Polymeric Thermoelectric Composites by Polypyrrole and Cheap Reduced Graphene Oxide in Towel-Gourd Sponge Fibers

Meng Xiang, Zhou Yang, Jianxiang Chen, Shilong Zhou, Wenjuan Wei, and Shuang Dong*

ABSTRACT: The thermoelectric (TE) materials can transform thermal energy into electrical energy, and polymer TE composites have attracted increasing interest for flexible semiconductors. However, polymer composites suffer from low TE performances due to the low electroconductibility ($\sigma$). Herein, grafted conducting networks were fabricated by grafting polypyrrole (PPy) onto the cheap graphene of reduced graphene oxide (rGO) in the bundled micro-tunnel of towel-gourd sponge (TS) fibers. Afterward, the TS powders containing grafted conducting networks were cured by the polydimethylsiloxane (PDMS). The PDMS/TS-rGO-PPy composites exhibited an $\sigma$ of 74 S/m, thermal conductivity of 0.249 Wm$^{-1}$K$^{-1}$, Seebeck coefficient of 84.2 $\mu$V/K, and thermoelectric figure of merit of 5.427 x 10$^{-4}$ with 10.0 wt % filler loading. Moreover, dynamic TE properties of our composites under tensile loading were investigated. The results show that the grafted conducting network maintained its integrity by interconnection of PPy between adjacent rGO nano-layers.

1. INTRODUCTION

Nowadays, polymeric thermoelectric (TE) composites have been the pressing issues for substitutes of semiconductors such as Bi$_2$Te$_3$ and PbTe. Polymers are versatile, flexible with good processability, and low cost. Furthermore, polymers have low thermal conductivity ($\kappa$) in the range of 0.1–0.6 Wm$^{-1}$K$^{-1}$, which is beneficial to increase their thermoelectric figure of merit ($ZT$, defined as $S^2\sigma T/\kappa$, where $S$ means the Seebeck coefficient, $\sigma$ means the electrical conductivity, and $T$ means the absolute temperature). Nevertheless, polymer composites suffer from low TE performances due to their low electroconductibility ($\sigma$). Introducing conducting fillers into the polymer hosts can improve their $\sigma$, while $\kappa$ of polymer materials is also increased, which offsets their TE performances. The mainstream to promote the ZT parameter of polymer composites is to optimize the power factor (PF, defined as $S^2\sigma$) through tuning the relationship between $\sigma$ and the Seebeck coefficient ($S$) while suppressing their $\kappa$.

Among the conducting polymers, polypyrrole (PPy) has been considered as a promising candidate for TE materials. As conducting fillers, conducting polymers such as PPy usually show lower $\kappa$, good processability by simpler processes, flexibility, abundance, and low manufacturing costs than semiconductor-based thermoelectric materials. In addition, recent studies suggest that graphene are promising fillers to promote the TE performances for conducting polymers caused by their high $\sigma$, lightweight, and high specific properties. The reduced graphene oxide (rGO) is usually prepared by thermal reduction of graphene oxide (GO), so-called “the cheap graphene” owing to its low cost and large production in an industrial scale. The oxygen-containing groups in rGO are hard to be cleaned up thoroughly under reduction. In this case, such oxygen group defects can be designed and controlled by chemical grafting with other groups. As a sustainable and renewable biomass material, towel-gourd sponge (TS) is widely used as food and cleaning tools in China and Southeast Asia due to its soft and elastic fiber and low cost. It comes from the mature fruit of a towel-gourd plant, which has a natural continuous three-dimensional huge pore assembly as an artificial sponge. Its pore diameter is between 10 and 100 $\mu$m. The pores of tens of microns provide a larger contact area for rGO and PPy grafting, while the pores of hundreds of microns make immersion of the liquid polydimethylsiloxane (PDMS) base easier. Moreover, TS fibers possess continuous one-dimensional micro-tunnels by...
which micro-ordered assemblies with excellent conductivity can be easily manufactured.

