Materials Research Express

PAPER

Preparation and thermoelectric properties of screen-printable rGO/Sb$_2$Te$_3$/SV$_4$/PEDOT:PSS composite thermoelectric film

QiQi Zhu$^1$, Yong Du$^{1,2,}$*, Qiufeng Meng$^{1,2,*}$ and Shirley Z Shen$^2$

$^1$ School of Material Science and Engineering, Shanghai Institute of Technology, Shanghai 201418, People’s Republic of China
$^2$ CSIRO Manufacturing, Clayton North, VIC 3168, Australia
* Authors to whom any correspondence should be addressed.

E-mail: ydu@sit.edu.cn and mengqiufeng@sit.edu.cn

Keywords: thermoelectric, flexibility, screen printing, rGO, Sb$_2$Te$_3$, conducting polymer

Abstract

Because of the advantages of facile and fast preparation process, screen printing technology shows great potentials in the prospective large-scale production of thermoelectric materials. Herein, rGO/Sb$_2$Te$_3$ composite powders have been prepared by a hydrothermal process, and then flexible rGO/Sb$_2$Te$_3$/SV$_4$/PEDOT:PSS composite films with different weights of rGO/Sb$_2$Te$_3$ composite powders have been prepared via a screen printing process. The effects of the contents of rGO/Sb$_2$Te$_3$ composite powders on thermoelectric properties of the rGO/Sb$_2$Te$_3$/SV$_4$/PEDOT:PSS composite films have been studied. The Seebeck coefficients of the achieved composite films was basically unchanged with the content of rGO/Sb$_2$Te$_3$ composite powders increasing, whereas the electrical conductivities decrease, resulting in a maximal power factor of $2.96\,\mu W/\text{mK}^2$ at 375 K for the composite film containing 85 wt.% rGO/Sb$_2$Te$_3$ composite powders. The cold pressing combining annealing process has been employed to improve the thermoelectric properties of the composite films. After the treatment, the electrical conductivity of the composite film with 85 wt.% rGO/Sb$_2$Te$_3$ powders has been significantly improved, while the corresponding Seebeck coefficient has slightly decreased. An optimal power factor of $14.13\,\mu W/\text{mK}^2$ has been acquired at 375 K, which is $\sim 5$ times higher when compared to the untreated composite film ($2.96\,\mu W/\text{mK}^2$ at 375 K).

1. Introduction

Thermoelectric (TE) technology can convert the low-grade heat into useful electrical power without causing additional pollutions [1, 2]. Nowadays, TE materials have aroused great interests [3, 4], mainly because of their TE performance significantly effecting conversion efficiencies of the assembled TE generators. The TE performance of a material is normally estimated by the dimensionless figure of merit $ZT = S^2\sigma T/\kappa$, where $S$ represents the Seebeck coefficient, $\sigma$ is the electrical conductivity, $\kappa$ stands for the thermal conductivity of the materials, and $T$ is the absolute temperature) [5, 6]. As a traditional TE material, antimony telluride (Sb$_2$Te$_3$) has a great potential for the application in the TE areas [7]. For instance, Sb$_2$Te$_3$ bulk materials were prepared via a hot press sintering approach, and a $ZT = 0.57$ was acquired at 565 K [8]. Sb$_2$Te$_3$ bulk samples were prepared via a spark plasma sintering (SPS) process, and a $ZT = 0.58$ was achieved at 420 K [9]. Graphene possesses unique advantages, such as high values of specific surface area, carrier mobility, mechanical and electrical properties [10]. Normally, graphene can be used as fillers for Sb$_2$Te$_3$ matrix to prepare the corresponding composites [11].

Poly(3,4-ethylenedioxythiophene):poly(styrenesulfonate) (PEDOT:PSS, PP) is a typical studied conducting polymer TE materials, on account of its low thermal conductivity, solution processability, good pliability and environmental stability [12]. However, the TE properties of PP are still far behind that of inorganic TE materials [13]. Mixing PP with inorganic TE materials is a valid approach to improve its $ZT$ value. One of the reasons is that the inorganic TE materials have good TE performance [14–16]. For instance, Goo et al [16] synthesized Bi$_2$Te$_3$/PP composite film via a drop casting method, and a power factor (PF) of $\sim 328 \pm 48\,\mu W/\text{mK}^2$ was

© 2021 The Author(s). Published by IOP Publishing Ltd
achieved at room temperature (RT) by decoupling the interdependent $\sigma$ and $S$. Moreover, the energy filtration effect might be formed between inorganic and PP components \[17, 18\], which is beneficial to enhance the ZT value of PP. For example, Kim et al\[18\] fabricated PP/Bi$_2$Te$_3$ nanowire composite film, and a PF of $\sim 205 \pm 18 \mu$W/mK$^2$ was obtained at RT by adjusting the work function of PP, and the barrier energy between Bi$_2$Te$_3$ nanowires and PP.

