Achieving High Thermoelectric Performance and Metallic Transport in Solvent-Sheared PEDOT:PSS

Allison C. Hinckley, Sean C. Andrews, Marc T. Dunham, Aditya Sood, Michael T. Barako, Sebastian Schneider, Michael F. Toney, Kenneth E. Goodson, and Zhenan Bao*

Polymer-based materials hold great potential for use in thermoelectric applications but are limited by their poor electrical properties. Through a combination of solution-shearing deposition and directionally applied solvent treatments, poly(3,4-ethylenedioxythiophene):poly(styrenesulfonate) (PEDOT:PSS) thin films with metallic-like conductivities can be obtained with high power factors in excess of 800 μW m⁻¹ K⁻². X-ray scattering and absorption data indicate that structural alignment of PEDOT chains and larger-sized domains are responsible for the enhanced electrical conductivity. It is expected that further enhancements to the power factor can be obtained through device geometry and postdeposition solvent shearing optimization.

1. Introduction

The growing market of wearable technologies has pushed scientific and industrial efforts in extending battery life through utilization of other power sources, including movement, pressure, and heat. The last of these can be accomplished through the use of thermoelectric devices, which directly convert heat to electricity. The efficiency of this solid-state conversion relates to the material-specific figure of merit $zT = \frac{S^2 T}{\kappa}$, where $S$, $\sigma$, $\kappa$, and $T$ are the Seebeck coefficient, electrical conductivity, thermal conductivity, and mean absolute temperature, respectively.

Dr. A. C. Hinckley, Dr. S. C. Andrews, S. Schneider, Prof. Z. Bao
Department of Chemical Engineering
Stanford University
Stanford, CA 94305, USA
E-mail: zbao@stanford.edu

Dr. M. T. Dunham, Dr. M. T. Barako, Prof. K. E. Goodson
Department of Mechanical Engineering
Stanford University
Stanford, CA 94305, USA

Dr. A. Sood
Stanford Institute for Materials and Energy Sciences
SLAC National Accelerator Laboratory
Menlo Park, CA 94025, USA

Prof. M. F. Toney
Stanford Synchrotron Radiation Laboratory
Menlo Park, CA 94025, USA

Prof. M. F. Toney
Department of Chemical and Biological Engineering
University of Colorado Boulder
Boulder, CO 80309, USA

The ORCID identification number(s) for the author(s) of this article can be found under https://doi.org/10.1002/aelm.202001190.

DOI: 10.1002/aelm.202001190
increased carrier mobility and improved molecular ordering.\cite{6,14} Seebeck coefficient can be further tuned by treating PEDOT:PSS films with n-type dopants to tune the oxidation level and carrier concentration.\cite{6,15–17} Solvent treatment in PEDOT:PSS films both pre- and postdeposition resulted in a record for solution-processable, organic \(zT\) of 0.42.\cite{18} While polymer materials can be deposited via different techniques, the chosen method can have a significant effect on the film morphology and the resulting properties of the deposited material due to molecular alignment and the conversion from solution phase to solid phase.

Recently, an electrical conductivity of \(\approx 6200 \text{ S cm}^{-1}\) in a PEDOT system was achieved through improvement of the morphology and doping level of the polymer using oxidative chemical vapor deposition.\cite{19} Similar improvements to conductivity have been reported for solution-deposition techniques that manipulate the polymer morphology. More specifically, it has been shown that PEDOT:PSS films deposited by solution shearing exhibit substantially higher electrical conductivity values than films deposited via spin coating.\cite{20} The directional nature of solution shear deposition promotes anisotropic structuring within the thin film, leading to higher conductivity along the direction of deposition. By applying this principle to postdeposition treatments, this study uses anisotropic application of various solvent-and-solvent combinations on solution-sheared PEDOT:PSS films to further enhance electrical properties.\cite{21} Compared to traditional postdeposition treatments, wherein solvent is applied by dropping on the film or by fully immersing the sample in a solvent for a long duration (minutes), application of solvents using a shearing blade (Figure 1A) could be fully integrated into a roll-to-roll process proceeding deposition. This methodology, defined here as solvent shearing, leads to record-high electrical conductivity (8500 \(\pm\) 400 S cm\(^{-1}\)) and power factor (\(\approx 800 \mu\text{W m}^{-1} \text{K}^{-2}\)) values measured in the shearing direction.

