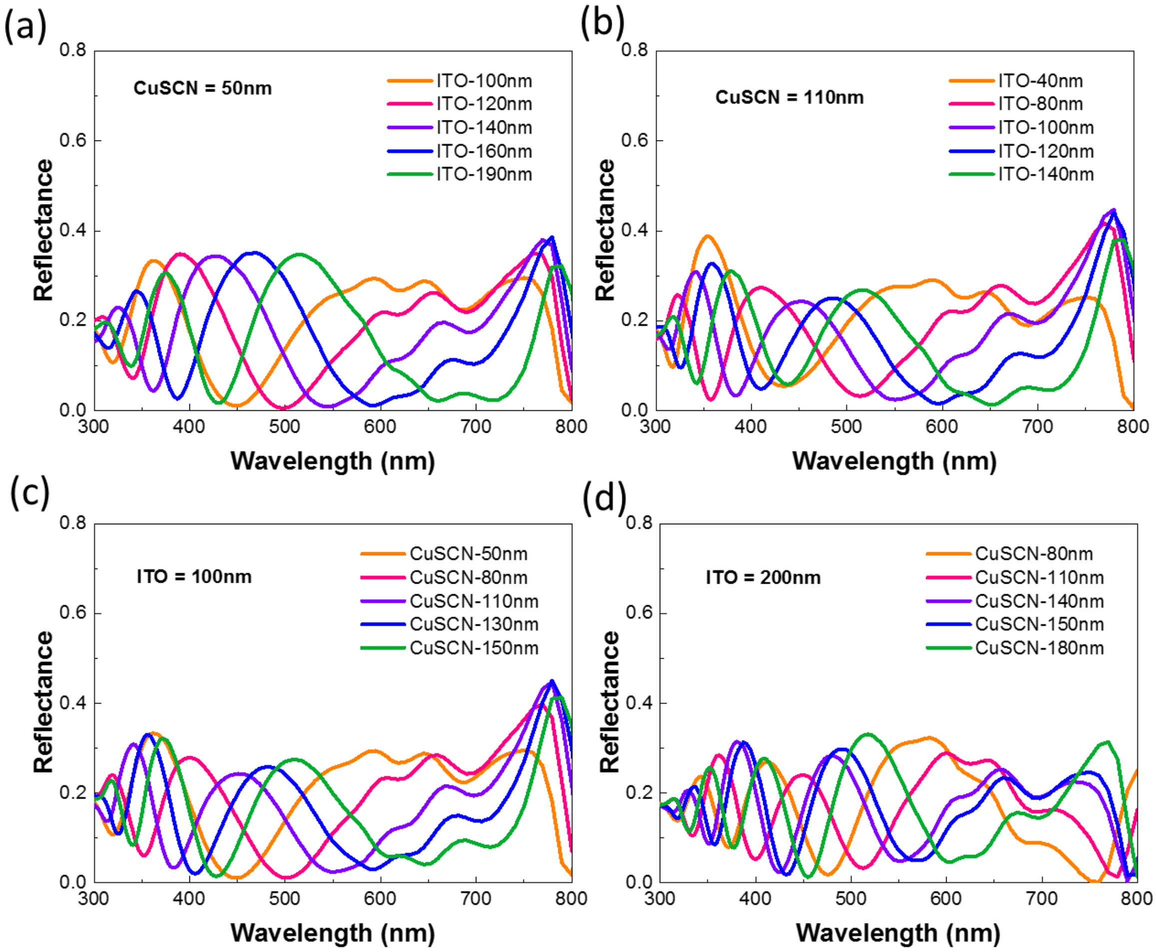

Figure S9: The reflectance spectra of the simulated CuSCN ST-PSCs with orange, pink, purple, blue and green color respectively, for (a) CuSCN = 50nm, with different ITO thickness, (b) CuSCN = 110nm, with different ITO thickness; (c) ITO = 100nm, with different CuSCN thickness, and (d) ITO = 200nm, with different CuSCN thickness.