Sb$_2$Te$_3$/PP composites have been previously prepared mainly in the form of bulk materials, for instance, Sb$_2$Te$_3$ bulk samples were prepared by a SPS process \[19\], and then soaked the prepared Sb$_2$Te$_3$ bulks into PP solution, consequently a $ZT = 1.18$ was gained at 523 K for the Sb$_2$Te$_3$/PP composite bulk material. Recently, various methods were attempted to fabricate the flexible Sb$_2$Te$_3$/PP composite films, which are facile for flexible wearable TE generators. For example, Sb$_2$Te$_3$/PP composite films were prepared via an aerosol jet printing method \[20\], and a PF of $\sim 28.3 \mu$W/mK$^2$ was acquired at RT for the Sb$_2$Te$_3$/PP sample with 85 wt.% Sb$_2$Te$_3$ nanoflakes. Sb$_2$Te$_3$ films on the polyimide substrate were prepared by a screen printing technology (SPT) \[21\], and then annealed it under N$_2$ atmosphere at 450 $^\circ$C, after that the annealing treated samples were covered with PP solution, and a $ZT = 0.2 \pm 0.02$ was received for the Sb$_2$Te$_3$/PP composite film at RT.

Considering the economy and the requirements of scale production, the cheap and high-throughput SPT has emerged as a promising fabrication route for preparation of flexible and wearable TE power generations \[21–25\]. While researches on the screen-printed rGO/Sb$_2$Te$_3$/SV4/PP (SV4 is an ink containing 1.5 wt.% PP) composite TE materials have not yet been reported. Herein, rGO/Sb$_2$Te$_3$ composite powders are synthesized via a hydrothermal method (HM), and then flexible rGO/Sb$_2$Te$_3$/SV4/PP composite films are prepared via a SPT. The cold pressing combining annealing treatment process is applied to enhance the TE properties of the as-prepared samples. The effects of the contents of rGO/Sb$_2$Te$_3$ composite powders as well as post-treatment process on the microstructures and TE properties of the rGO/Sb$_2$Te$_3$/SV4/PP composite films are also investigated.
2. Experimental section

2.1. Materials
Antimony trichloride (SbCl₃), potassium borohydride (KBH₄), and tellurium dioxide (TeO₂) were bought from Adamas Reagent Co., Ltd. Poly(vinyl alcohol) (PVA) and potassium hydroxide (KOH) were bought from General Reagent Co., Ltd. Graphene oxide (GO) was bought from Nanjing XFNANO Materials Tech Co., Ltd. CLEVIOS™ SV4 slurry was bought from Germany Heraeus Co., Ltd. PP (Clevios™ PH 1000) was bought from H. C. Stark, Inc. Dimethyl sulfoxide (DMSO) and nylon filter membrane (pore size = 0.22 μm) were purchased from Shanghai Titan chem Co., Ltd. The SbCl₃ and TeO₂ are guaranteed reagent, while the KBH₄, PVA, KOH, and DMSO are analytical reagent. All the materials were employed without farther purification.

2.2. Synthesis of rGO/Sb₂Te₃ composite powders
The rGO/Sb₂Te₃ composite powders were prepared by a HM, and the details are as below. A certain weight of GO was put into deionized (DI) water (80 ml), and a solution A (GO dispersion) was obtained after sonicated for 2 h. An appropriate mass of SbCl₃, TeO₂, PVA, and KOH were put into the solution A and then stirred at RT for 1 h (solution B). The excessive KBH₄ was put into the solution B and stirred to form a uniform dispersion (solution C). The solution C was then transferred to a Teflon-lined autoclave (100 ml) and heated to 180 °C and kept for 24 h. Afterwards, the autoclave was slowly cooled to RT, and the achieved precipitates were alternately washed for several times by absolute ethanol and DI water. In the end, the samples were dried in vacuum for 8 h at 60 °C. The mass ratio of rGO was 0.4 wt.% in the rGO/Sb₂Te₃ composite powders.

