Contributions to composite conductivity and Seebeck coefficient in commercial Bi$_2$Te$_3$—Conjugated polymer composites

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ABSTRACT
We demonstrated the use of as-received conjugated polymer P3HT [poly (3-hexylthiophene-2,5 diyl)] doped with F4TCNQ (2,3,5,6-tetrafluoro-7,7,8,8-tetracyanoquinodimethane) as a matrix for forming a composite with as-received, commercially available p-type Bi$_2$Te$_3$ powder. The optimized formulation exhibits a power factor of up to 5.3 $\mu$W K$^{-2}$m$^{-1}$, about nine times higher than the highest power factor that we achieved from mixtures of only P3HT and F4TCNQ. Bi$_2$Te$_3$ was responsible for increases in both the Seebeck coefficient and the electrical conductivity. P3HT, with a higher hole mobility, was superior to PQT-12 [poly(bisdodecylquaterthiophene)], and F4TCNQ was at least as good as FeCl$_3$, for matrix and dopant, respectively, for this purpose. The power factor obtained is about 40% of that reportedly obtained from synthesized Bi$_2$Te$_3$ nanowires in FeCl$_3$-doped P3HT. We calculated the expected contributions of the bulk Bi$_2$Te$_3$ to the composite conductivity and then examined the resistance caused by interfaces on four different size distributions of Bi$_2$Te$_3$ particles, as well as a solid macroscopic ingot. A nonlinear I–V relationship was found for the doped P3HT-ingot bilayer. While our doped conjugated polymer system made only from commercial-grade components was shown to support the extraction of thermoelectric performance by a commonly used inorganic semiconductor, our results also suggest that an advantage of the smallest Bi$_2$Te$_3$ domains, including nanowires, may arise from their having less interfacial resistance than larger Bi$_2$Te$_3$ particles and pieces.

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I. INTRODUCTION
The relationship of energy conversion for thermoelectric performance is

$$ZT = S^2\sigma T / \kappa,$$

where $S$ is the Seebeck coefficient (also known as thermopower, the change in voltage with the change in temperature), $\sigma$ is the electrical conductivity, $T$ is the temperature in Kelvin, and $\kappa$ is the thermal conductivity.$^{1,2}$ The power factor $P$ incorporates the Seebeck coefficient and electrical conductivity according to the equation $P = S^2\sigma$. While the original thermoelectric materials, such as Bi$_2$Te$_3$, are inorganic, organic materials have recently been considered because of their potential printability, mechanical flexibility, and use of earth-abundant elements,$^3$ as described in multiple comprehensive reviews.$^4$–$^7$ Many of the organic materials are conjugated thiophene polymers, including the prototypes poly(3-hexylthiophene-2,5 diyl) (P3HT) and poly(3,3’-didodecylquaterthiophene) (PQT-12). While in special cases,
power factors of about 10 μW/mK² can be obtained from all-organic systems,⁴⁹ values of 1 μW/mK² are more typical.¹⁰ Thus, it is attractive to use polymers as matrices of hybrid materials in which the higher performance characteristics of inorganic or all-carbon materials can be captured. The cited reviews list a wide range of polymer choices, including P3HT as a representative conjugated polymer and even the nonconjugated polymers poly(vinylidene fluoride), poly(vinyl acetate), and poly(lactic acid). The possible inorganic and carbon materials are even more varied, including heavy element alloys and compounds of bismuth, lead, and tin as metal element components and selenium and tellurium as nonmetallic element components. Tellurium and nickel themselves were used in nanowire form, and germanium in nanoparticle form. Metal dichalcogenide layered solids such as titanium, tantalum, and molybdenum sulfides are another class of inorganic phase. Carbon nanotubes, graphene, and graphene oxide are also widely used as additives to polymer matrices. For some outstanding hybrids, that may have included ionic contributions, power factors reportedly exceeded 100 μW/mK².