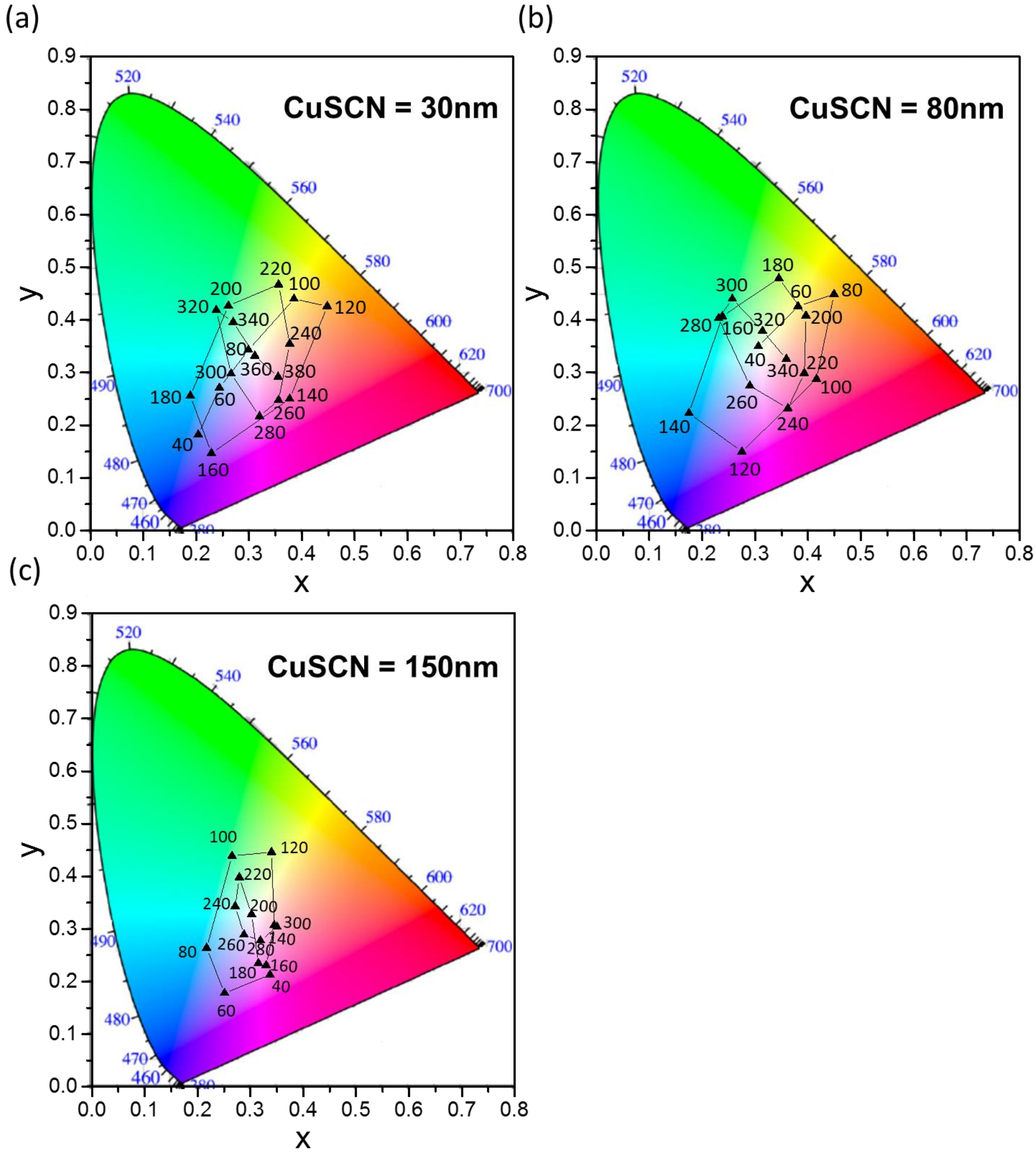

Figure S10: Color coordinates (x, y) representation in the CIE 1931 chromaticity diagram of optical simulated light reflectance spectra of CuSCN ST-PSCs from ITO electrode side based on a fixed bottom layer stack: FTO(400nm)/TiO2(50nm)/Perovskite(500nm)/CuSCN/ITO. (a) CuSCN = 30nm, with different ITO thickness. (b) CuSCN = 80nm, with different ITO thickness. (c) CuSCN = 150nm, with different ITO thickness.