2.3. Preparation and post-treatment of rGO/Sb₂Te₃/SV4/PP composite films
0.6 ml SV4 slurry and 0.4 ml PP solution (with 5 wt.% DMSO) were put to a 10 ml beaker and then stirred for 1 h to form paste A. Afterwards, different mass ratio of rGO/Sb₂Te₃ composite powders were put into the paste A,
and continually stirred for 2 h to form a uniformly mixed paste B (the content of rGO/Sb$_2$Te$_3$ composite powders was 85 wt.%, 90 wt.%, and 95 wt.%, respectively). The paste B was poured on the screen printing plate, and the flexible rGO/Sb$_2$Te$_3$/SV4/PP composite films were prepared by a SPT on the nylon filter membrane. The obtained composite films were dried off in vacuum for 15 min at 130 °C, and denoted as SP85, SP90, and SP95, corresponding to the rGO/Sb$_2$Te$_3$ composite powders content of 85 wt.%, 90 wt.%, and 95 wt.%, respectively. Subsequently, the as-prepared composite films were sequentially subjected to cold pressing (20 MPa, 10 min) and annealing treatment in Ar atmosphere (210 °C, 1 h). The corresponding post-treated composite films were named as CASP85, CASP90, and CASP95, respectively. Figures 1(a)–(g) schematically represent the preparation and post-treatment procedures of the rGO/Sb$_2$Te$_3$/SV4/PP composite films.

2.4. Characterization and measurement
The X-ray diffraction (XRD, Bruker D8 Advance, Karlsruhe) was used to study the compositions of samples. The morphologies, thicknesses and energy-dispersive spectroscopy (EDS) mapping of the as-prepared films were characterized by scanning electron microscopy (SEM, Tescan Mira 3 XH, equipped with Oxford EDS AZtec X-MaxN 80). The $\sigma$ and $S$ of the samples were performed by an MRS-3 TE test system produced by Wuhan Giant Instrument Technology Co., Ltd. from 315 K to 375 K under low-vacuum ($\leq$ 40 Pa), and the instrument test errors for the $S$ is 7% and the $\sigma$ is 5%. Before the measurement, the standard sample nickel tape was taken to calibrate the equipment to guarantee that the equipment is in normal working condition. The resistance of the rGO/Sb$_2$Te$_3$/SV4/PP composite films after being bent for different times was performed by a digital multimeter (VC9807A+).

3. Results and discussion
Figure 1(h) reveals the XRD patterns of rGO/Sb$_2$Te$_3$/SV4/PP composite films with different contents of rGO/Sb$_2$Te$_3$ composite powders. All the characteristic peaks of the as-prepared composite films were consistent with the standard powder diffraction file of Sb$_2$Te$_3$ (JCPDS number 15-0874) [8], while the peaks of rGO and PP were not observed, which was mainly because of the low content of rGO [11, 26] and the amorphous
characteristics of PP [27]. Besides, as the contents of the inorganic component rGO/Sb2Te3 composite powders increased, the peak intensities of Sb2Te3 for the composite films also enhanced.

Figures 2(a)–(c) are the surface SEM images of rGO/Sb2Te3/SV4/PP composite films with different contents of rGO/Sb2Te3 composite powders. With the loadings of rGO/Sb2Te3 powders increased, the surface morphologies of the composite films became rougher, which might be due to the poor film-forming properties of rGO/Sb2Te3 powders. This phenomenon is adverse to enhance the σ of the composite films. Figures 2(d)–(i) present the SEM image and SEM-EDS mappings of Sb, Te, C, O, and S elements for the SP85 composite film, manifesting that Sb2Te3 and rGO are evenly distributed in the rGO/Sb2Te3/SV4/PP composite film.

Figures 3(a)–(c) display the relationship between temperature and TE properties of rGO/Sb2Te3/SV4/PP composite films from 315 K to 375 K. As the mass fraction of rGO/Sb2Te3 composite powders enhanced from 85 wt.% to 95 wt.% , the σ decreased from 24.3 S/cm to 16.6 S/cm at 315 K, whereas the S of the composite films was basically unchanged (e.g. the values of the S were in the ranges of 29.7 μV/K–32.2 μV/K at 315 K). The PF was decreased with the contents of rGO/Sb2Te3 composite powders increasing, and a PF of 2.15 μW/mK² was obtained at 315 K for the SP85 sample. When the testing temperature rose from 315 K to 375 K, the σ was not significantly changed, while the S increased constantly. For example, the S of SP85 sample increased from 29.7 μV/K to 35.1 μV/K when the temperature increasing from 315 K to 375 K, and a maximal PF of 2.96 μW/mK² was achieved at 375 K for the SP85.

