Electronic Supplementary Information

for

Flexible Te/PEDOT:PSS Thin Films with High Thermoelectric Power Factor and Their Application as Flexible Temperature Sensors

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I. Hot-pressing treatment

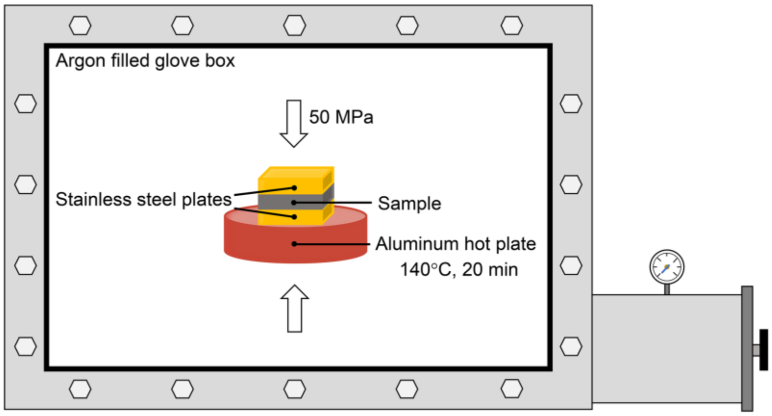

Figure S1. Schematic of the experimental setup for the hot-pressing treatment.

II. Thickness characterization of the thin films

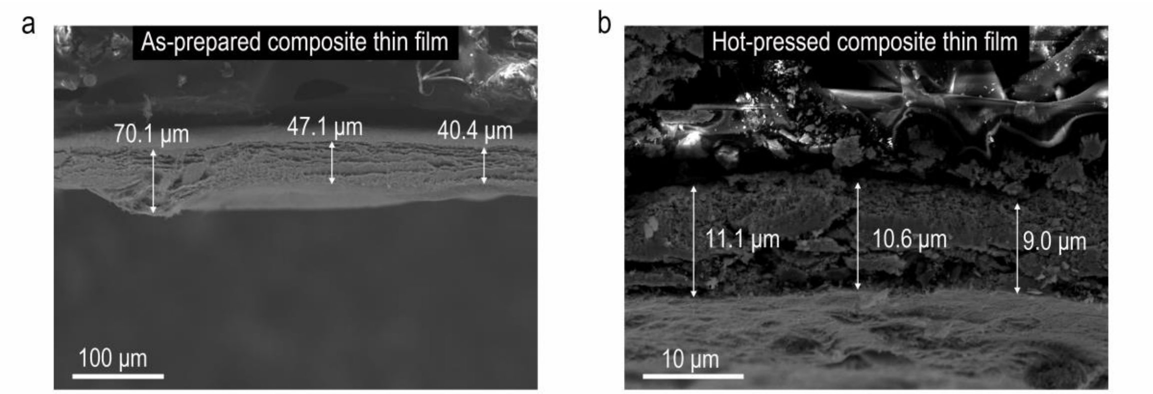

Figure S2. Cross-sectional SEM micrographs of (a) the as-prepared and (b) the hot-pressed Te/PEDOT:PSS thin films. The average value of several independent measurements was taken as the film thickness.

