

## **Supporting Information**

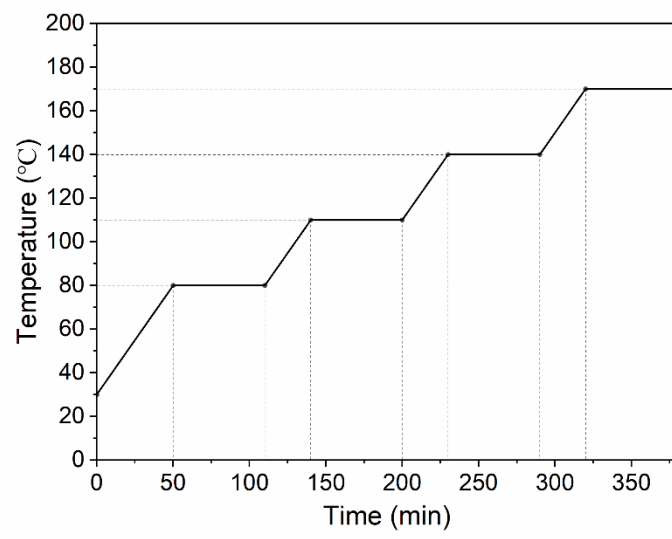
# **Citric Acid Modified Semi-Embedded Silver Nanowires/Colorless Polyimide Transparent Conductive Substrates for Efficient Flexible Perovskite Solar Cells**

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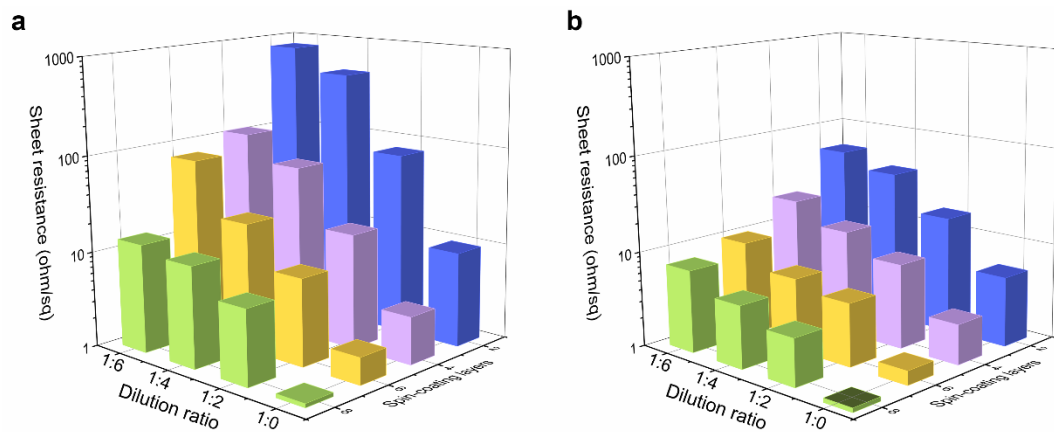
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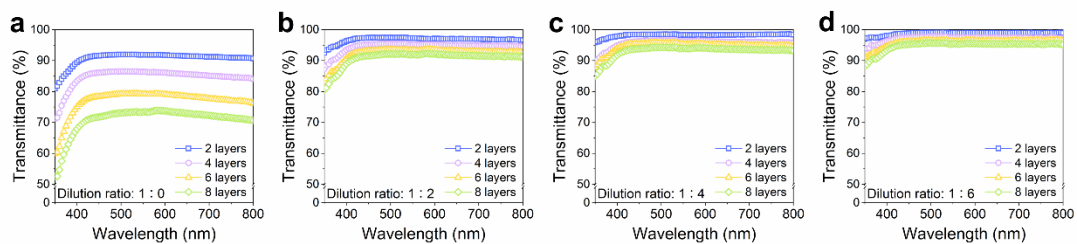


**Figure S1** Temperature-time curve of gradient heating process.

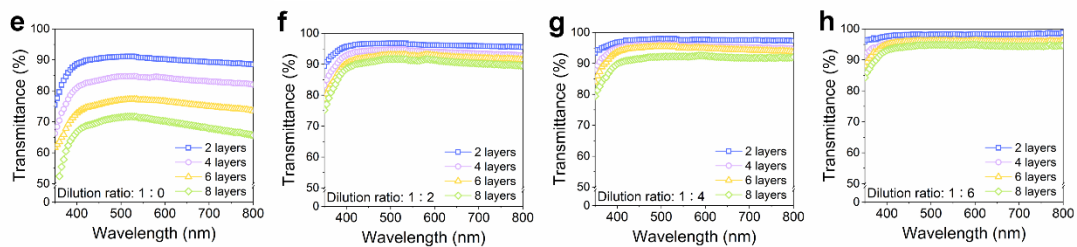


**Figure S2** Sheet resistance of AgNWs/glass samples for (a) 20 μm AgNWs and (b) 100 μm AgNWs with various AgNWs suspension dilution ratios and spin-coating layers.