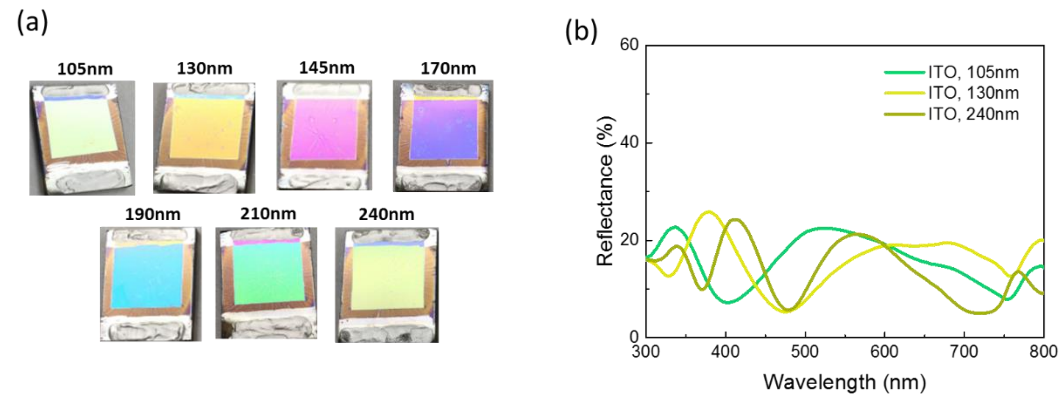

Figure S11: (a) Photographs of fabricated CuSCN-based colourful ST-PSCs with different ITO thicknesses, showing various physical colour against indoor LED light (photo taken from ITO side). (b) The reflectance spectra of the cells with ITO thickness of 105nm (green-yellow), 130nm (yellow-brown), 240nm (yellow-green) and 320nm (pink-purple).

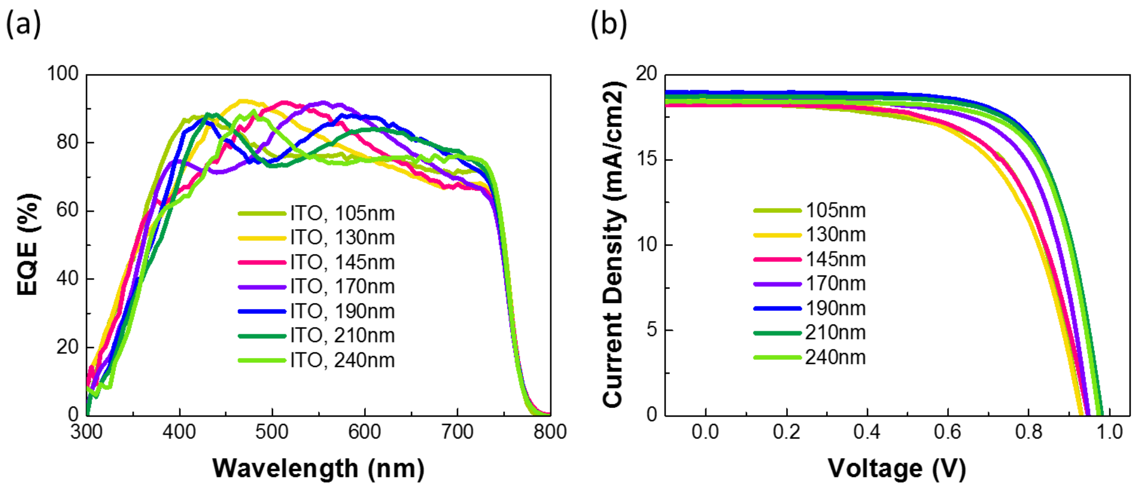

Figure S12: (a) Back EQE spectra and (b) Current-voltage characteristics of bifacial ST-PSC when illuminated through ITO side for various ITO thicknesses.

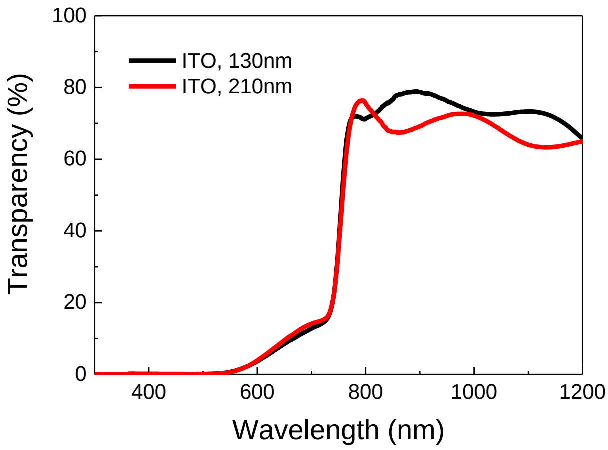

Figure S13: Transmission spectra of CuSCN ST-PSCs full device with rear ITO electrode of two different thickness of 130 nm and 210 nm.

References

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