III. Size distributions of the synthesized Te nanostructures

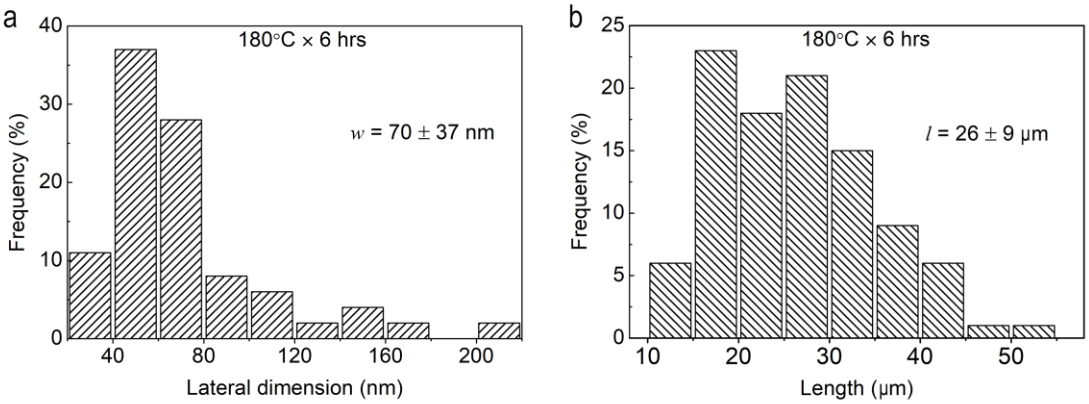

Figure S3. (a) Lateral dimension and (b) length distributions of Te nanostructures synthesized at 180°C for 6 hrs. The size distributions were determined by measuring 100 Te nanostructures in SEM images.

IV. Thermoelectric properties characterization of individual Te nanowires

Fig. S4a shows the SEM micrograph of a Te nanowire (sample S4) on a four-probe microdevice. The microdevice consists of two suspended membranes separated by several microns. An individual Te nanowire can be placed bridging two suspended membranes by using a micromanipulator. A serpentine platinum (Pt) coil and two separate Pt electrodes are patterned on each membrane. The Pt coil can serve as a resistance heater to increase the temperature of the heating membrane, and meanwhile a resistance thermometer to measure the temperature of the heating or sensing membrane. During thermal measurement, a temperature gradient is established along the Te nanowire by passing a direct current (DC) through the Pt coil on the heating membrane. The generated Joule heat will increase the temperature of the heating membrane (T_h) accordingly. Part of the heat will flow through the nanowire to the sensing membrane and raise its temperature (T_s). A small alternating current (AC) is applied to the Pt coil on each membrane to measure the coil resistance using a four-probe method, and then the temperature rise of each membrane can be calculated from the coil resistance change. The total thermal resistance (R_{tot}) of the Te nanowire can be determined by solving the heat transfer equation for the microdevice and eliminating the contribution of background conductance between two membranes.[1] Two Pt electrodes on each membrane enable the four-probe measurement of the electrical resistance (R_e) of the Te nanowire. The Seebeck coefficient is determined by measuring the voltage difference between two inner or outer Pt electrodes of two membranes induced by a temperature difference. Two commonly used methods in the literature were adopted to ensure good thermal and electrical contact between the Te nanowire and the underlying electrodes.[2,3] For sample S2, the platinum/carbon (Pt/C) composite was locally deposited at the contacts between the nanowire and four Pt electrodes through electron-beam-induced deposition (EBID) to improve the electrical and thermal contact, as shown in Fig. 3a. For other samples, the electron beam of a SEM with a high magnification is focused on the contact region to improve the contacts between the nanowire and Pt electrodes.