In our previous work, electrically conductive composites were prepared by covalently bonding TS fibers with rGO and polyamide-6 molecules. Based on the trans-scale conducting paths inside TS fibers, the composite exhibited electrical conductivity of 0.57 S/m with 1.2 vol % rGO loading.

Herein, we report a simple method to fabricate grafted conducting networks for polymeric TE composites by grafting polypyrrole (PPy) onto the cheap graphene of reduced graphene oxide (rGO) in the bundled micro-tunnel of towel-gourd sponge (TS) fibers. Due to the graft of PPy onto rGO in the conducting network, the PDMS/TS-rGO-PPy composites exhibit high \( \sigma \) and high \( S \). The interfacial effects of phonon scattering resulted in low \( \kappa \) of the composites. Furthermore, dynamic TE performance of the composites under tensile loading was studied.

2. MATERIALS AND METHODS

2.1. Materials. The TS powders were bought from market in Zhongjiang county. RGOs were bought from Sixth Element Materials Technology Company in Jiangsu. The monomers of pyrrole, thionyl chloride (SOCl\(_2\)), potassium hydride, ferric chloride (FeCl\(_3\)), cetyltrimethylammonium bromide (CTAB), stannous octoate, toluene-2,4-diisocyanate (TDI), acetone, ethanol, hydrochloric acid (HCl), and \( N,N \)-dimethylformamide (DMF) were bought from Kelong Company in Chengdu. PDMS (E605) was received from Hongye Company in Shenzhen.

2.2. Methods. 2.2.1. Preparation of TS-rGO-PPy. TS was washed with acetone and deionized water alternately to remove the adhered impurities. After the treatment, TS was dried and ground into powders. The rGO (0.51 g), TDI (0.3 g), and TS powder (1.00 g) were dispersed in DMF (1.0 L) under ultrasonic at 40 °C for 60 min. Then, 30 mg of stannous octoate was dropped in to aggravate the binding between hydroxyls of rGO and hydroxyls of TS fibers with the isocyanate group of TDI. The precursor of TS-rGO was obtained.

The synthesis of TS-rGO-PPy from TS-rGO was followed by a reported procedure. Briefly, 0.3 g of the as-prepared TS-rGO, owning carboxyl on the fringe of rGO layers, was reacted with SOCl\(_2\) in the DMF. At the same time, potassium pyrrole salt was synthesized by pyrrole (2.0 mL) and potassium hydride.
hydride (1.20 g). The acylated TS-rGO was put into the potassium pyrrole salt and stirred at 1 °C for 14 h. After that, the precursor, named as TS-rGO-pyrrole, was obtained. The TS-rGO-pyrrole was dispersed in 0.05 L of HCl under 0 °C. Then, 0.001 g of the pyrrole monomer was dropped into the mixture and stirred for 0.5 h. Then, 0.05 L of 0.58 M FeCl3 and 0.2 g of CTAB was put in and reacted for 8 h. The TS-rGO-PPy was finally acquired by washing with ethanol and water. For comparison, the un-TS-rGO-PPy sample lacking of SOCl2 was prepared in the same way.

2.2.2. Preparation of PDMS/TS-rGO-PPy Composites. The given mass of TS-rGO-PPy was dispersed in the PDMS base by mechanical stirring for 0.5 h. After that, a curing agent was put into the solution and degassed to remove air bubbles. After 20 min of violent stirring under 20 °C, the mixture was put into a polytetrafluoroethylene mold under 100 °C for 50 min to cure. After solidifying, PDMS/TS-rGO-PPy composite samples were obtained, as shown in Figure 1. In our research, the resultant PDMS/TS-rGO-PPy composites were named as PDMS/x TS-rGO-PPy, in which x means the total filler content in the composite. For the sake of contrast, PDMS/TS-rGO composites without PPy were prepared in the same way. The proposed formation scheme of TS-rGO-PPy is shown in Figure 2.

