Electronic Supplementary Information (ESI)

Highly Robust and Stable Graphene-Encapsulated Cu-Grid Hybrid Transparent Electrode Demonstrating Superior Performance in Organic Solar Cells

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Table S1. Optical transmittance and sheet resistance of the Cu grid and Cu grid/graphene with various geometry.

Cu grid	Transmittance [%]	R_{sh} [Ω/sq]
D100W3	89.7	6.02
D100W5	87.2	4.37
D100W10	76.7	2.13
D200W3	95.8	9.78
D200W5	93.6	6.19
D200W10	87.5	5.08
D300W3	97.3	10.8
D300W5	95.4	7.40
D300W10	91.0	5.76
D100W3/GR	87.2	4.45
D200W3/GR	93.5	8.54
D300W3/GR	94.9	9.60

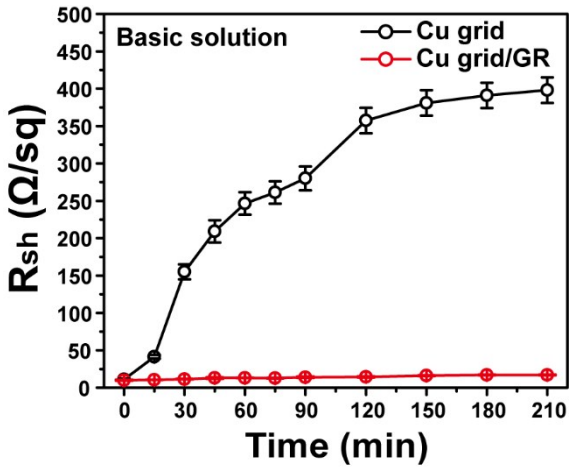

Fig. S1. Change in sheet resistance of the pristine Cu grid and Cu grid/graphene exposed to basic condition of 0.5 M sodium cholate solution.

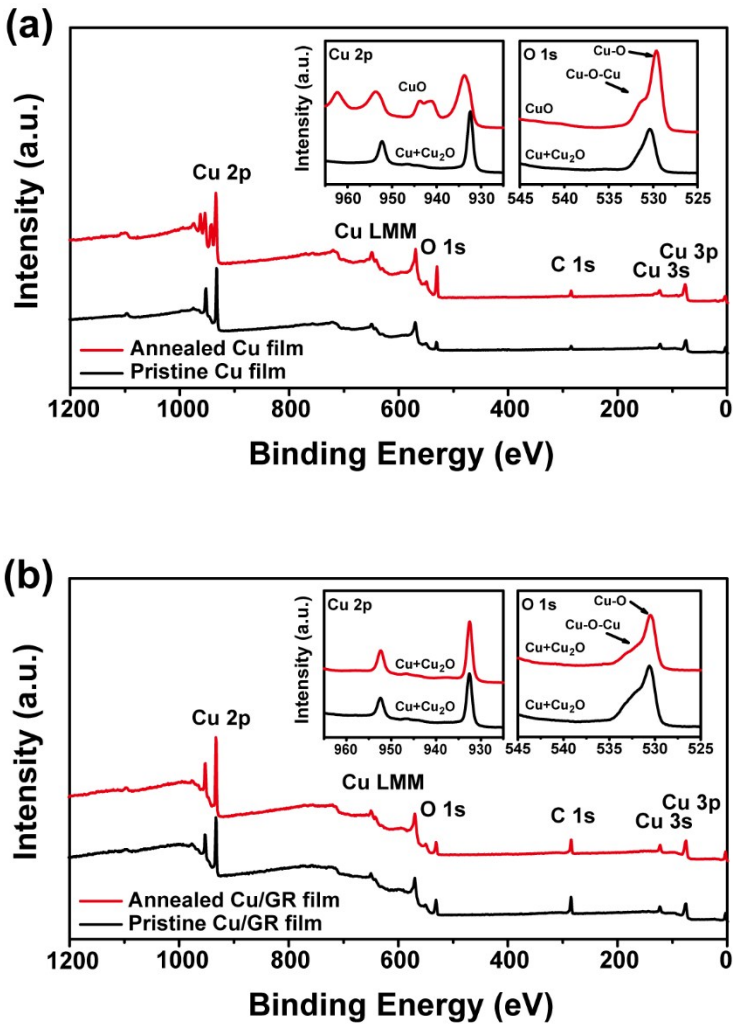

Fig. S2. Chemical composition analysis of the Cu film and Cu/graphene film. (a) XPS spectra of the pristine Cu films and annealed Cu films at 240 ˚C and 50% relative humidity for 10 min. (b) XPS spectra of the pristine Cu/graphene film and annealed the Cu/graphene film at 240 ˚C and 50% relative humidity for 10 min.