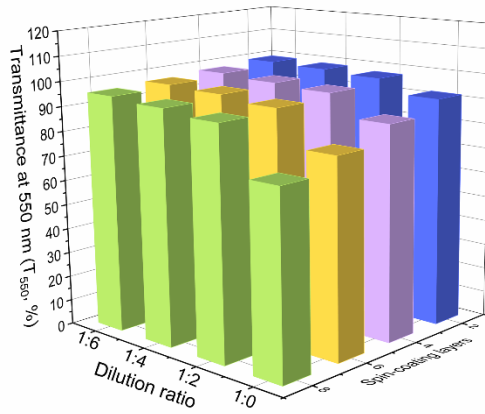
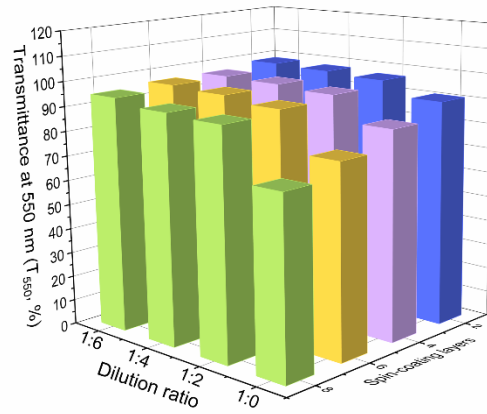
### 20 $\mu\text{m}$ length AgNWs:



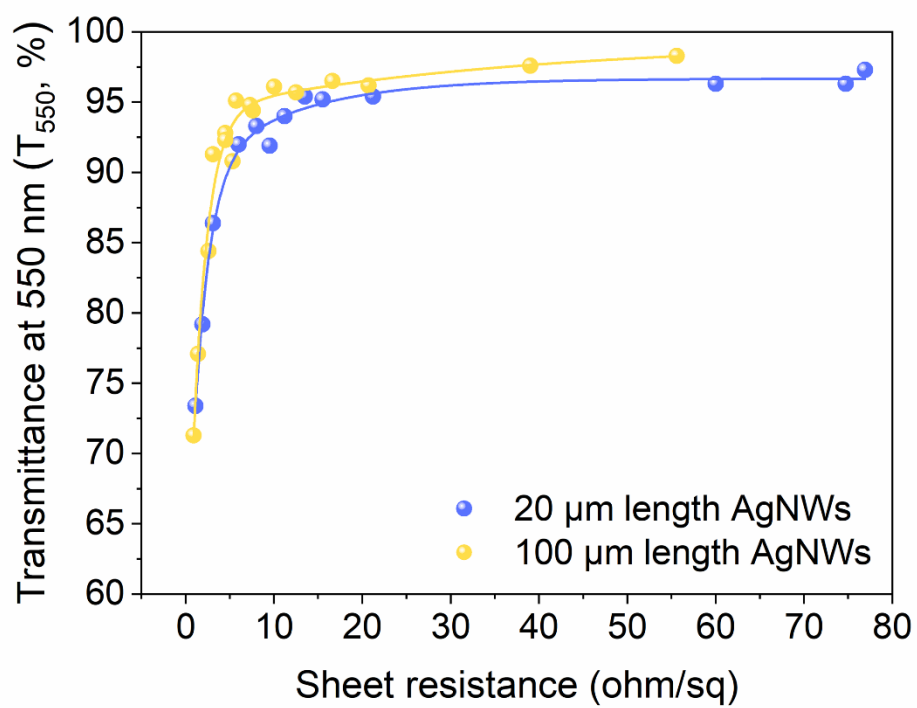
### 100 $\mu\text{m}$ length AgNWs:



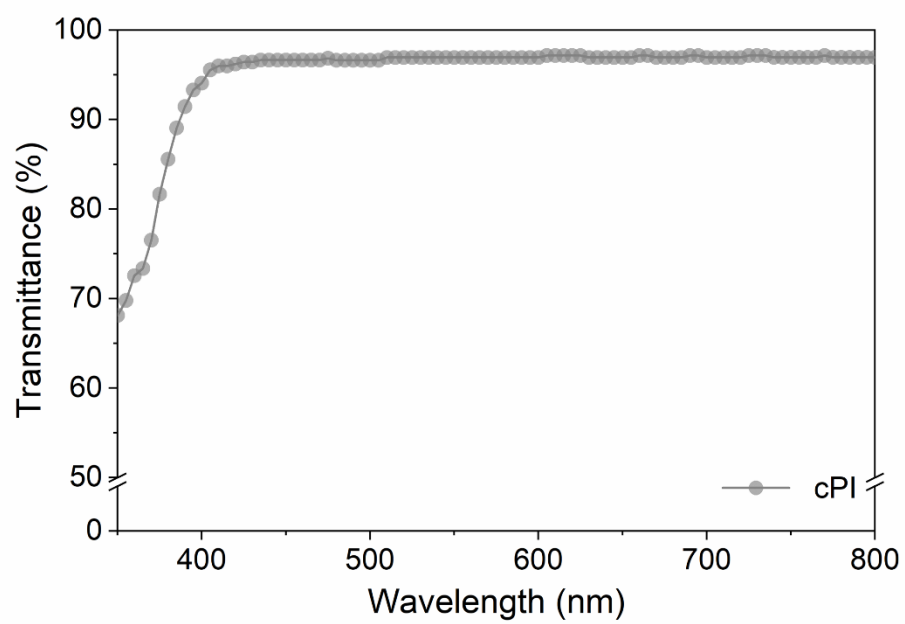
**Figure S3** The visible light transmittances (glass supporter as reference) of AgNWs/glass samples with various AgNWs suspension dilution ratios and spin-coating layers: (a~d) 20  $\mu\text{m}$  length AgNWs, (e~h) 100  $\mu\text{m}$  length AgNWs.