2.3. Measurements. Fourier-transform infrared (FT-IR) curves of the samples were tested by a Nicolet-560 spectrometer (USA). An X-ray photoelectron spectroscopy XSAM 800 spectrometer (KRATOS Co., UK) was used to test the relative element content on the surface of the samples. A scanning electron microscope (SEM, VEGA3-LMH, TESCAN Corp., Czech Republic) was used to survey the surface morphologies of the samples. A Keithley DMM 7510 digital multimeter (U.S.A) and a ZC36 high-insulation resistivity spectrometer (China) were used to measure conductivity of the samples. A MRS-3 L thin-film thermoelectric test system (China) was used to measure the Seebeck coefficient of the samples at room temperature. An NETZSCH-LFA 447 (Germany) instrument was used to measure the thermal conductivity of the samples. The mechanical and thermoelectric coupling measurement system composed of a universal tensile tester, Keithley 2400 source meter, and MRS-3 L thin-film thermoelectric test system was used to test the electrical conductivity and Seebeck coefficient signal of the samples under dynamic loading.

3. RESULTS AND DISCUSSION

3.1. Synthesis of TS-rGO-PPy. The FT-IR curves of rGO, TS-rGO, and TS-rGO-PPy with varying PPy contents are displayed in Figure 3. The rGO shows characteristic absorption bands at 3425 cm\(^{-1}\) (C–OH), 1624 cm\(^{-1}\) (C=O in aromatic ring), and 1380 cm\(^{-1}\) (C–OH deformation).\(^{11}\) TS-rGO manifests the bands at 1052.4 cm\(^{-1}\) (C=O–C pyranose ring), and 894.3 cm\(^{-1}\) (C\(_1\)–H) corresponds to the groups of cellulose in the TS fibers.\(^{12}\) For TS-rGO-PPy samples, the bands at 1541 and 1452 cm\(^{-1}\) correspond to C–C and C–N in the PPy ring, respectively, and the band at 3202 cm\(^{-1}\) (N–H) demonstrate the emergence of PPy. The band at 1171 cm\(^{-1}\) indicates that PPy is in the doping state.\(^{13}\) Moreover, the band belonging to carboxyl is shifted to 1616 cm\(^{-1}\) with increasing PPy content, resulting from the conjugation effect between rGO and PPy.\(^{14}\) All the variations in FT-IR curves demonstrate that PPy has been covalently grafted onto rGO in the TS-rGO-PPy.

![Figure 3. FT-IR data of rGO, TS-rGO, and TS-rGO-PPy with increasing PPy content.](https://dx.doi.org/10.1021/acsomega.0c04356)

The surface components of rGO, TS-rGO, and TS-rGO-PPy are studied by XPS (Figure 4a). The rGO and TS-rGO possess two composition peaks: C \(_1\)s at 284.6 eV and O \(_1\)s at 531.3 eV.\(^{15}\) However, the emerging band of N \(_1\)s arises in TS-rGO-PPy. Moreover, the C/O atomic ratio indicates a significant promotion in TS-rGO-PPy caused by the high proportion of carbon in PPy rings.\(^{16}\) These results confirm that PPy is grafted on rGO.\(^{17}\)

The C\(_{\text{xx}}\) spectrum for rGO (Figure 4b) indicates four component parts: O–C=C at 285.4 eV, C=O at 284.1 eV, C=O at 283.6 eV, and sp\(^3\) C–C with sp\(^2\) C=C at 283.1 eV. For TS-rGO (Figure 4c), all C\(_{\text{xx}}\) band strengths of carbon belong to oxygen, particularly the band of O–C=C(O) diminishes.\(^{18}\) Nevertheless, for TS-rGO-PPy (Figure 4d), the C–N band (283.7 eV) emerges. Furthermore, the \(\pi-\pi^*\) band of the conjugated system at 285.9 eV appears, informing that the \(\pi-\pi^*\) interaction lies betwixt rGO and PPy inside the sample.\(^{19}\) The N\(_{\text{xx}}\) region in Figure 4e displays two bands at 398.5 and 401.4 eV, attributing to pyrrolic N and \(-\text{NH}_2\), separately. These peak positions are in well agreement with those observed for grafted PPy. The FT-IR, XPS results above, Raman, and XRD results in the Supporting Information together demonstrate the graft of PPy on the rGO in the TS fibers.