Bi₂Te₃ powder as received and compared with two other processed forms, and the organic dopant F4TCNQ. With this material set, we observe the pronounced contribution of Bi₂Te₃. The highest power factor we obtained, about 5.3 μW/mK², came from the as-received form and is 40% of the value that was reported by He et al.¹⁶ for the specifically synthesized nanowire-polymer combination. The influence of charge carrier mobility of the matrix polymer on the composite performance was also shown. Finally, we distinguish contributions to conductivity from bulk Bi₂Te₃ and to resistance from the interfaces around the Bi₂Te₃ domains in order to point out possible reasons for the enhancements reported previously.¹⁶

II. EXPERIMENTAL SECTION

A. Materials

Commercial P3HT [poly(3,3’-didodecylquaterthiophene)] was purchased from Solaris Chem Inc. Commercial F4TCNQ (2,3,5,6-tetrafluoro-7,7,8,8-tetracyanoquinodimethane) was purchased from Ossila. Commercial Bi₂Te₃ powder, 99.99% trace metals basis, was purchased from Sigma Aldrich. A 200 g p-type bismuth telluride ingot was purchased from Thermoelectric Generator.

B. Sample preparation

1. Films

P3HT powder was dissolved into chlorobenzene with a concentration of 10 mg (P3HT)/ml (chlorobenzene). F4TCNQ was dissolved into chlorobenzene with a concentration of 2 mg (F4TCNQ)/ml (chlorobenzene). The P3HT solution was heated on a hot plate at 45 °C for 30 min. The F4TCNQ solution was heated on a hot plate at 60 °C for 30 min. The two solutions were combined, with further heating at 60 °C for 30 min. Bi₂Te₃ powder was added directly into the mixed solution, which was then heated at 60 °C for 1 h.

The solution was drop cast onto a glass substrate with 2 gold electrodes on it. The glass substrate was precleaned with deionized water, acetone, and 2-propanol. The gold electrodes were prepared by thermal evaporation and their thickness was 50 nm. The film area was 7 mm long and 9 mm wide. The width of the gold electrodes and that of the space between the 2 electrodes was 3 mm. After most of the solvent was evaporated from the dropcast films, they were baked at 60 °C in a nitrogen filled glove box. Above that temperature, we found significant electronic property degradation.

2. Ingot devices

Aliquots of solutions of P3HT and F4TCNQ were blended together to form doped polymer solutions that contained 30% and 40% by weight of the dopant. These solutions were heated at 50 °C and sonicated for 30 min to create the doped polymer solutions. Gold electrodes were evaporated onto glass substrates with a channel length of 2.75 mm and a channel width of 5 mm. Novec 1700 fluorinated polymer was used to pattern the substrate by forming rectangular wells around 4 parallel electrodes. The substrate was cut along the patterning to form pieces, each of which containing 4 electrodes surrounded by the Novec coating. The bismuth telluride ingot was cut by hand to form pieces that were between 80 μm and 180 μm in thickness. The lengths of the pieces were between 1.67 mm and 1.81 mm, and the widths were between 2.35 mm and 2.66 mm. These Bi₂Te₃ pieces were centered between the two center electrodes, and the doped polymer solution was drop cast over this configuration and left to dry overnight to form the devices. Bismuth slices were also prepared by machine sawing.

3. Ball-milled powder

As-received Bi₂Te₃ particles and stainless steels ball were mixed in 1:10 weight ratio and placed into stainless steel jars in a glove box in a nitrogen atmosphere. Isopropyl alcohol (IPA) was added as a solvent to the particles in 1:1 weight ratio. Ball milling was performed using an Across International ball milling machine at 35 Hz speed for 150 min. The ball milling solvent was evaporated at 35 °C for 3 h in the glove box and the particles were sieved into clean glass jars.
C. Characterization

Dropcast polymer film thickness was measured using a laser microscope and was consistently 2 μm +/−25%. Surface morphology was characterized using scanning electron microscopy (SEM). Carbon coating prior to imaging was performed in an Edwards 306 system. The microscopy was performed in a JEOL 6700 F cold field emitter SEM. S and σ were measured using techniques previously described.17 Voltage and temperature difference were each probed over the electrodes for S measurement, while σ was measured using four points, two over the electrodes and two in the space between the electrodes. When measuring the resistances across the pieces of the Bi₂Te₃ ingot coated in the polymer, a portable digital multimeter was used. The distances between the probes, widths and lengths of the films and Bi₂Te₃ pieces, and film thicknesses were measured using a KEYENCE VK-X100 laser microscope. These measurements were used together to calculate the apparent resistivity and apparent conductivity. The step-by-step procedure for characterizing samples with small ingot pieces is integrated with Sec. III.