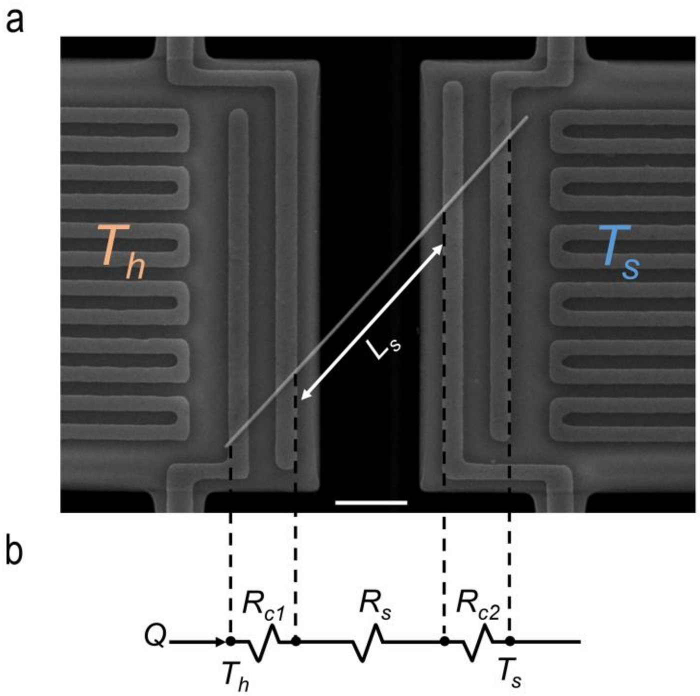

Figure S4. (a) SEM micrograph of an individual Te nanowire (sample S4). Scale bar: 3 µm. L_s is the suspended length of the nanowire. (b) Equivalent thermal circuit for thermal measurement of the Te nanowire in (a).

We note that the measured R_{tot} consists of the intrinsic thermal resistance (R_s) of the suspended nanowire segment and the thermal contact resistance between the nanowire and two membranes (R_{c1} and R_{c2}). Herein, a four-probe thermoelectric measurement method was adopted to determine R_s.[3] In this method, the nanowire itself was used as a thermometer to determine the temperature drop along the nanowire segment in contact with two membranes. The total thermal contact resistance between the nanowire and two membranes (R_{cm}) can be calculated by $R_{cm} = R_{c1} + R_{c2} = R_{tot} - R_s$. Fig. S5 shows the extracted R_s and R_{cm} for four measured Te nanowires. R_{cm} is found to be around 3 to 12% of R_{tot} at 300 K.

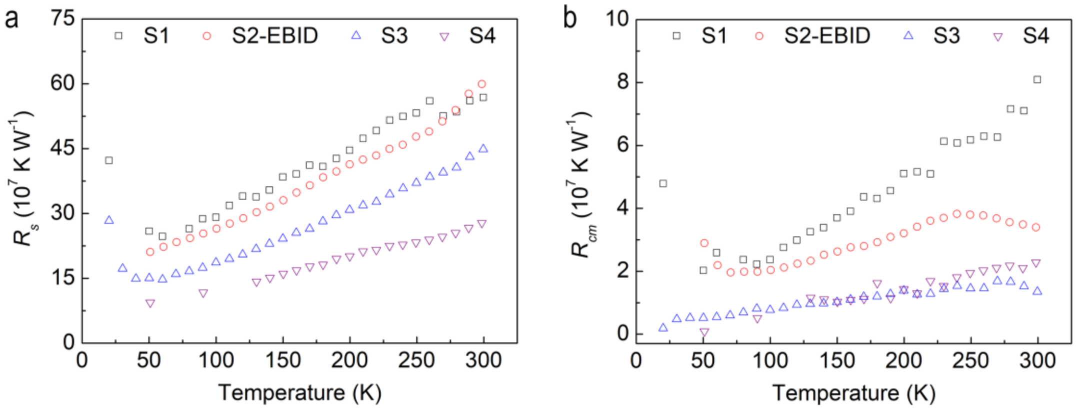

Figure S5. (a) Extracted R_s and (b) R_{cm} for four measured Te nanowires.

The electrical and thermal conductivity of the Te nanowire can be determined from the measured R_e and R_s, respectively, and the dimensions of the nanowire. The suspended length (L_s) and the lateral dimension of the Te nanowire can be determined from the SEM micrograph. As shown in Fig. S6, the measured Te nanowire has a hexagonal cross section, and the cross-sectional area (A) can be estimated from the lateral dimension of the nanowire. The dimensions of the Te nanowires measured in this work were listed in Table S1.