**a****b**

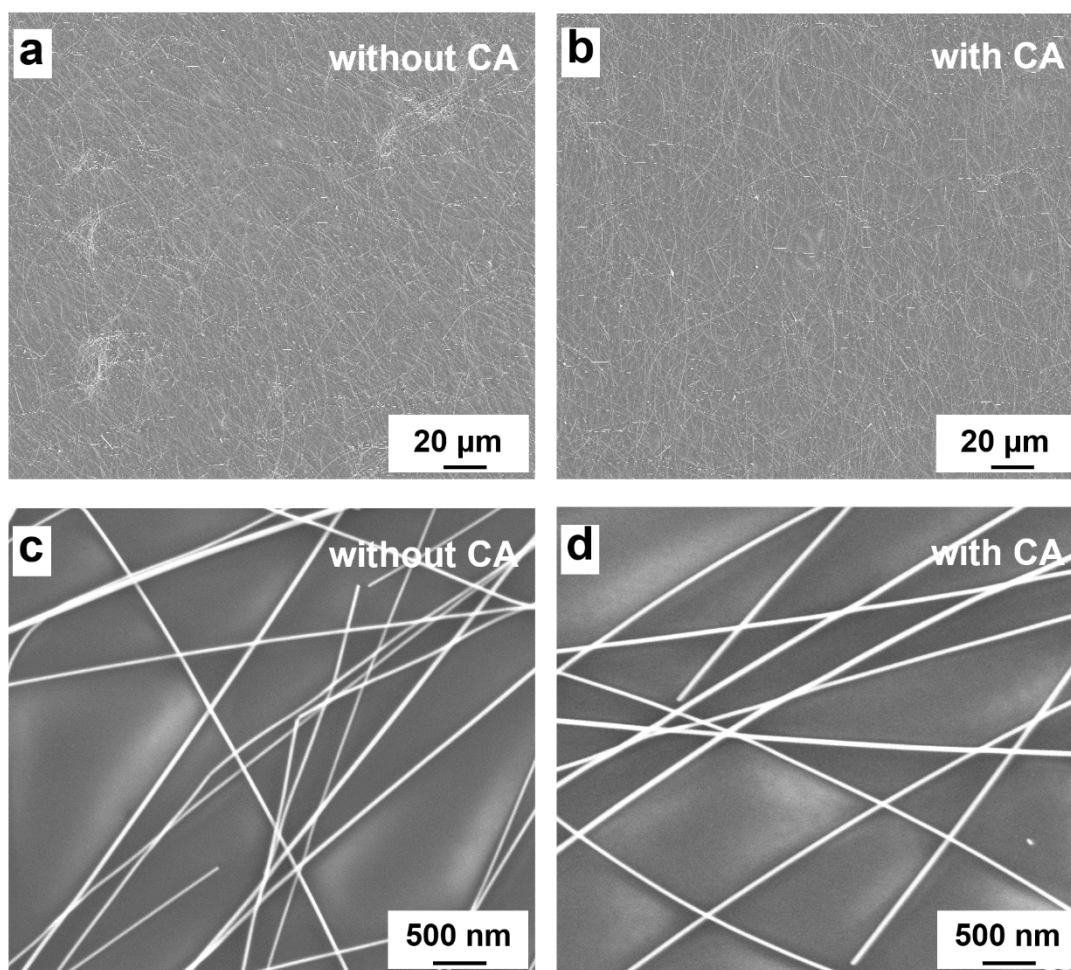
**Figure S4** Transmittance at 550 nm ( $T_{550}$ , glass supporter as reference) of AgNWs/glass samples for (a) 20  $\mu\text{m}$  AgNWs and (b) 100  $\mu\text{m}$  AgNWs with various AgNWs suspension dilution ratios and spin-coating layers.



**Figure S5** Relationship between sheet resistance and  $T_{550}$  (glass supporter as reference) of AgNWs/glass samples with 20 or 100  $\mu\text{m}$  lengths