3.2. Formation of the Grafted Conducting Network. To investigate the grafted conducting network, the micro-tunnel structure of TS-rGO-0.1PPy is conducted by SEM survey. As seen in Figure 5a, the TS fiber diameter is about 250–300 μm. When examined in the transversal surface, the TS fiber includes micro-tunnels, revealing a beehive-like cellular structure (Figure 5b). Such a beehive-like cellular structure possessing micro-tunnels can supply plenty of contact sites for grafting of nano-fillers. In Figure 5c, the PPy are grafted onto the wrinkled surface of rGO in the 3D-bundled micro-tunnel of the TS fiber. Furthermore, in SEM element mappings of TS-rGO-0.1PPy (Figure 5d–f), the carbon and oxygen elements originated from both rGO and PPy, but the nitrogen element was only originated from PPy.\(^{20}\) These results show that rGO and PPy are evenly distributed throughout a selected region of the micro-tunnel. It can be clearly observed from Figure 5g that a lot of PPy are withheld onto the face of rGO in TS-rGO-0.1PPy via the grafting reaction. The two-dimensional lamellar morphology of rGO is hard to be detected in TS-rGO-0.3PPy in the higher PPy content caused by the masking effect of too much PPy particles.
While the agglomerated PPy particles are separated from adjacent rGO nano-sheets in un-TS-rGO-PPy of Figure 5i, attributing to the weak interfacial interaction between rGO and PPy. These results proved that acylated TS-rGO provided more responder loci for pyrrole molecular compared with ungrafted rGO.

### 3.3. Static TE Performance of the Composites

The TS-rGO-PPy (TS fiber incorporated by PPy particles and rGO nano-sheets with a weight ratio of 1:1:0.3 in sequence) was infiltrated with a PDMS host. After that, PDMS/TS-rGO-PPy composites, by varying the PPy dosage, are fabricated by heat treating then at 100 °C to cure the PDMS. For comparison, a series of samples prepared in the absence of PPy were fabricated and were labeled as PDMS/TS-rGO composites by different rGO loadings.

Figure 6 depicts electrical conductivity (σ) of two composites with varying conducting filler contents. Pure PDMS suffers from a poor σ of 3.5 × 10−14 S/m. The σ in PDMS/TS-rGO-PPy composites increases rapidly with PPy loading, and the percolation threshold is about 3.38 wt %. With
the highest PPy loading of 10.0 wt %, the composite possesses a final \( \sigma \) of 74.1 S/m, denoting ultimate improvement of the grafted conducting network.\(^{23}\) However, the \( \sigma \) of the PDMS/TS-rGO composite is always lower than that of the PDMS/TS-rGO-PPy composite, with a higher percolation threshold of 3.61 wt % and ultimate \( \sigma \) of 0.91 S/m, indicating that the graft of PPy can improve the \( \sigma \) of the grafted conducting network.\(^{24}\)

The thermal conductivity (\( \kappa \)) of primitive PDMS is 0.18 W\( \cdot \)m\(^{-1}\)K\(^{-1}\). With increasing filler loading, \( \kappa \) of both two composites rise slowly caused by the high \( \kappa \) of rGO nano-sheets (Figure 7). Totally, \( \kappa \) of both two composites limits about 0.3 W\( \cdot \)m\(^{-1}\)K\(^{-1}\), resulting from the low \( \kappa \) of the PDMS host. Specifically, the \( \kappa \) of the PDMS/10.0 TS-rGO composite increases by 61.3\% (from 0.181 to 0.292 W\( \cdot \)m\(^{-1}\)K\(^{-1}\)) caused by the shorter distances among rGO nano-sheets. The \( \kappa \) of PDMS/TS-rGO-PPy composites rises slower than those of PDMS/TS-rGO composites, resulting from the improving phonon scattering caused by an increased interfacial energy barrier between rGO and PPy in the micro-tunnel of TS fibers. Thus, the phonon transport along the micro-tunnel was prevented, leading in low \( \kappa \) values. Finally, the low \( \kappa \) maintains temperature difference in the composites, resulting in the emergence of charge carriers.