Figure 3(d) shows the relationship between resistance change rate and bending times of SP85 sample. The SP85 was cut into a rectangle shape (25 × 5 mm²) and bent for several times with a radius of 11 mm. When the bending times increased from 100 to 400, the corresponding resistance change rate was slightly increased from 0.62% to 5.0%, indicating good flexibility of the composite film.

The cold pressing combining with annealing treatment was introduced to improve TE properties of the rGO/Sb2Te3/SV4/PP composite films. The XRD patterns of the post-processed samples manifested that the peaks’ position of Sb2Te3 in the composite films was not obviously changed, while the peaks’ intensities of Sb2Te3 slightly increased.

Figures 4(a)–(c) reveal the surface SEM images of rGO/Sb2Te3/SV4/PP composite films after being cold pressing combining with annealing treatment. Compared with the pristine composite films, there is no significantly variation for the morphology of the post-processed composite films. Figures 4(d) and (e) are the
cross-section SEM images of the CASP series samples, revealing that the thicknesses of CASP series samples are lower than 1 μm.

Figures 5(a)–(c) show the temperature dependence of TE parameters of the post-treated composite films. Compared with the untreated composite films, the σ was significantly increased, while the S was not significantly changed. A highest σ of the CASP85 sample was 298.46 S/cm at 375 K, which is ∼12 times higher compared to the untreated SP85 (24.03 S/cm at 375 K). This phenomenon may be due to the dense structure of the treated films with the help of the cold pressing combining annealing treatment. As the test temperature rose from 315 K to 375 K, the σ remained unchanged, whereas the S showed an upward trend, and a maximum PF of 14.13 μW/mK² was gained at 375 K for CASP85, which is ∼5 times higher compared to the SP85 (2.96 μW/mK² at 375 K) [28], but lower than the values of the screen printable PP layer (34 μW/mK² at 200 °C) [29], and the Sb₂, Bi₀.₅Te₃ film (∼77 μW/mK² at 75 °C) prepared by a inkjet printing technology [30]. Table 1 compared TE properties of CASP85 with those of previously reported PP-based materials. Figure 5(d) presents the relationship between resistance change rate and bending times of CASP85. When the bending times were increased from 100 to 400, the resistance change rate of the post-treated CASP85 increased from 1.45% to 5.0%, indicating that the flexibility of the composite films is not obviously changed when compared with the untreated samples (figure 3(d)).

4. Conclusions

In this work, rGO/Sb₂Te₃/SV4/PEDOT:PSS composite films have been prepared by a screen printing technique, and the effects of the content of rGO/Sb₂Te₃ composite powders and post-treatment on the microstructures and TE properties of the composite films have been studied. As the mass fraction of rGO/Sb₂Te₃ component increases from 85 wt.% to 95 wt.%, the electrical conductivity of the composite films decreases from 24.42 S/cm to 15.92 S/cm, while the Seebeck coefficients do not change much. When the content of rGO/Sb₂Te₃ is 85 wt.%, a power factor of 2.96 μW/mK² has been acquired at 375 K. After the cold pressing combining with annealing treatment, the electrical conductivity increased to 298.46 S/cm for the
Table 1. Comparisons of the TE properties of CASP85 with previously reported PP-based materials

| Methods                                                                 | Materials                                      | $\sigma$ (S/cm) | $S$ ($\mu$V/K) | $PF$ ($\mu$W/mK$^2$) | Temperature | References |
|------------------------------------------------------------------------|-----------------------------------------------|-----------------|----------------|-----------------------|-------------|------------|
| SPT combining cold-pressing and annealing treatment                   | rGO/Sb$_2$Te$_3$/Si/PP composite film         | 298.46          | 21.76          | 14.13                 | 375 K       | This work  |
| SP                                                                    | PP film                                       | 550             | 25             | 34                    | 473 K       | [29]       |
| Solution coating process                                              | PP/PEDOT/wool composite fabrics              | ~16             | ~18            | 0.5                   | 360 K       | [31]       |
| Aerosol-jet printing method with ethylene glycol treatment            | Sb$_2$Te$_3$/PP composite film               | ~247.3          | ~33.8          | ~28.3                 | RT          | [20]       |
| Multiple solution deposition                                          | PANI-CSA/PP multilayer film                  | 1280.8          | 19             | 49                    | RT          | [32]       |
| In situ chemical polymerization combining solution coating process     | PP/polypyrrole/paper film                    | ~0.48           | ~17.8          | ~1.5 × 10$^{-2}$     | 370 K       | [33]       |
| Casting method                                                        | PP/GQDs film                                 | 71.72           | 14.6           | ~1.53                 | RT          | [34]       |