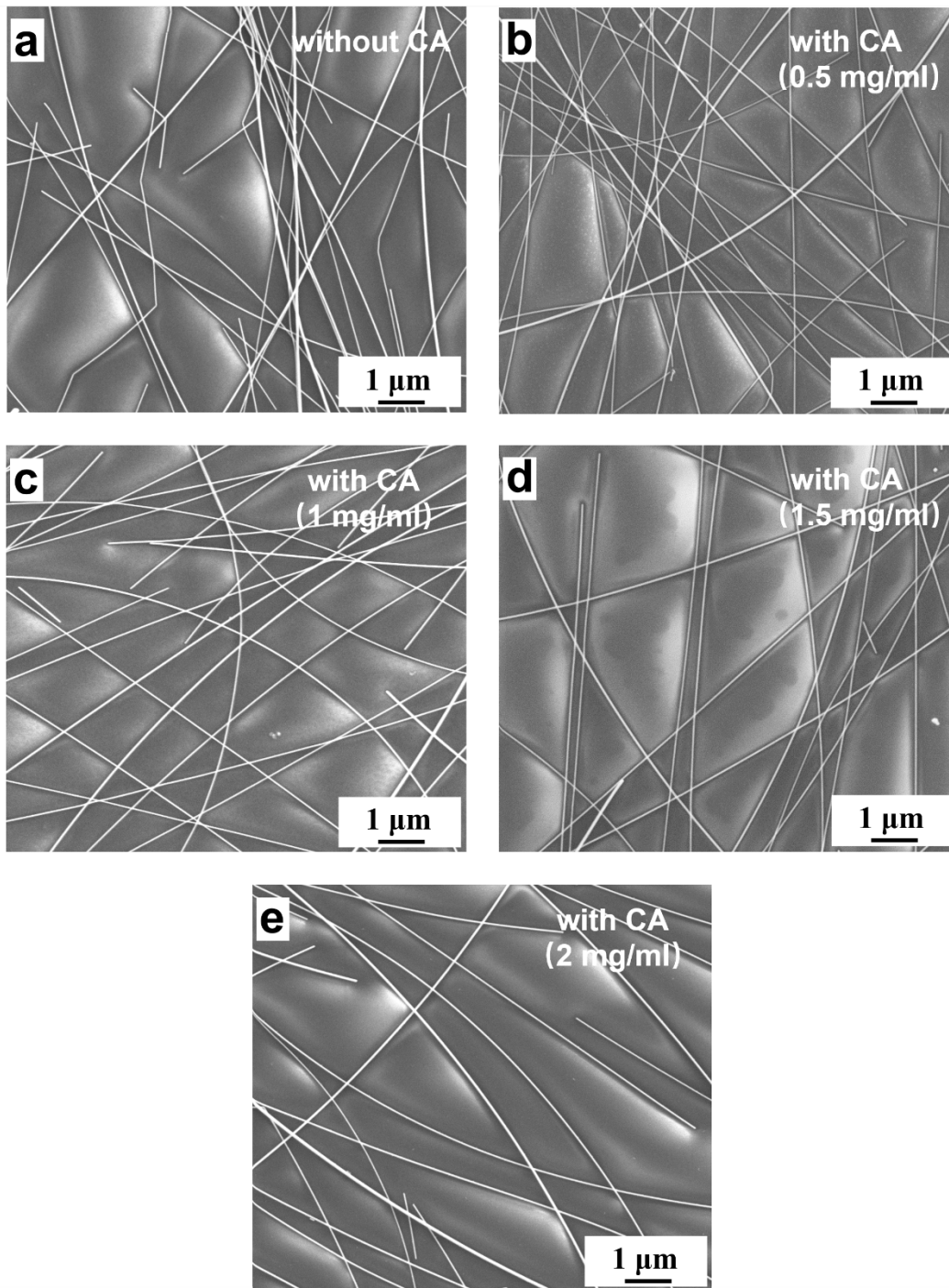


**Figure S6** Visible light transmittance (air as reference) of pure cPI flexible substrate.

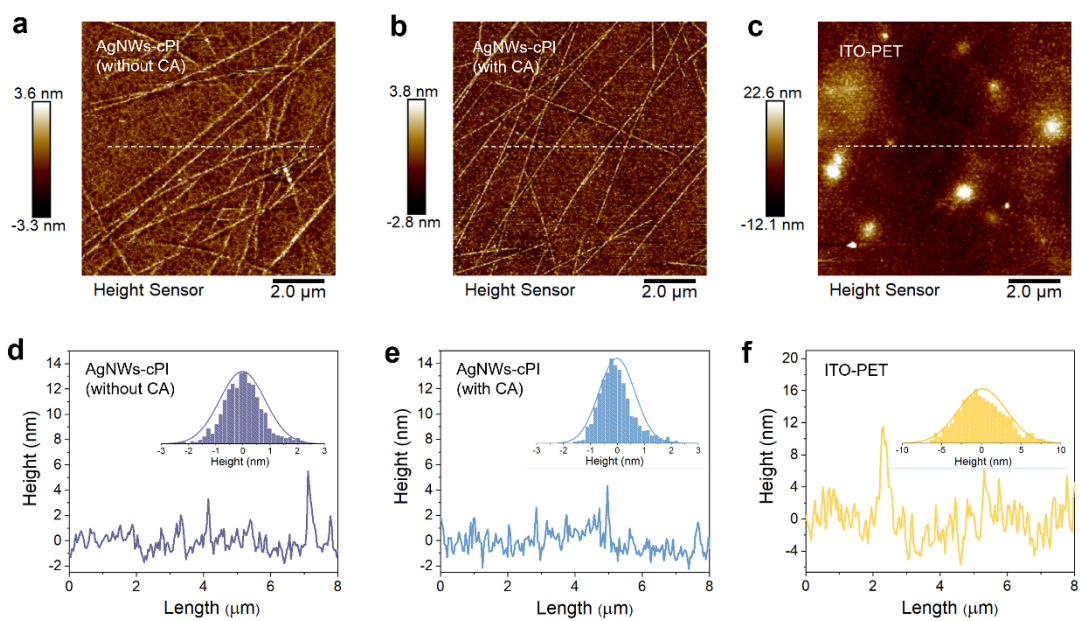


**Figure S7** SEM images of the surface of AgNWs/glass samples prepared without (a,c) or with (b,d) CA.

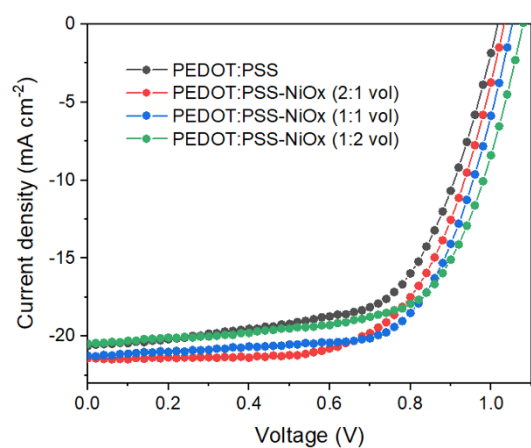




**Figure S8** SEM images of the surface of AgNWs/glass samples prepared with different CA content: (a) without CA, (b) 0.5 mg/ml CA, (c) 1 mg/ml CA, (d) 1.5 mg/ml CA, (e) 2 mg/ml CA.