III. RESULTS AND DISCUSSION

We first checked the thermoelectric parameters of pure commercial P3HT, which were very poor. The typical conductivity was \(10^{-4}\) S/cm and \(S\) was about 800 μV/K, for a power factor of about 0.001–0.01 μW K⁻² m⁻¹. We then characterized P3HT with F4TCNQ added at various weight ratios. We found that a weight ratio of 2:1 [66.6% (P3HT):33.3% (F4TCNQ)] gave the best parameters. The average power factor was 0.5 μW/m K² (standard deviation: 0.4, highest: 0.9), from a conductivity of 3 S/cm (resistivity: 0.3 Ω cm) and \(S\) of 40 μV/K. Both of these materials give parameter pairs that correspond exactly with recently published empirical relationships.16,18

We added the commercial, as-received Bi₂Te₃ powder at different weight ratios into the P3HT-F4TCNQ solution. Thermoelectric parameters are listed for these ratios in Table I. The evolution is also shown graphically in Fig. 1.

We found that the best ratio for the 3 materials is 2:1:10 (weight ratio, P3HT:F4TCNQ:Bi₂Te₃) or 15% polymer, 8% dopant, and 77% Bi₂Te₃. Because the density of Bi₂Te₃ is between 7.5 and 8, this corresponds to about 1/3 of the volume fraction. We reached a maximum power factor of 5.3 μW/m K², average power factor: 4.2 μW/m K², and standard deviation: 1.0, about 9 times higher than for the P3HT/F4TCNQ device. This conclusion is based on three P3HT/F4TCNQ devices and three P3HT/F4TCNQ/Bi₂Te₃ devices. The power factor is higher than typical (in the upper quartile) for a simple doped

<table>
<thead>
<tr>
<th>Weight ratio</th>
<th>Seebeck coefficient (μV/K)</th>
<th>Conductivity, resistivity (S/cm, ohm cm)</th>
<th>Maximum power factor (μW/m K²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2:1:5</td>
<td>58</td>
<td>4, 0.25</td>
<td>1.2</td>
</tr>
<tr>
<td>2:1:10</td>
<td>87</td>
<td>7, 0.14</td>
<td>5.4</td>
</tr>
<tr>
<td>2:1:14</td>
<td>62</td>
<td>6, 0.17</td>
<td>2.4</td>
</tr>
<tr>
<td>2:1:20</td>
<td>44</td>
<td>1.2, 0.8</td>
<td>0.23</td>
</tr>
</tbody>
</table>

![FIG 1](https://example.com) Evolution of thermoelectric parameters with increasing addition of the as-received Bi₂Te₃ powder to polymer and F4TCNQ in 2:1 ratio. The multiples along the x-axis refer to the relative amounts of Bi₂Te₃ to the polymer.
polymer with this conductivity.\textsuperscript{17,18} As the ratio of Bi$_2$Te$_3$ to P3HT exceeds 5:1, the thermoelectric performance of the composite starts to decrease. This seems to be because too much Bi$_2$Te$_3$ powder will compromise the integrity and continuity of the composite, creating highly resistive interruptions in the form of cracks or voids and uneven distribution of the powder. As will be seen later, this effect is more pronounced with ball milled Bi$_2$Te$_3$.

When we used PQT-12 in these doped composite formulations instead, we achieved a power factor of 0.96 $\mu$W/m K$^2$. This is also $\sim$9 times higher than what we obtained from PQT-12 and F4TCNQ composite, but not quite as high as for the P3HT samples, as shown graphically in Fig. 2. We spincoated pure P3HT/PQT-12 onto 300 nm SiO$_2$ wafers under the same conditions as used for forming composite films and vapor-deposited gold electrodes to form field-effect transistors. Mobilities measured from these devices were 0.001 and 0.0004 cm$^2$/V s (10\% standard deviations). The higher P3HT mobility was consistent with the higher power factor it seems to confer. The absolute mobility is lower than what is sometimes obtained from transistors\textsuperscript{19} because the annealing temperature that we used was lower than what has been suggested for transistors,\textsuperscript{18} to match what was used for doped samples.