$a$ Some values were estimated as per the raw data in the corresponding References;

$b$ CSA = camphorsulfonic acid;

$c$ GQDs = graphene quantum dots.
composite film with 85 wt.% rGO/Sb$_2$Te$_3$. A power factor of 14.13 μW/mK$^2$ has been achieved at 375 K. This is a simple and easy-to-operate method for the preparation of thermoelectric composite films.

Acknowledgments

This work has been supported by the Shanghai Innovation Action Plan Project (17090503600), Shanghai Sailing Program (20YF1447300), and National Natural Science Foundation of China (11811530636).

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

ORCID iDs

Yong Du @ https://orcid.org/0000-0002-7981-6373

References

[1] Du Y, Xu J Y, Paul B and Eklund P 2018 Flexible thermoelectric materials and devices Appl. Mater. Today 12 366–88
[2] Gao Q F, Jiang Q L, Cai K F and Chen L D 2019 Preparation and thermoelectric properties of PEDOT:PSS coated Te nanorods// PEDOT:PSS composite films Org. Electron. 87 79–85
[3] Yang L, Chen Z G, Dargusch M S and Zou J 2018 High performance thermoelectric materials: progress and their applications Adv. Energy Mater. 8 1–28
[4] Wang Y, Yang L, Shi X L, Shi X, Chen L D, Dargusch M S, Zou J and Chen Z G 2019 Flexible thermoelectric materials and generators: challenges and innovations Adv. Mater. 31 1–47
[5] Chen G M, Xu W and Zhu D B 2017 Recent advances in organic polymer thermoelectric composites J. Mater. Chem. C 5 4350–60
[6] Du Y, Shen S Z, Cai K F and Casey P S 2012 Research progress on polymer–inorganic thermoelectric nanocomposite materials Prog. Polym. Sci. 37 820–41
[7] Chen J et al 2010 Sb$_2$Te$_3$ nanoparticles with enhanced Seebeck coefficient and low thermal conductivity Chem. Mater. 22 3086–92
[8] Sun S L, Peng J, Jin R X, Song S Y, Zhu P W and Xing Y 2013 Template-free solvothermal synthesis and enhanced thermoelectric performance of Sb$_2$Te$_3$ nanosheets J. Alloy. Compd. 558 6–10
[9] Dong G H, Zhu Y J and Chen L D 2010 Microwave-assisted rapid synthesis of Sb$_2$Te$_3$ nanosheets and thermoelectric properties of bulk samples prepared by spark plasma sintering J. Mater. Chem. 20 1976–81
[10] Yu X W, Cheng H H, Zhang M, Zhao Y, Qu L T and Shi G Q 2017 Graphene-based smart materials Nat. Rev. Mater. 2 17046
[11] Kumar S, Faraz M and Khare N 2019 Enhanced thermoelectric properties of Sb$_2$Te$_3$–graphene nanocomposite Mater. Res. Express 6 085079
[12] Liu X, Du Y, Meng Q F, Shen S Z and Xu J Y 2019 Flexible thermoelectric power generators fabricated using graphene/PEDOT:PSS nanocomposite films J. Mater. Sci. Mater. El. 30 20369–75
[13] Kim G H, Shao L, Zhang K and Pipe K P 2013 Engineered doping of organic semiconductors for enhanced thermoelectric efficiency Nat. Mater. 12 719–23
[14] Kim S I et al 2015 Dense dislocation arrays embedded in grain boundaries for high-performance bulk thermoelectrics Science 348 109–14
[15] Zhao L D, Lu S H, Zhang Y S, Sun H, Tan G J, Uber C,Voltmeron C, Dravid V P and Kanatzidis M G 2014 Ultralow thermal conductivity and high thermoelectric figure of merit in SnSe crystals Nature 508 373–7
[16] Goo G, Anoop G, Unithrattil S, Kim W S, Lee H J, Kim H B, Jung M H, Park J J, Ko H C and Jo J Y 2019 Proton-irradiation effects on the thermoelectric properties of flexible Bi$_2$Te$_3$/PEDOT:PSS composite films Adv. Electron. Mater. 5 1800786
[17] Du Y, Cai K F, Chen S, Cizek P and Lin T 2014 Flexible preparation and thermoelectric properties of Bi$_2$Te$_3$ based alloy nanosheet// PEDOT:PSS composite films ACS Appl. Mater. Interfaces 6 5735–43
[18] Kim W S et al 2020 Feasible tuning of barrier energy in PEDOT:PSS/Bi$_2$Te$_3$ nanowires-based thermoelectric nanocomposite thin films through polar solvent vapor annealing Nano Energy 67 104207
[19] Zheng W W, Bi P, Kang H C, Wei W, Liu F M, Shi J, Peng L X, Wang Z Y and Xiong R 2014 Low thermal conductivity and high thermoelectric figure of merit in p-type Sb$_2$Te$_3$/poly(3,4-ethylenedioxythiophene) thermoelectric composites Appl. Phys. Lett. 105 023901
[20] Ou C, Sangle A I, Datta A, Jing Q S, Busolo T, Chalklen T, Narayan V and Narayan S K 2018 Fully printed organic–inorganic nanocomposites for flexible thermoelectric applications ACS Appl. Mater. Interfaces 10 19580–7
[21] Wei H, Kim S J and Cho B J 2014 Hybrid composite of screen-printed inorganic thermoelectric film and organic conducting polymer for flexible thermoelectric power generator Energy 73 506–12
[22] Shin S et al 2017 High-performance screen-printed thermoelectric films on fabrics Sci. Rep. 7 7317
[23] Caq Z, Kukharlenko E, Rudor M J, Toronto R N and Beebay S P 2013 Screen printed flexible Bi$_2$Te$_3$–Sb$_2$Te$_3$ based thermoelectric generator J. Phys. Conf. Ser. 476 012031
[24] Kim S J, Wei H and Cho B J 2014 A wearable thermoelectric generator fabricated on a glass fabric Energ. Environ. Sci. 7 1959–65
[25] Kim S J, Wei H, Kim J S, Kim G S and Cho B J 2014 Thermoelectric properties of P-type Sb$_2$Te$_3$ thick film processed by a screen-printing technique and a subsequent annealing process J. Alloy. Compd. 582 177–80
[26] Du Y, Li J, Xu J Y and Eklund P 2019 Thermoelectric properties of reduced graphene oxide/Bi$_2$Te$_3$ nanocomposites Energies 12 2430
[27] Lu Y, Ding Y F, Qu Y, Cai K F, Yao Q, Song H J, Yong L, He J Q and Chen L D 2019 Good performance and flexible PEDOT:PSS/Cu$_2$Se nanowire thermoelectric composite films ACS Appl. Mater. Interfaces 11 12819–29
[28] Navone C, Soulier M, Plissonnier M and Seiler A L 2010 Development of (Bi,Sb)2(Te,Se)3-based thermoelectric modules by a screen-printing process J. Electron. Mater. 39 1755–9