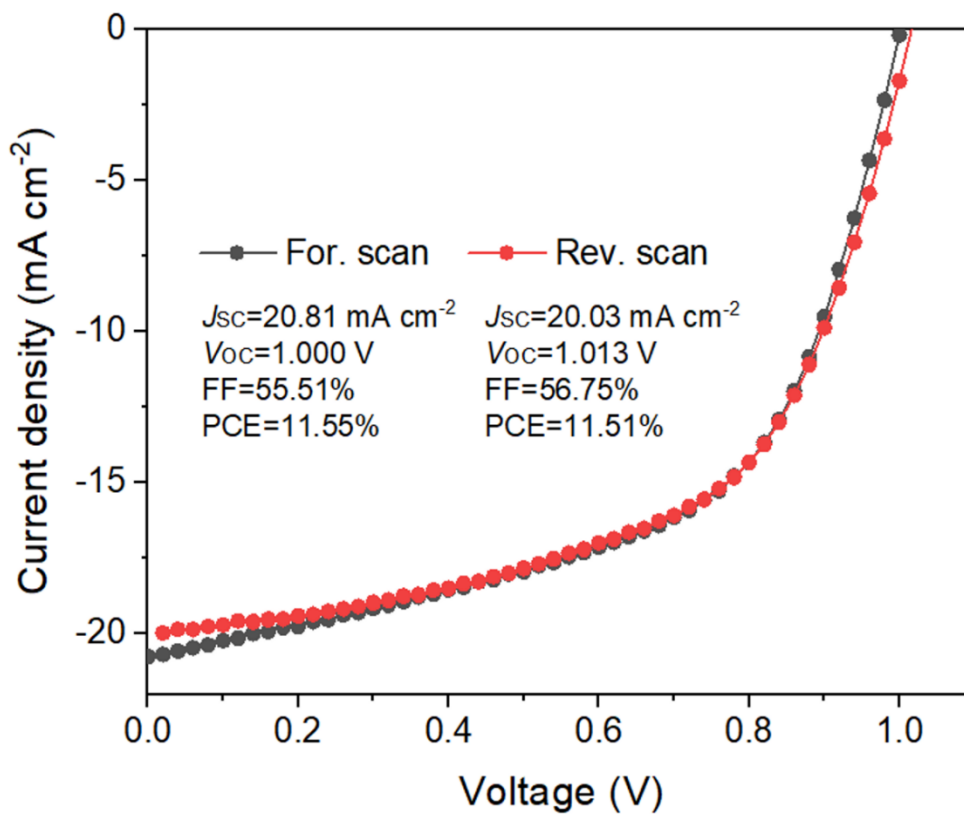


**Figure S9** (a-c) AFM images of the flexible AgNWs/cPI samples prepared without (a), with (b) CA and commercial ITO-PET (c), respectively. (d-f) Surface roughness profiles of the flexible AgNWs/cPI samples prepared without (d), with (e) CA, and commercial ITO-PET (f).