We also performed the experiment analogous to the study that used FeCl$_3$ and Bi$_2$Te$_3$ nanowires in P3HT.\textsuperscript{15} We doped P3HT with FeCl$_3$, with a weight ratio of 30\%-33\% FeCl$_3$ to P3HT by adding FeCl$_3$ powder to the P3HT solution, as done in the previously published study. Because FeCl$_3$ is only slightly soluble in chlorobenzene, we also made a comparison experiment to check if there is difference between adding the FeCl$_3$ powder directly into the P3HT solution and adding the FeCl$_3$ solution [50 °C heated, sonicated for 30 min, using very dilute FeCl$_3$ (2 mg/ml) in chlorobenzene] into the P3HT solution, which we found gave better results and was therefore done to produce data reported here. The highest thermoelectric performance we obtained from FeCl$_3$-doped P3HT was 24 $\mu$V/K for the Seebeck coefficient and 21 S/cm for the electrical conductivity. A power factor of 3.8 $\mu$W/m K$^2$ was achieved from these data, of the same order but not exceeding what we obtained from F4TCNQ.

To gain further insight into P3HT–Bi$_2$Te$_3$ interactions, the organic and inorganic materials were deployed so the resistance at the interface between the two materials could be assessed. P3HT was doped with F4TCNQ in amounts of 30\% and 40\% by weight. Macroscopic sized pieces of Bi$_2$Te$_3$ were combined with F4TCNQ doped P3HT in a manner such that the devices mirrored the functionality of 2 resistors in series with an additional pair of parallel resistors (referred to here as a “bilayer”). The device architecture is illustrated schematically in Fig. 3. Using this architecture, the

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig2}
\caption{Graphical comparison of composite power factor and polymer hole mobility of P3HT and PQT-12.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig3}
\caption{Domains of doped P3HT in series with Bi$_2$Te$_3$ and P3HT in parallel, with schematic circuit diagram.}
\end{figure}
resistances of the bilayer devices could be compared to the resistances of the polymer and Bi$_2$Te$_3$ segments of these devices. By doing so, it is possible to determine the magnitude of interfacial resistance between the two materials.

A diagram of the final device architecture can be seen in Fig. 4, along with a top view image of a completed device. This architecture was chosen so that measurements could be taken across the polymer film by measuring across electrodes 1 and 2 or electrodes 3 and 4. Taking measurements across electrodes 2 and 3 would then provide resistance values for the bilayer material. Before performing measurements, the devices were annealed at 60 °C for 10 min in a glovebox under N$_2$.

Resistances of the polymer film were measured and compared with resistance values taken across the bilayer material (polymer and Bi$_2$Te$_3$ piece in parallel). The resistance measurements across the polymer films were carried out by placing the four probes equal distances apart with the current probes across electrodes 1 and 2 or across 3 and 4 and by placing the voltage probes between the current probes. Measurements on the bilayer portions were carried out by placing the voltage probes across electrodes 2 and 3 and the current probes on electrodes 1 and 4. These measurement configurations are shown in Fig. 5.

To assure that the probe contacts were secure, additional gold electrodes were evaporated on top of the polymer portion of the devices and on top of the bismuth telluride pieces coated in P3HT. These electrodes were 50 nm in thickness, with a channel length of 0.25 mm. The polymer portions were again measured using the 4-probe method, with the voltage probes placed on these new electrodes. Measurements on the Bi$_2$Te$_3$ bilayers were performed using a handheld multimeter, with the one probe placed on each electrode on top of the bilayer. To determine the magnitude of the interfacial resistance, the resistances of the polymer portion and the bismuth telluride with polymer coating portion (“bilayer”) were calculated to estimate each of their individual contributions to the overall bilayer resistance. Resistances measured with and without the additional gold electrodes were consistent.

Apparent resistivities for the Bi$_2$Te$_3$ pieces (1 m$^2$ cm$^2$) coated with doped P3HT were much lower than those of just the doped polymers (0.3 Ω cm), though the measured resistances for the Bi$_2$Te$_3$ pieces were slightly higher than the values measured for Bi$_2$Te$_3$ alone. This would stand to reason because the probes were placed on the polymer film coating the Bi$_2$Te$_3$. The current produced by the measurement probes travelled out of one probe, through the polymer film, into Bi$_2$Te$_3$, through the film again, and into the other probe. Therefore, the polymer film contributed to the overall resistance, causing the probe measurements to give larger resistance values than those gathered from the pure Bi$_2$Te$_3$.