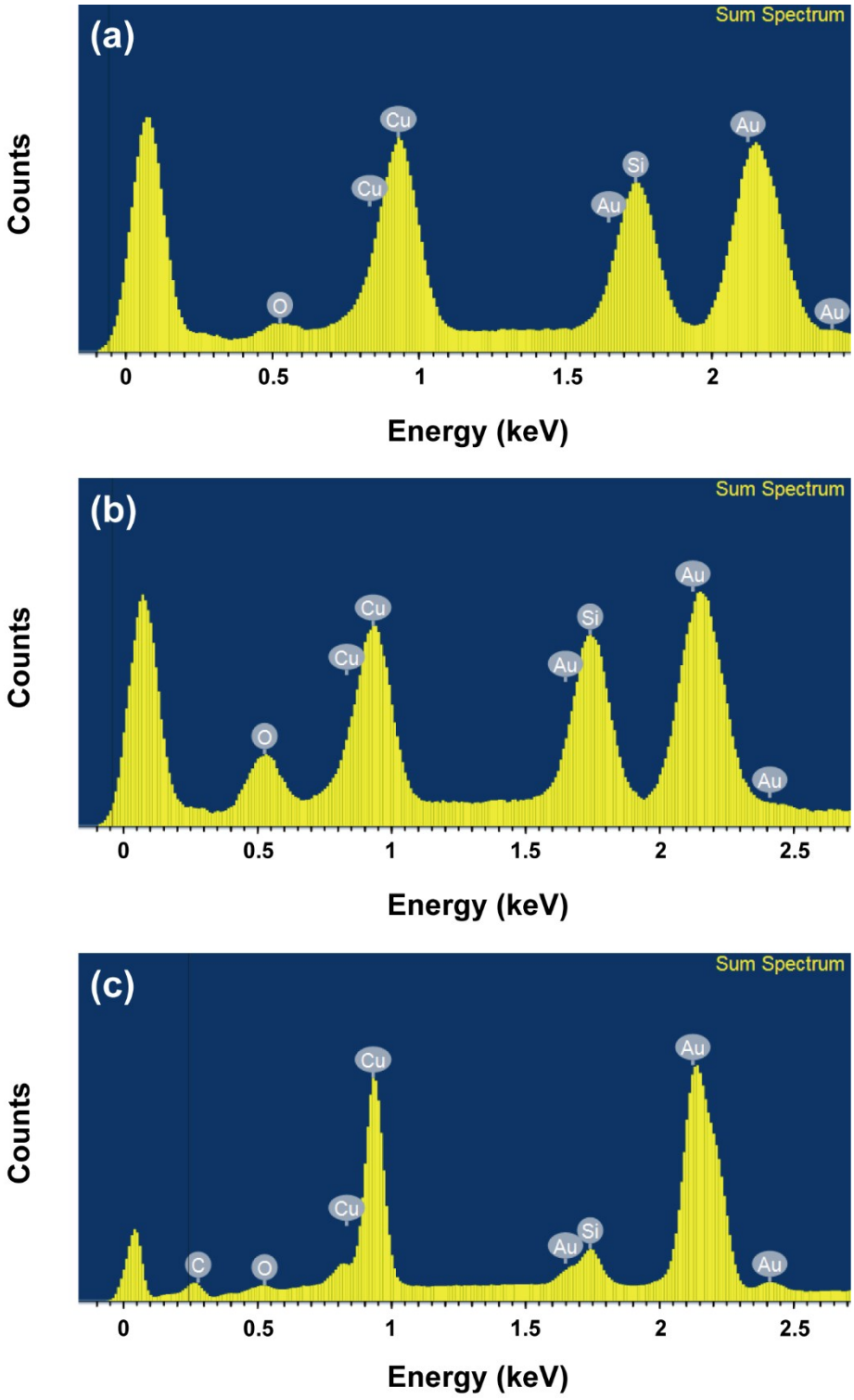

Fig. S3. EDS spectra of the Cu grid and Cu grid/graphene. (a) Pristine Cu grid. (b) Annealed Cu grid and (c) annealed Cu grid/graphene at 240 ˚C for 10 min in ambient air condition.