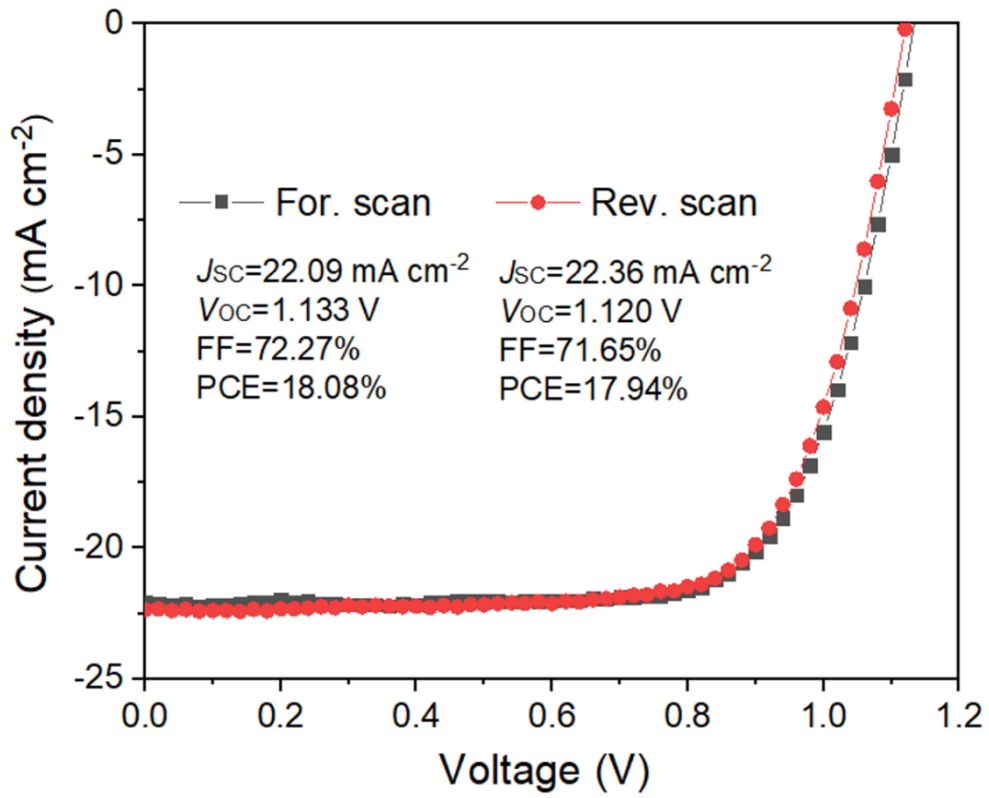


| HTL                      | J <sub>sc</sub><br>(mA cm <sup>-2</sup> ) | V <sub>oc</sub><br>(V) | FF<br>(%) | PCE<br>(%) |
|--------------------------|---|------------------------|-----------|------------|
| PEDOT:PSS                | 20.64                                     | 1.016                  | 62.34     | 13.07      |
| PEDOT:PSS-NiOx (2:1 vol) | 21.47                                     | 1.030                  | 66.27     | 14.65      |
| PEDOT:PSS-NiOx (1:1 vol) | 21.23                                     | 1.052                  | 67.08     | 14.98      |
| PEDOT:PSS-NiOx (1:2 vol) | 20.43                                     | 1.073                  | 63.51     | 13.92      |

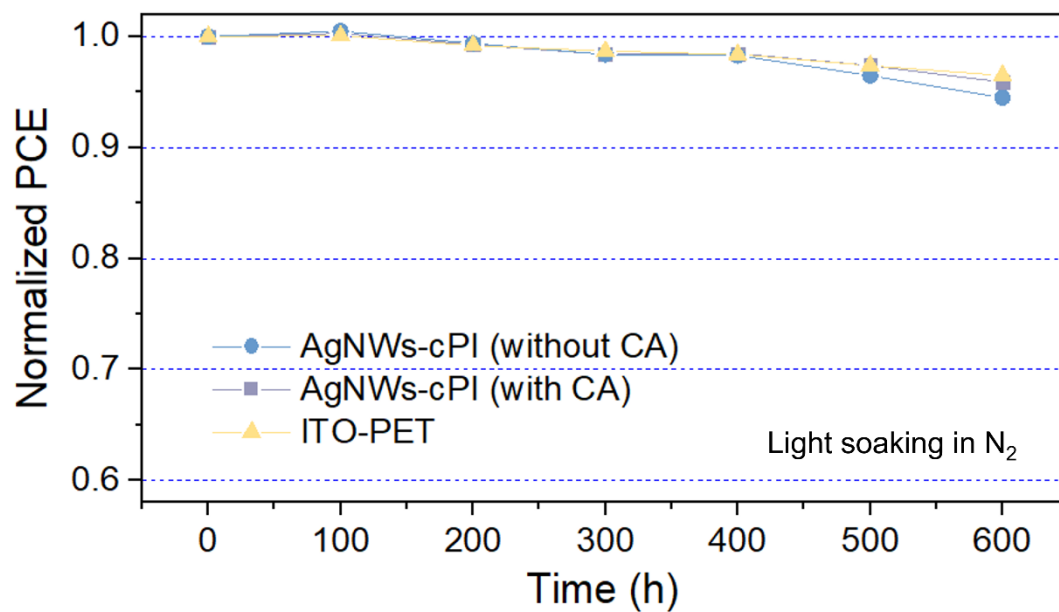
**Figure S10** *J-V* curves of the best performing flexible PSCs based on AgNWs-cPI substrates with different HTLs.



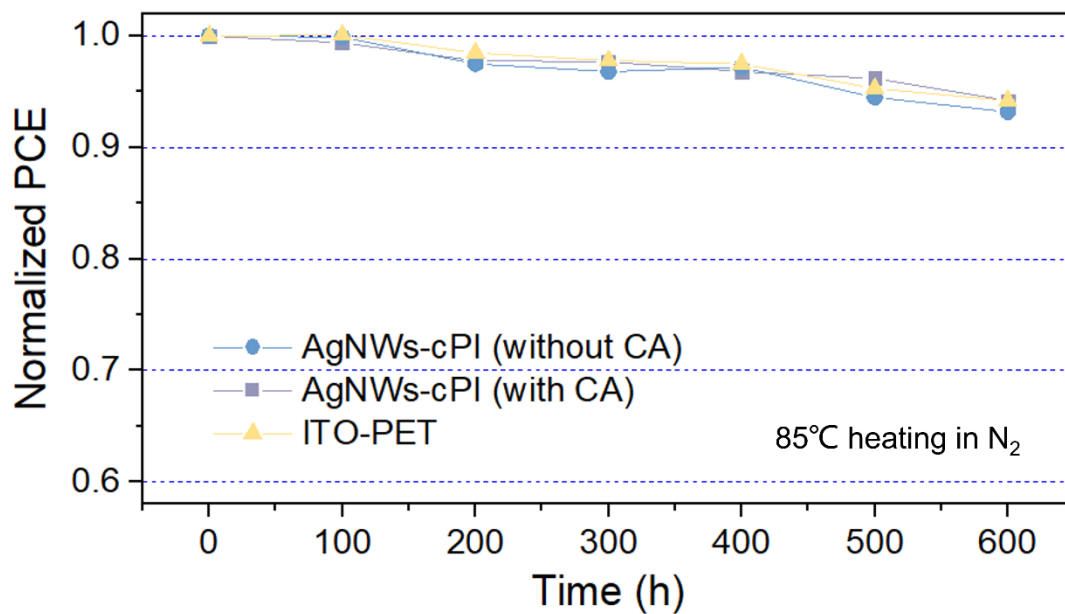
**Figure S11**  $J$ - $V$  curves of the best performing flexible PSCs based on AgNWs-cPI substrate without CA under forward and reverse scans.