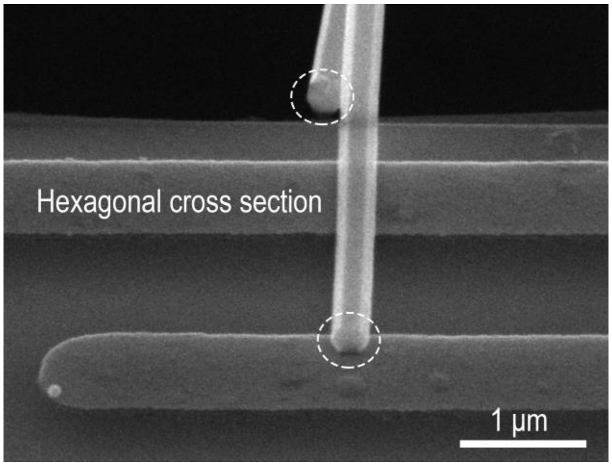

Figure S6. SEM micrograph of a Te nanowire taken at a tilted angle of 45°.

Table S1. The dimensions of the Te nanowires measured in this work.

Sample	Lateral dimension (nm)	Suspended length (μm)
S1	95	8.2
S2-EBID	95	8.5
S3	121	10.3
S4	150	8.9

It is worth noting that a four-probe method is adopted to eliminate the effect of the electrical contact resistance on the electrical conductivity measurement of the Te nanowire. The thermal contact resistance between the nanowire and the underlying electrodes was determined through a four-probe thermoelectric measurement method.[3] Therefore, the effect of the electrical and thermal contact resistance on the thermoelectric properties measurement of the Te nanowire was carefully eliminated in this work. The design of the four-probe microdevice enables us to determine all three thermoelectric properties of a Te nanowire in one measurement. Thus, the thermoelectric figure of merit (*ZT*) of the Te nanowire can be obtained.

V. Characterization of various thin films fabricated in this work

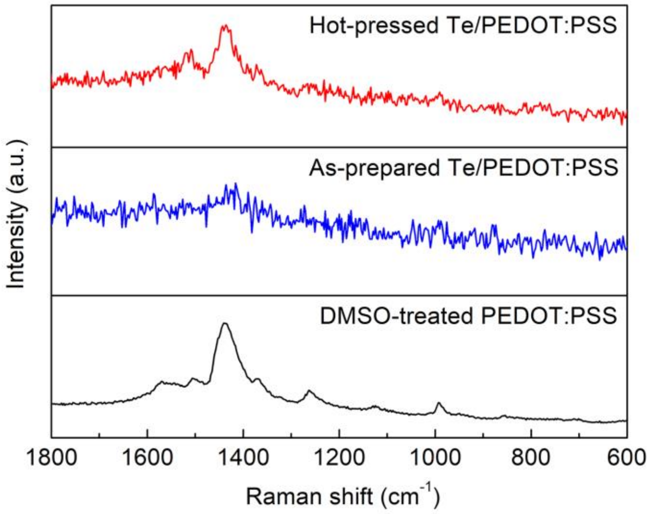

Figure S7. Raman spectra of the DMSO-treated PEDOT:PSS thin film and the as-prepared and hot-pressed Te/PEDOT:PSS thin films.

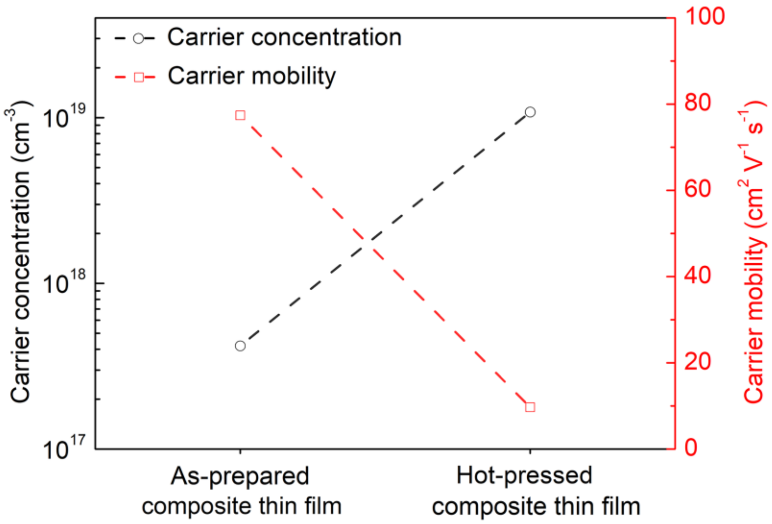

Figure S8. Room-temperature carrier concentration and mobility of the as-prepared and hot-pressed Te/PEDOT:PSS thin films.