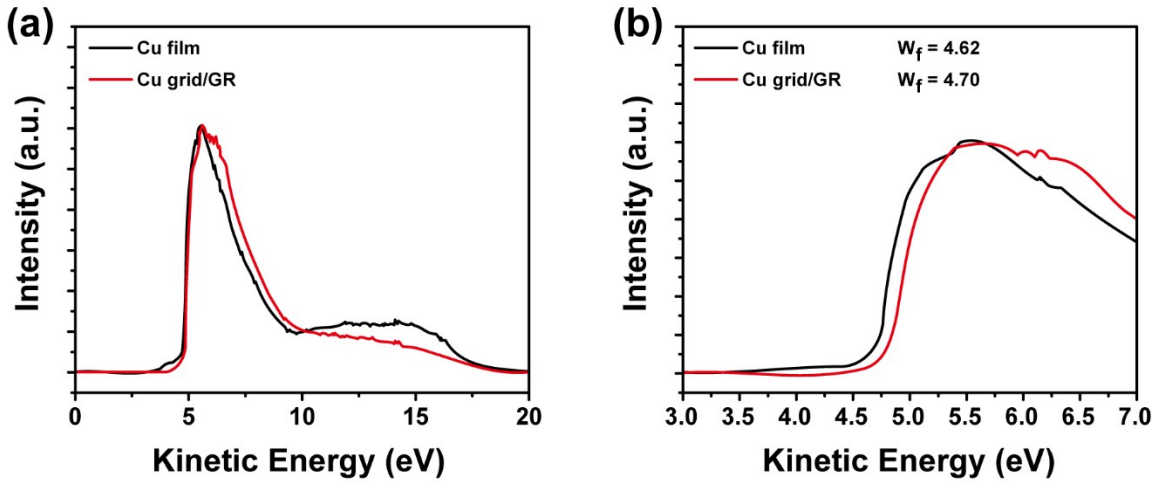

Fig. S4. (a) UPS spectra of the Cu film and Cu grid/graphene. (b) Secondary electron cut-off region of the UPS spectra.

Table S2. Comparison of the OSC performances based on metal transparent electrodes.

Transparent electrode	Transmittance	Width, Spacing	R_{sh} [Ω/sq]	PCE [%]	Ref
Ag grid/conducting polymer	85%	3 μm, 130 μm (Hexagon)	6.1	1.36	1
Au mesh	84%	70 nm, 700 nm × 10 μm (Rectangle)	24	1.96	2
Ag mesh	78%	70 nm, 700 nm × 10 μm (Rectangle)	23	2.00	2
Cu mesh	83.5%	3.0 μm (Circle)	28.7	2.04	3
Cu mesh	83%	70 nm, 700 nm × 10 μm (Rectangle)	28	2.06	2
Conducting polymer/Ag grid	93.1%	70 μm, 1.1 mm (Grid bar)	8.7	2.8	4
Ag mesh	-	65–85 μm, 300 nm (Square)	-	2.82	5
Ag grid/conducting polymer	85%	5 μm , 50 μm (Square)	2.8	3.21	6
Ag grid-graphene/conducting polymer	93%	2 μm, 200 μm (Square)	55	3.8	7
Au grid-graphene	89%	4.5 μm, 150 μm (Square)	97	4.38	8
Ag mesh	88.1%	150 nm, 1.6 μm (Square)	7.5	7.25	9
Ag mesh/conducting polymer	-	10 μm, 212 μm (Square)	16	7.8	10
Ag mesh	86%	5 μm, 45 μm (Square)	17	8.18	11
Cu grid/graphene	94.9%	3 μm, 300 μm (Hexagon)	9.60	8.5	**Our work**