The TE composites should possess a high \( \sigma \) and a low \( \kappa \).\(^{25}\) In addition, based on the equation \( ZT = S^{2}\sigma T/\kappa \), a high Seebeck coefficient (\( S \)) is important for a high ZT parameter.\(^{26}\) Figure 8 shows the \( S \) of the composites under increasing filler content in ambient condition (298.15 K). The \( S \) of PDMS/TS-rGO composites decreases monotonically from 26.4 to 16.9 \( \mu \)V/K with filler loading. This tendency is in accordance with bulk semiconducting materials whose \( \sigma \) often declines while their \( S \) rises.\(^{27}\) For PDMS/TS-rGO-PPy composite samples, \( S \) increases monotonically from 39.0 to 84.2 \( \mu \)V/K with filler loading. The increased \( S \) may be due to the introduction of more interfacial energy barriers in the grafted conducting network that prevent a low-energy carrier from transporting across the interfaces, which agrees well with FTIR results.\(^{28}\) In addition, the one-dimensional micro-tunnel structure in TS fibers can also result in the increase in \( S \) caused by the boundary conducting energy-filtering effect.\(^{22}\) The potential boundary barriers in the interfaces would pre-emptively permit the carriers with high energy to traverse, leading to a stronger scattering of carriers with low energy. At the same time, carriers with high energy are uninfluenced. Hence, the average carrier energy in the flow is grown.\(^{20}\)

The power factor (PF, defined as \( S^{2}\sigma \)) can be used to survey the energy transfer capability of the samples via \( \sigma \) and \( S \). Table 1 shows the PF of the samples under increasing filler content in ambient condition. The calculated PF of PDMS/TS-rGO-PPy composites increases with the filler loading due to the simultaneous improvement of the \( \sigma \) and \( S \). The supreme value of 5.977 \( \mu \)W\( \cdot \)m\(^{-1}\)K\(^{-2}\)\(^{-1}\) is reached for the PDMS/10.0 TS-rGO-PPy composite, nearly 300 multiples more than the PDMS/10.0 TS-rGO composite (0.020 \( \mu \)W\( \cdot \)m\(^{-1}\)K\(^{-2}\)\(^{-1}\)).

Even if former researches indicate the improvement of the TE property by mixing conductive polymers with CNT or rGO,\(^{31}\) the PDMS/TS-rGO-PPy composites here depicts an improvement of the TE property. The improvement of the TE performance is due to two reasons. First is the fabrication of

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**Figure 6.** \( \sigma \) of PDMS/TS-rGO-PPy composites and PDMS/TS-rGO composites with increasing filler content.

**Figure 7.** \( \kappa \) of PDMS/TS-rGO-PPy composites and PDMS/TS-rGO composites with increasing filler content.

**Figure 8.** \( S \) of PDMS/TS-rGO-PPy composites and PDMS/TS-rGO composites with increasing filler content.

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**Table 1. PF and ZT Parameters of PDMS/TS-rGO Composites and PDMS/TS-rGO-PPy Composites with Increasing Filler Loading**