VI. Characterization of the flexible temperature sensor

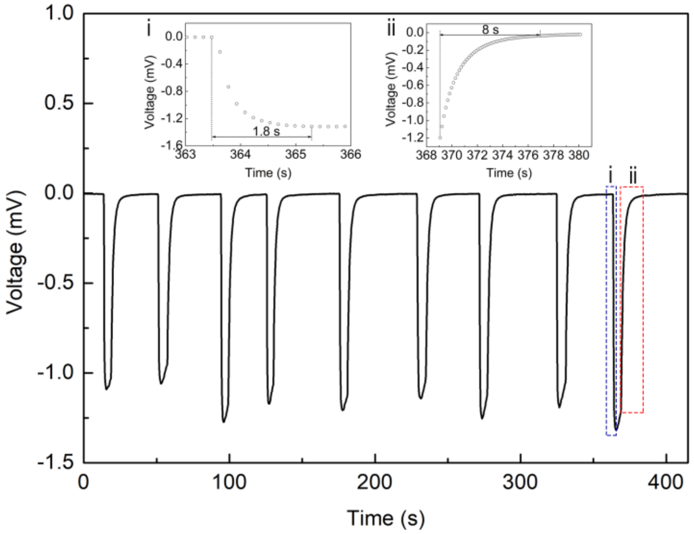

Figure S9. Recorded voltage of the temperature sensor when the sensing node is tapped by a finger. The inset Figures (i) and (ii) show the response and recovery times of the sensor, respectively.

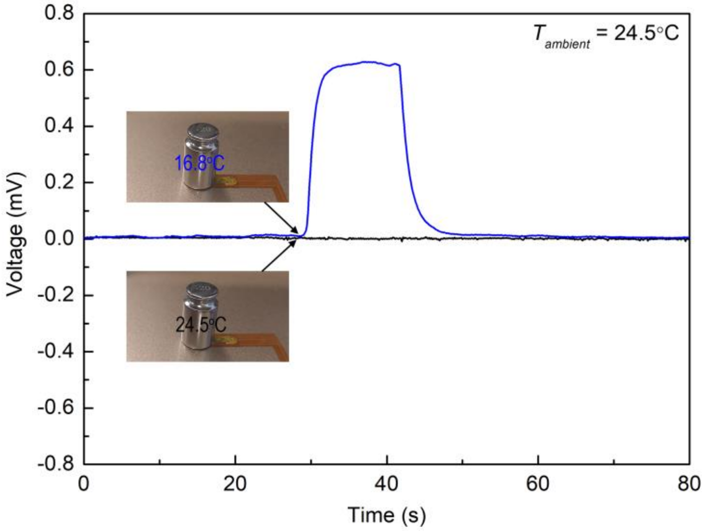

Figure S10. Recorded voltages of the temperature sensor when a 20 g weight with the ambient temperature or 16.8°C was placed on the sensing node.

References

1. M. C. Wingert, Z. C. Chen, S. Kwon, J. Xiang and R. Chen, *Rev. Sci. Instrum.*, 2012, **83**, 024901.
2. L. Shi, D. Li, C. Yu, W. Jang, D. Kim, Z. Yao, P. Kim and A. Majumdar, *J. Heat Transfer*, 2003, **125**, 881-888.
3. A. Mavrokefalos, M. T. Pettes, F. Zhou and L. Shi, *Rev. Sci. Instrum.*, 2007, **78**, 034901.