[29] Wei Q S, Mukaida M, Kirihara K, Naitoh Y and Ishida T 2014 Polymer thermoelectric modules screen-printed on paper RSC Adv. 4 28802–6

[30] Lu Z Y, Layani M, Zhao X X, Tan I P, Sun T, Fan S F, Yan Q Y, Magdassi S and Hng H H 2014 Fabrication of flexible thermoelectric thin film devices by inkjet printing Small 10 3351–4

[31] Du Y, Tian T, Meng Q F, Dou Y C, Xu J Y and Shen S Z 2020 Thermoelectric properties of flexible composite fabrics prepared by a gas polymerization combining solution coating process Synth. Met. 260 116254

[32] Lee H J et al 2016 Enhanced thermoelectric performance of PEDOT:PSS/PANI–CSA polymer multilayer structures Energy, Environ. Sci. 9 2806–11

[33] Li J, Du Y, Jia R P, Xu J Y and Shen S Z 2017 Thermoelectric properties of flexible PEDOT:PSS/polyprrole/paper nanocomposite films Materials 10 780

[34] Du F P, Cao N N, Zhang Y F, Fu P, Wu Y G, Lin Z D, Shi R, Amini A and Cheng C 2018 PEDOT:PSS/graphene quantum dots films with enhanced thermoelectric properties via strong interfacial interaction and phase separation Sci. Rep. 8 6441