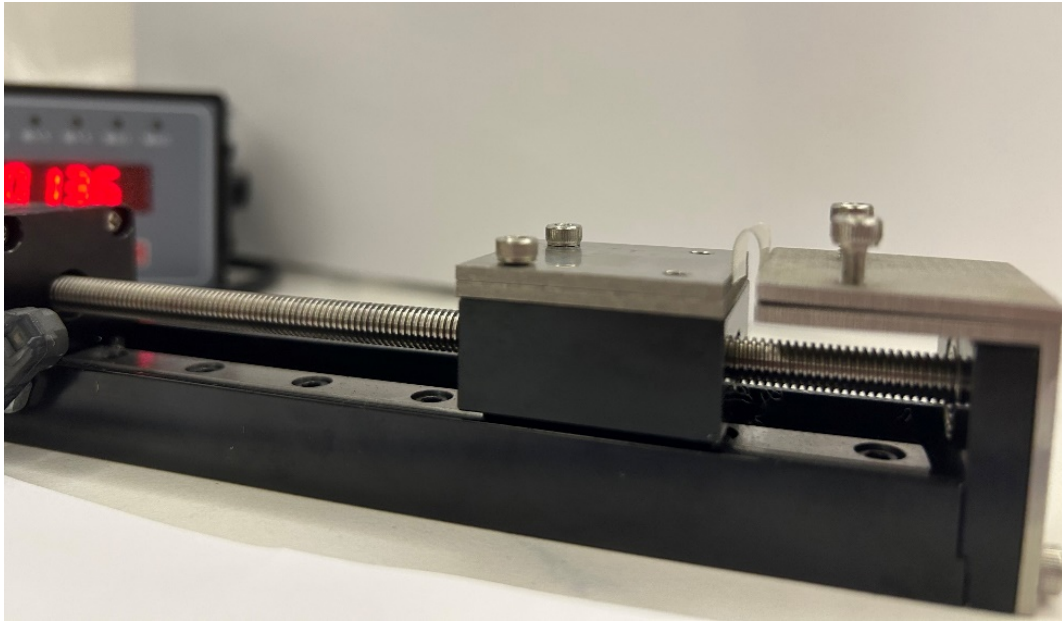
**Figure S12**  $J$ - $V$  curves of the best performing flexible PSCs based on ITO-PET substrate.



**Figure S13** Light stability measurements of unencapsulated devices at room temperature in N<sub>2</sub> atmosphere under AM 1.5 G simulated sunlight illumination.



**Figure S14** Heat stability measurements of unencapsulated devices at room temperature in  $N_2$  atmosphere under continues  $85^\circ C$  heating.



**Figure S15** Automatic mechanical device for bending tests.



**Table S1** A summary of the sheet resistance of AgNWs/glass samples with various AgNWs suspension dilution ratios and spin-coating layers.

| Dilution ratio | Spin-coating layer | Sheet resistance (ohm/sq)     |                                |
|----------------|--------------------|-------------------------------|--------------------------------|
|                |                    | 20 $\mu\text{m}$ length AgNWs | 100 $\mu\text{m}$ length AgNWs |
| 1 : 0          | 2                  | 9.5 $\pm$ 1.01                | 5.3 $\pm$ 0.28                 |
|                | 4                  | 3.1 $\pm$ 0.15                | 2.6 $\pm$ 0.10                 |
|                | 6                  | 1.9 $\pm$ 0.15                | 1.4 $\pm$ 0.07                 |
|                | 8                  | 1.1 $\pm$ 0.13                | 0.9 $\pm$ 0.11                 |
| 1 : 2          | 2                  | 76.9 $\pm$ 10.56              | 16.6 $\pm$ 1.27                |
|                | 4                  | 15.5 $\pm$ 1.56               | 7.6 $\pm$ 0.41                 |
|                | 6                  | 8.0 $\pm$ 0.69                | 4.5 $\pm$ 0.50                 |
|                | 8                  | 6.0 $\pm$ 0.58                | 3.1 $\pm$ 0.34                 |
| 1 : 4          | 2                  | 459.4 $\pm$ 66.06             | 39.0 $\pm$ 3.94                |
|                | 4                  | 60.0 $\pm$ 7.00               | 12.5 $\pm$ 1.20                |
|                | 6                  | 21.2 $\pm$ 1.32               | 5.7 $\pm$ 0.52                 |
|                | 8                  | 11.2 $\pm$ 1.33               | 4.5 $\pm$ 0.36                 |
| 1 : 6          | 2                  | 801.8 $\pm$ 108.88            | 55.6 $\pm$ 4.58                |
|                | 4                  | 111.1 $\pm$ 9.62              | 20.7 $\pm$ 1.93                |
|                | 6                  | 74.7 $\pm$ 5.48               | 10.0 $\pm$ 0.41                |
|                | 8                  | 13.5 $\pm$ 1.67               | 7.3 $\pm$ 0.47                 |

**Table S2** A summary of the transmittance at 550 nm ( $T_{550}$ , glass supporter as reference) of AgNWs/glass samples with various AgNWs suspension dilution ratios and spin-coating layers.