With the apparent resistivities of both the polymer and the Bi$_2$Te$_3$ coated in polymer, the resistance contribution of each to the bilayer devices could be estimated. The length of the Bi$_2$Te$_3$ bilayer segments was measured using the laser microscope. Then, as the voltage probes were placed on electrodes 2 and 3 and that distance between those was measured to be 2.75 mm, the length of the polymer film between the probes and the Bi$_2$Te$_3$ pieces was calculated by subtracting the width of each piece from 2.75 cm. We found that the total observed resistance was about 300 Ω higher than would have been expected from the sum of resistances of the individual materials in series, which was of the same order of magnitude. Thus, either the current is not entering Bi$_2$Te$_3$ at all, or the current is entering Bi$_2$Te$_3$, but experiencing a high interfacial resistance that increases the total resistance measured substantially. In either case, the results seem to suggest the presence of a substantial interfacial resistance that is either causing the current to avoid Bi$_2$Te$_3$ altogether and go through the polymer film, or it goes through Bi$_2$Te$_3$, but only after overcoming the resistance at the interface. This leads us to hypothesize that Bi$_2$Te$_3$ particles above a certain critical size show interfacial resistance that is of the same magnitude as the resistance of a similarly sized domain of doped polymer.

We considered two possible origins for the interfacial resistance. Most simply, there could be a lack of complete wetting of the
Bi$_2$Te$_3$ particles by polymer as the films formed and dried. It is conceivable that the largest particles, with the largest absolute roughnesses as well, may be the least wettable by P3HT and thus present the largest interfacial resistances. A more substantial reason would be an interfacial electronic barrier between the polymer and Bi$_2$Te$_3$. A recent statement of the work function of Bi$_2$Te$_3$ is 5.3 eV. There is a range of reported highest occupied molecular orbital (HOMO) values for P3HT, with a recent average value being 4.9 eV. Thus, a band offset between these materials is plausible.

Figure 6 shows representative I–V plots for two-probe vertical measurements on bilayer samples where one layer is a cleaved slice from a Bi$_2$Te$_3$ or a packed Bi$_2$Te$_3$ powder, and the other layer is drop-cast 2:1 P3HT:F4TCNQ, on top of the ingot and contacted with gold, or under the Bi$_2$Te$_3$ powder and contacted via an indium tin oxide (ITO) substrate. Bi$_2$Te$_3$ and its polymer interface were the limiting resistors. For both kinds of samples, we observed space charge limited current-like or Schottky diode-like behavior, as current dependence on voltage raised to a power showed an increase in the power from close to 1 (ohmic) at 0–1 V between top and bottom contacts to a power near 2 at 1–4 V between the contacts. A similar nonlinear space charge limited current behavior was reported for molybdenum oxides with the organic hole transport material N,N'-diphenyl-N,N'-bis(1-naphthyl)-1,1'-biphenyl-4,4'-diamine (NPD), associated with interfacial electronic effects. The work functions of P3HT and higher work function ITO were offset enough for contact doping to occur.

Every length of Bi$_2$Te$_3$ should decrease the resistive effect of the polymer fraction along a series path. For 1/3 of the volume fraction, particles would be on average 44% of the total length of a series path if they were perfectly isotropic and fit entirely inside the polymer film, so series resistance of the composite would be 56% of that of the doped polymer alone (3 S/cm), making the apparent conductivity 1.8 times higher in the composite than in doped P3HT alone, or between 5 and 6 S/cm, which is close to what we measured (Table I). However, as shown in the SEM images of Fig. 7, the particles are obviously not isotropic, and their larger dimensions are more likely to be parallel to the conducting path (horizontal) than vertical because of how they would settle in a drying polymer film. Finally, particles with their smallest dimension <1 µm would contribute more proportional length to the conducting path, in parallel with polymer in which they were embedded. This would make the 5–6 S/cm value a lower limit of the predicted conductivity. However, every pair of interfaces would add some additional measured resistance, as determined from the above experiment. Particularly high-resistance interfaces would simply be avoided, while current would go through lower-resistance interfaces in order to enter the much lower-resistance particles. It seems that the effects of particle anisotropy and interfacial resistance cancel each other out in our composite samples. Furthermore, because the measured
resistances in our composite samples (3:1 W/L ratios) were on the order of 100–1000 Ω, the added resistance from interfaces appears to be the equivalent of just a few times the macroscopic ingot-like interfacial resistance. Representative SEM micrographs of our samples are shown in Fig. 7, illustrating the particles distributed throughout the samples, from fractions of a micrometer to several millimeters in size.