![Figure 1. Optimization of postdeposition solvent shearing. A) Schematic of sheared deposition of PEDOT:PSS and B) postdeposition sheared solvent treatment. C) Typical conductivities of sheared PEDOT:PSS films with postdeposition treatments with different solvents by drop (black) and shear (red) methods. MeOH/EtOH shear films achieved 8500 \(\pm\) 400 S cm\(^{-1}\) measured from five representative samples. D) Temperature dependence of the conductivity of individual PEDOT:PSS films deposited by different methods and subjected to different solvent treatments. EG: ethylene glycol, MeOH: methanol, and EtOH: ethanol.](image)

**2. Results and Discussion**

**2.1. Optimization of Postdeposition Solvent Shearing**

Based on our previous shearing work with PEDOT:PSS,\cite{20} we hypothesized that using the same method for the postdeposition solvent treatment could further induce PEDOT-rich domain ordering through the structural rearrangement and relaxation caused by postdeposition PSS solvation and removal.\cite{20,22,23} A schematic for the film deposition and subsequent solvent treatment is depicted in Figure 1A,B. Over 100 films were created, resulting in various levels of conductivity depending on the solution-shearing conditions as well as the solvent-treatment conditions. Some of those conditions, shown in Figure 1C, exhibit the effect of solvent shearing on electrical conductivity of solution-sheared PEDOT:PSS thin films at room temperature. All films were prepared by solution shearing (90 °C, 1.5 mm s\(^{-1}\)) and subsequently treated with a specified solvent by either the drop or shear method (see “Experimental Section” for full description). When either MeOH or ethanol (EtOH) was applied via solvent shearing, electrical conductivity in the direction of shearing was observed to improve by 44% or 91%, respectively, when compared to application via the drop method. However, there was no observable difference between methods when EG was used. Solvent treatments can affect film conductivity through selective removal of nonconducting PSS; in the solution-sheared films, subsequent solvent shearing results in a reduction of film thickness by as much as 60%. On average, across both shear and drop methods, however, EG-treated films exhibited a thickness reduction of only 35%, whereas MeOH- and EtOH-treated films were reduced by 52% and 56%, respectively. The short duration of either of these solvent treatment methods relative to previous...
studies may limit the ability of the EG to selectively solvate PSS. As previously demonstrated with polystyrene, the local segmental chain dynamics are strongly affected by solvent viscosity.[24] Thus, the high viscosity of EG may limit solvation at the time scale of these treatment methods. The highest conductivities within a given treatment method were obtained using a 1:1 ratio of MeOH/EtOH. We hypothesized that these solvents might combine synergistically. MeOH effectively segregates PSS from PEDOT but evaporates too quickly to have maximum effect when deposited via solvent shearing. EtOH is less effective than MeOH at segregating PSS from PEDOT, but its higher boiling point sustains a longer retention time with the film. The combined solvent system appears to leverage the positive aspects of each solvent to produce a larger conductivity increase than achieved with either solvent employed independently. This solvent combination, when applied via solvent shearing, yields PEDOT:PSS thin films with the highest electrical conductivity of 8500 ± 400 S cm⁻¹ (standard deviation) from five representative samples measured in the direction of shearing at room temperature. Further differences in these films are demonstrated in the temperature-dependent electrical conductivity of the various prepared PEDOT:PSS thin films (Figure 1D). While most PEDOT:PSS samples exhibit classical semiconducting behavior as determined by negative temperature coefficients of resistance (TCR), PEDOT:PSS thin films that achieve the highest conductivity values show metallic-type behavior (positive TCR). This dependency has been observed before in highly doped, crystalline PEDOT:PSS, and other high conductivity PEDOT derivatives.[3,25,26]

2.2. Shearing-Induced Anisotropy in PEDOT:PSS

The anisotropy of both deposition and solvent treatments results in highly anisotropic electrical conductivities and Seebeck coefficients. This electrical anisotropy is shown in Figure 2A, which compares the electrical conductivities, Seebeck coefficients, and resulting power factors of solution-sheared samples further solvent-treated via the shear and drop methods relative to the shearing direction. The most conductive direction for both preparations is 0° offset to the shearing direction, i.e., parallel to the direction of deposition and treatment. As the angle of the electrodes is increased relative to the shearing direction, the conductivity decreases significantly for both treatment types, with the lowest value occurring completely perpendicular to the direction of shearing, while the Seebeck coefficient increases. The ratio of parallel-to-perpendicular electrical conductivity for the solvent-shearing treatment (4.2) is only slightly higher than the drop method (3.6), indicating that the solution shear deposition induces most of the anisotropy responsible for this behavior. Additional anisotropic application of the solvents modestly enhances the conductivity anisotropy. The electrical conductivity values measured at 90° are in the range of what can be obtained through spin coating and subsequent solvent treatments, indicating that the structural ordering in the parallel direction does not induce similar structuring in the perpendicular direction. As shown in the bottom section of Figure 2A, the power factor of the resulting films is maximized at an angle of 45° relative to the shearing direction, suggesting that higher thermoelectric efficiencies could be attained through further angle-dependent geometric optimization. Structural differences between solvent-treatment conditions are also evident in the polarized UV–vis spectroscopy of solution-sheared films. Drop and shear post-treatment spectra were taken and referenced to drop-cast films with drop post-treatment (Figure 2B). All films showed similarly broad absorption in the perpendicular direction (top), but differences can be observed parallel to the direction of shearing (bottom). The solvent-sheared films exhibit new weak optical transitions in the visible region at 605 and 660 nm in addition to the broad absorption background. Peaks at 600 nm are attributed to neutral PEDOT chains obtained through loss of oxidizing PSS.[27] The presence of these peaks in the direction of shearing indicates anisotropic alignment of PEDOT-rich domains in the direction of shearing.
2.3. X-Ray Characterization of PEDOT:PSS Films