| Dilution ratio | Spin-coating layer | Transmittance at 550 nm ( $T_{550}$ , %) |                                |
|----------------|--------------------|--|--------------------------------|
|                |                    | 20 $\mu\text{m}$ length AgNWs            | 100 $\mu\text{m}$ length AgNWs |
| 1 : 0          | 2                  | 91.9                                     | 90.8                           |
|                | 4                  | 86.4                                     | 84.4                           |
|                | 6                  | 79.2                                     | 77.1                           |
|                | 8                  | 73.4                                     | 71.3                           |
| 1 : 2          | 2                  | 97.3                                     | 96.5                           |
|                | 4                  | 95.2                                     | 94.4                           |
|                | 6                  | 93.3                                     | 92.8                           |
|                | 8                  | 92.0                                     | 91.3                           |
| 1 : 4          | 2                  | 98.4                                     | 97.6                           |
|                | 4                  | 96.3                                     | 95.7                           |
|                | 6                  | 95.4                                     | 95.1                           |
|                | 8                  | 94.0                                     | 92.3                           |
| 1 : 6          | 2                  | 99.0                                     | 98.3                           |
|                | 4                  | 97.5                                     | 96.2                           |
|                | 6                  | 96.3                                     | 96.1                           |
|                | 8                  | 95.4                                     | 94.8                           |

**Table S3** A summary of the sheet resistance of AgNWs/glass samples with different citric acid content.

| Citric acid content (mg/ml) | Sheet resistance (ohm/sq) |
|-----------------------------|---------------------------|
| 0                           | 40.6±4.34                 |
| 0.5                         | 36.1±3.73                 |
| 1                           | 28.5±2.48                 |
| 1.5                         | 52.9±4.82                 |
| 2                           | 133.2±5.77                |

**Table S4** A summary of the sheet resistance of AgNWs/glass samples and AgNWs/cPI products obtained under different gradient heating conditions.

| AgNWs/glass Samples | Sheet resistance (ohm/sq) | Gradient heating condition                  | Sheet resistance of AgNWs/cPI product (ohm/sq) |
|---------------------|---------------------------|---|--|
| without CA          | 39.7±3.63                 | 60, 90, 120, and 150 °C for 1 h each step   | 56.5±3.79                                      |
| without CA          | 40.5±4.21                 | 80, 110, 140, and 170 °C for 1 h each step  | 93.9±4.65                                      |
| without CA          | 41.2±4.07                 | 100, 130, 160, and 190 °C for 1 h each step | 157.2±13.82                                    |
| with CA             | 28.9±2.67                 | 60, 90, 120, and 150 °C for 1 h each step   | 32.6±2.05                                      |
| with CA             | 29.3±2.84                 | 80, 110, 140, and 170 °C for 1 h each step  | 21.3±2.26                                      |
| with CA             | 29.5±3.02                 | 100, 130, 160, and 190 °C for 1 h each step | 52.4±3.94                                      |

**Table S5** A summary of PCE variation of flexible PSCs during mechanical bending test with different curvature radius.

| Samples               | Flat | 10          | 8           | 6           | 4           | 3           | 2           |
|-----------------------|------|-------------|-------------|-------------|-------------|-------------|-------------|
| AgNWs/c PI with CA    | 1    | 1.000±0.007 | 0.993±0.009 | 0.994±0.006 | 0.994±0.007 | 0.973±0.007 | 0.938±0.006 |
| AgNWs/c PI without CA | 1    | 0.999±0.005 | 0.996±0.004 | 0.996±0.004 | 0.994±0.003 | 0.979±0.005 | 0.944±0.012 |
| ITO-PET               | 1    | 1.000±0.007 | 0.992±0.008 | 0.987±0.005 | 0.986±0.005 | 0.952±0.009 | 0.922±0.025 |

**Table S6** A summary of the sheet resistance variation ( $R_0/R$ ) of the flexible substrate tested under different bending cycles at a curvature radius of 4 mm.

| <b>Samples</b>       | <b>0</b> | <b>500</b>  | <b>100</b>  | <b>1500</b> | <b>2000</b> |
|----------------------|----------|-------------|-------------|-------------|-------------|
| AgNWs/cPI with CA    | 1        | 0.980±0.016 | 0.975±0.011 | 0.957±0.009 | 0.931±0.013 |
| AgNWs/cPI without CA | 1        | 0.954±0.021 | 0.927±0.014 | 0.861±0.035 | 0.797±0.035 |
| ITO-PET              | 1        | 0.830±0.020 | 0.600±0.046 | 0.230±0.040 | 0.099±0.026 |

**Table S7** A summary of the PCE of flexible PSCs fabricated on the substrates that have been bend tested.

| <b>Samples</b>       | <b>0</b> | <b>500</b>  | <b>100</b>  | <b>1500</b> | <b>2000</b> |
|----------------------|----------|-------------|-------------|-------------|-------------|
| AgNWs/cPI with CA    | 1        | 0.996±0.009 | 0.985±0.009 | 0.967±0.008 | 0.958±0.007 |
| AgNWs/cPI without CA | 1        | 0.978±0.004 | 0.930±0.011 | 0.921±0.025 | 0.887±0.035 |
| ITO-PET              | 1        | 0.980±0.010 | 0.783±0.038 | 0.680±0.056 | 0.480±0.056 |

**Table S8** A summary of the PCE variation of flexible PSCs tested under different bending cycles at a curvature radius of 4 mm.

| <b>Samples</b>       | <b>0</b> | <b>500</b>  | <b>100</b>  | <b>1500</b> | <b>2000</b> |
|----------------------|----------|-------------|-------------|-------------|-------------|
| AgNWs/cPI with CA    | 1        | 0.989±0.014 | 0.985±0.021 | 0.921±0.014 | 0.878±0.014 |
| AgNWs/cPI without CA | 1        | 0.954±0.015 | 0.894±0.010 | 0.821±0.026 | 0.733±0.015 |
| ITO-PET              | 1        | 0.903±0.040 | 0.453±0.051 | 0.163±0.032 | ---         |