Figure 7(a) shows a representative SEM image for one of our highest conductivity composite samples. The measured resistance across the 3 mm device length of our standard 9 mm-wide sample was 200 Ω. Because of the relatively few large particles and many small, needle-like particles, the interfacial resistance contribution was noticeable but not particularly deleterious. On the other hand, Fig. 7(b), which is from a sample in which the largest particles were preferentially dislodged from a P3HT–F4TCNQ–Bi2Te3 2:1:10 chlorobenzene suspension by sonication and overrepresented in the sample. Because of the increased number density of large particles, the measured resistance was 1 kΩ, five times higher. This comparison, along with the measurements on the single pieces of ingot, suggests a particle-size dependence of the interfacial resistance.

Additional doped P3HT composite samples were made from Bi2Te3 that were ball milled. These samples, which were also of the same nominal composition and film thickness as the ones above, show slightly lower conductivity, 1–3 S/cm, than the best sample made from commercially obtained Bi2Te3. While such samples show few, if any, particles >2 μm, there are many particles altogether >100 nm in size, and fewer that are <100 nm, so that the interfacial resistance could still be a factor. The interfaces are less regularly shaped and may have been chemically changed by the milling. However, it also seems that the particles showed greater tendency to cluster during the drop casting, including at film boundaries outside the conducting path, so large portions of the films have relatively fewer particles than in the above case. The resistance measured for the sample used in the micrograph of Fig. 7(c) was about 600 Ω. Considering this clustering tendency, it seems that the interfacial contribution to the resistance of this sample was lower than for the samples made from the commercial Bi2Te3 powder.

Finally, we checked samples made from a hammer-crushed, powdered Bi2Te3 ingot from the same source that was used for the pieces to measure the individual interfacial resistances. The crushing process led to the largest distribution of particle sizes, with a few large chunks but also many submicrometer needle-like and dot-shaped features, as shown in Fig. 7(d). This sample had a low resistance of 250 Ω (although its Seebeck coefficient of 17 μV/K was lower as well, so the material of this ingot is not as effective as the commercial powder for high power factor).

IV. DISCUSSION AND CONCLUSION

We demonstrated that thermoelectric contributions of as-received Bi2Te3 powders are obtainable in mixtures of commercially available conjugated polymers and dopants. Compared with Ref. 15, the major differences are the dopant and the Bi2Te3 powder we used. The dopant F4TCNQ results in lower conductivity but higher Seebeck coefficient than FeCl3. The Bi2Te3 source is likely a more important difference with the prior work. We obtained Seebeck coefficients that were similar to those reported in the prior work, but lower conductivities. After observing a direct interfacial resistance between doped P3HT and single macroscopic pieces of Bi2Te3, we hypothesize that this resistance is dependent on the Bi2Te3 particle size. While crystallinity and interconnectivity may also be better in nanowire composites, interfacial resistance...
lowering is another possible reason for the superiority of the nanowire composite. It is possible that for the nanowire case, this interfacial resistance is related to the energy filtering phenomenon that was proposed as an explanation for enhanced Seebeck coefficients. On the other hand, interfacial resistance could also be used as a modifying parameter in series and parallel models that might also be sufficient to explain composite properties, as was recently explained for a P3HT-tellurium system.24

We considered whether percolation theory was consistent with our results or not. The SEMs shown in Fig. 6 do not indicate obvious percolation among the Bi2Te3 domains, as was also the case for the micrographs of He et al.25 Even so, if the domains were percolated, then they would have formed a parallel conducting path alongside the polymer matrix. With a 1/3 volume fraction of Bi2Te3 and a parallel model,25 taking our determined values of 3 S/cm for $\sigma$ and 40 $\mu$V/K for S of the polymer phase and literature values26,27 of 200 S/cm and 150 $\mu$V/K for the p-type Bi2Te3, we would calculate unrealistically high values of 70 S/cm and 140 $\mu$V/K for our materials.

Finally, our work did demonstrate that a significant fraction (about a third) of the nanowire composite power factor can be achieved using only readily available commercial materials with minimal processing. The combination of conductivity and the Seebeck coefficient that we obtained is also in agreement with recently published empirical relationships.

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