| samples                | PF (\( \mu \)W\( \cdot \)m\(^{-1}\)K\(^{-2}\)) | ZT      |
|------------------------|---------------------------------------------|---------|
| PDMS/2.5 TS-rGO-PPy    | 2.740 \times 10^{-5}                        | 3.667 \times 10^{-8} |
| PDMS/5.0 TS-rGO-PPy    | 2.343 \times 10^{-2}                        | 2.966 \times 10^{-4} |
| PDMS/7.5 TS-rGO-PPy    | 1.829 \times 10^{-1}                        | 2.094 \times 10^{-4} |
| PDMS/10.0 TS-rGO-PPy   | 5.246 \times 10^{-1}                        | 5.427 \times 10^{-4} |
| PDMS/2.5 TS-rGO        | 7.667 \times 10^{-7}                        | 9.055 \times 10^{-10} |
| PDMS/5.0 TS-rGO        | 1.452 \times 10^{-4}                        | 1.447 \times 10^{-7} |
| PDMS/7.5 TS-rGO        | 1.818 \times 10^{-4}                        | 1.402 \times 10^{-7} |
| PDMS/10.0 TS-rGO       | 2.599 \times 10^{-4}                        | 1.688 \times 10^{-7} |
the grafted conducting network structure by the graft of PPy onto rGO, which unites the high $\sigma$ of rGO nano-sheets and the low $\kappa$ of PPy nanoparticles. The grafted conducting network greatly facilitates the carrier movement. The covalent combination between PPy and rGO supplies speedy conductive paths for electron transmission. Second, the robust interface $\pi-\pi$ interactions between rGO and PPy are important for this improvement. The ordered arrangement along the 1D micro-tunnel decreases the $\pi-\pi$-conjugated drawbacks in the PDMS host and reduces the carrier-hopping barrier. Thus, the carrier movability is enhanced.

The ambient condition ZT parameters of all the composites are also reckoned (Table 1). The ZT parameter of PDMS/TS-rGO-PPy composites showed growth after adding their filler loading from 2.5 to 10 wt %. The low $\kappa$ and the enhanced $\sigma$ and $S$ generate a maximum ZT parameter of $5.427 \times 10^{-4}$ for the PDMS/10.0 TS-rGO-PPy composite, which is approximately thousands of times higher than that of the PDMS/10.0 TS-rGO composite. The ZT parameter obtained here is a little lower than that of the conducting polymer-based bulk materials, for instance, the PANi-41.4 wt % carbon nanotube composite (highest ZT of $4.0 \times 10^{-3}$ at 300 K)$^{33}$ and PANi-50 wt % graphite composite (highest ZT of $1.4 \times 10^{-3}$ at 390 K). However, the filler content in our composites is much lower than them (10 wt % compared with 41.4 and 50 wt %), which brings in good flexibility for the PDMS/TS-rGO-PPy composites. In view of applications for flexible TE composites in wearable devices, the dynamic TE properties of our composites under tensile loading should be investigated.

3.4. Dynamic TE Properties of the Composites under Tensile Loading. To evaluate the influence of tensile loading on TE parameters of the composites, $\sigma$, $S$, and the corresponding PF response characteristics of the PDMS/10.0 TS-rGO composite and PDMS/10.0 TS-rGO-PPy composite over a single cycle are tested. The $\sigma$ of both composites declined evidently as the strain increased (Figure 9a), owing to an increase in the spacing among conducting filler nanoparticles making up the grafted conducting network and partial breakdown of the network. During the releasing process, the spacing between the nano-particles constituting the grafted conducting network became smaller, and parts of the damaged conducting network were recovered, thereby increasing the $\sigma$. The variation degree of the PDMS/10.0 TS-rGO-PPy composite is lower than its counterpart caused by the strong covalent bonding between PPy and rGO in the grafted conducting network. The $S$ (Figure 9b) of both composites changed a little during the tensile cycle, maybe resulting from the fact that the expansion of the interfacial energy barrier was prevented by the flexibility of TS fibers. Finally, the changing trend of PF is similar with $\sigma$ of both composites under tensile loading (Figure 9c). Nevertheless, the maintaining of $S$ delays the rapidly decrease in PF.