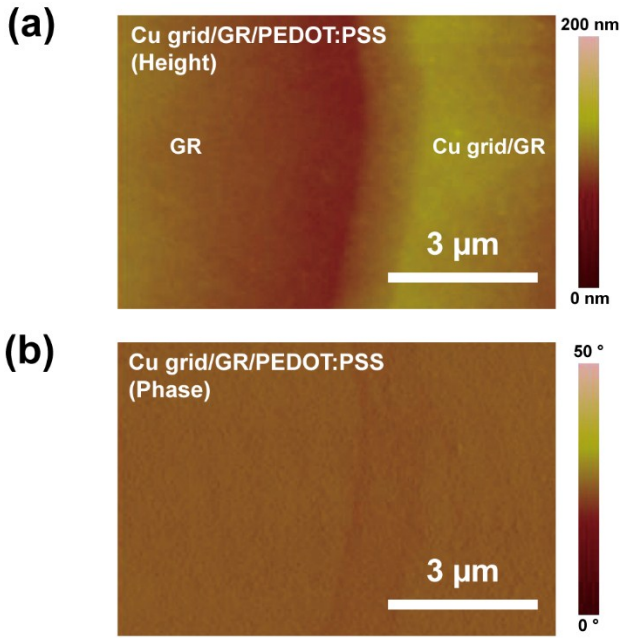

Fig. S5. Surface morphology characterization of Cu grid/graphene/PEDOT:PSS. (a) The AFM height image and (b) AFM phase image of Cu grid/graphene/PEDOT:PSS morphology.

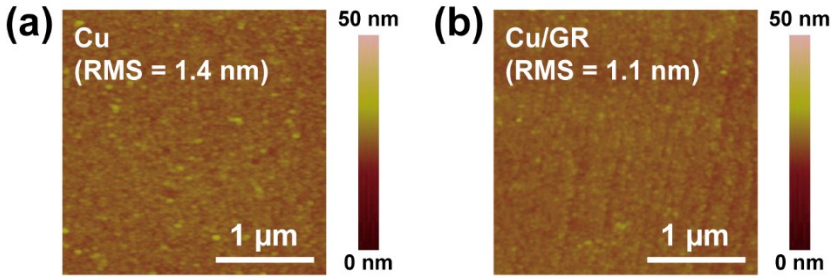

Fig. S6. AFM images of (a) Cu film and (b) Cu film/graphene. Comparison of RMS roughness Cu film and Cu film/graphene.

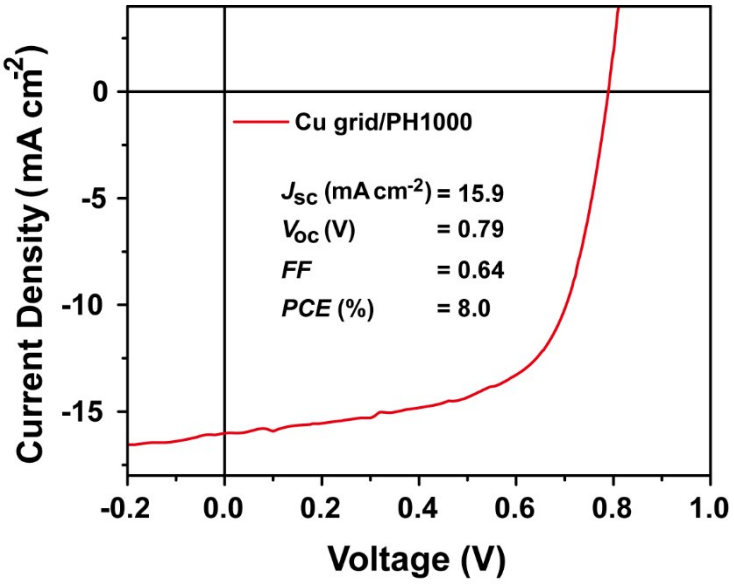

Fig. S7. *J–V* characteristic of the PTB7-Th:$PC_{71}BM$-based OSCs using Cu grid/PH1000 electrode.

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