Microstructural changes in both composites were investigated by SEM with in situ mode to demonstrate the variation in the grafted conducting networks under elongation. As shown in Figure 10a, the conducting network in the PDMS/10.0 TS-rGO composite was concentrated and integral before elongation. However, the conducting network became sparse and fractured (shown in red lines) after elongation of 30.0% strain in Figure 10b. The PDMS/10.0 TS-rGO-PPy composite and the fringe of rGO nano-layers were grafted by PPy in the conducting network in Figure 10c. After elongation, the density of the grafted conducting network became smaller; however, the grafted conducting network maintained its integrity by interconnection of PPy (shown in green lines) between adjacent rGO nano-layers in Figure 10d.
more conductive paths are reserved, which delayed the rupture of the grafted conducting network under stretching cycles, and result in the higher σ and stable S values.

4. CONCLUSIONS

Grafted conducting networks for polymeric TE composites were simply fabricated by grafting PPy onto the rGO surface in the bundled micro-tunnel of TS fibers (TS-rGO-PPy). The XRD, Raman, FTIR, XPS, and TGA results confirmed the high grafting ratio. SEM results showed that the grafted conducting network was spatially established. The obtained PDMS/TS-rGO-PPy composites exhibited a high σ of 74 S/m and S of 84.2 μV/K with 10.0 wt % filler loading due to the unique multi-dimensional architecture of the grafted conducting network. Meanwhile, the composite showed a depressed κ of 0.249 W·m⁻¹·K⁻¹ with the same filler content, resulting from the interfacial effects of phonon scattering. These results together led to a PF of 5.977 μW·m⁻¹·K⁻² and ZT parameter of 5.427 × 10⁻⁴ for the PDMS/10.0 TS-rGO-PPy composite. The dynamic TE properties of the samples under tensile loading were surveyed and showed that the grafted conducting network maintained its integrity by interconnection of PPy between adjacent rGO nano-layers. Therefore, more conductive paths are reserved, which delayed the rupture of the grafted conducting network under stretching cycles and resulted in the higher σ and stable S values. The design strategy proposed here may be applied as a general design rule for high TE performance polymer-based nanocomposites, such as implantable and wearable electronics.

ASSOCIATED CONTENT

Supporting Information
The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acsomega.0c04356.

AFM and TEM tests of rGO; Raman spectra of rGO, TS-rGO, and TS-rGO-PPy with varying PPy contents; XRD spectra of rGO, TS-rGO, and TS-rGO-PPy with varying PPy contents; TGA curves of rGO, TS-rGO, and TS-rGO-PPy with varying PPy contents; and TEM image of TS-rGO-PPy in the composites (PDF).

AUTHOR INFORMATION

Corresponding Author
Shuang Dong — School of Chemical Engineering and Materials, Changzhou Institute of Technology, Changzhou 213032, China; orcid.org/0000-0002-8992-225X, Email: dongs@czu.cn

Authors
Meng Xiang — School of Materials Engineering, Jiangsu University of Technology, Changzhou 213001, China
Zhou Yang — School of Materials Engineering, Jiangsu University of Technology, Changzhou 213001, China
Jianxiang Chen — School of Materials Engineering, Jiangsu University of Technology, Changzhou 213001, China
Shilong Zhou — School of Materials Engineering, Jiangsu University of Technology, Changzhou 213001, China
Wenjuan Wei — School of Materials Engineering, Jiangsu University of Technology, Changzhou 213001, China

Complete contact information is available at: https://pubs.acs.org/doi/10.1021/acsomega.0c04356

Notes
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Figure 10. SEM graphs of the inwall of TS-rGO in the PDMS/10.0 TS-rGO composite (a) before and (b) after elongation of 30.0% strain. Inwall of TS-rGO-PPy in the PDMS/10.0 TS-rGO-PPy composite (c) before and (d) after elongation of 30.0% strain.
by conductive cellulose skeleton structure and its conductive behavior. 

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