Evidence of structural and/or dopant position changes is observed in the extended X-ray absorption fine structure (EXAFS) plots derived from sulfur-edge EXAFS spectra (Figure 3A) on solution-sheared PEDOT:PSS samples relative to spin-cast PEDOT:PSS (top). The spectra of solution-sheared PEDOT:PSS samples are replicated below to allow for easy comparison with solution-sheared films further treated via solvent shearing. The two spectra (Figure 3A, bottom) show similar first-shell interactions (1 Å peak, *), presumably from adjacent carbons.[28] Another scattering peak appears around 3 Å (#), though it is slightly shifted to smaller radial distance in the solvent-sheared sample. The peak at 4 Å (·) only appears in the solvent-sheared sample. Although the qualitative comparison of the spectra reveals meaningful differences, the complexity of the PEDOT:PSS system and the lack of a suitable PEDOT standard make structural precise modeling of this system for specific structures futile. However, the extra feature at 4 Å may indicate tighter sulfonate coupling with the PEDOT backbone, closer proximity of the thiophene to the remaining PSS, or smaller PEDOT–PEDOT distance. Any of these structural changes could manifest in higher carrier concentrations and metallic behavior.

Additional X-ray studies were performed to determine whether any structural or morphological anisotropy could be observed in the sheared PEDOT:PSS films. Significant changes in the domain morphology are observed in the grazing-incidence small-angle X-ray scattering (GISAXS) spectra (Figure 3B) for the sheared and spin-cast PEDOT:PSS films. The characteristic domain length ($R_g$, radius of gyration) was fit at low $q$ at 0° and 90° angles with respect to shearing direction by orienting the sample relative to incoming X-ray beam (see the “Experimental Section”). As seen in Figure 3B, the spin-cast PEDOT:PSS film shows nearly identical lengths (~15 nm) of the domains in all directions, which is expected given the slightly radial deposition nature of spin-cast films. However, strong domain length anisotropy is observed in films deposited via solution shearing, specifically an elongation of the domains in the direction of shearing (Table 1). Furthermore, the Porod region at higher $q$ shows a lower scaling for both directions of the solvent-sheared sample, indicating more distinct boundaries between PEDOT and the remaining PSS.[29] The above characteristics suggest that the solvent treatment via shearing enhances the elongation, increasing the ratio of measured domain length from 1.3 to over 1.5 (Figure 3C). The highest direction of electrical conduction coincides with the direction of elongation.

Grazing-incidence wide-angle X-ray scattering (GIWAXS) patterns shown in Figure 4A further illustrate the dependence of morphology and composition on deposition technique and subsequent solvent treatment. The prominent peaks occurring at 1.2 Å$^{-1}$ (0.52 nm) and 1.8 Å$^{-1}$ (0.35 nm) correspond to PSS halo and π–π stacking in PEDOT, respectively.[30] The integrated intensities near the horizon (0°–20° for edge-on PEDOT stacking), when the X-ray beam is aligned along the direction of shearing (parallel) and 90° rotated from the direction of shearing (perpendicular), across various samples are shown in Figure 4B and the ratios of the normalized peak heights plotted in Figure 4C. The two as-deposited samples have the lowest PEDOT/PSS ratios, with the shear deposition resulting in a slightly larger PEDOT/PSS ratio than the spin-cast sample. Even before solvent treatments, a slight anisotropy induced from the shear deposition is observed in comparison with the isotropic spin-cast sample.

Table 1. Average radius of gyration ($R_g$) in PEDOT:PSS films with different treatments relative to direction of shearing determined by GISAXS.

<table>
<thead>
<tr>
<th>Film treatment</th>
<th>0° $R_g$ [nm]</th>
<th>90° $R_g$ [nm]</th>
<th>$R_g$ ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spin/Drop</td>
<td>6.9</td>
<td>7.2</td>
<td>0.96</td>
</tr>
<tr>
<td>Shear/Drop</td>
<td>13.1</td>
<td>9.2</td>
<td>1.4</td>
</tr>
<tr>
<td>Shear/Shear</td>
<td>18.8</td>
<td>12.0</td>
<td>1.6</td>
</tr>
</tbody>
</table>
After solvent treatment, the PEDOT/PSS ratio for all samples increases due to the partial removal of PSS and improved PEDOT \(\pi-\pi\) stacking, the latter evidenced by the narrowing of the full width at half maximum of the PEDOT \(\pi-\pi\) peak. The isotropic application of solvent maintains the isotropic structure of the PEDOT in the spin/drop sample, while both drop and shear applications of solvent treatment yield large differences in PEDOT/PSS ratio between directions, with the latter being the largest. The amount of aligned PEDOT first induced by the deposition and, second, increased by the solvent shearing create conductive domains preferentially oriented in the direction of shearing.

These data indicate that structural alignment and increased dopant effectiveness are responsible for the large gains in electrical conductivity achieved in solvent-sheared PEDOT:PSS films. Additionally, elongated PEDOT domains may have more contact area between them, thereby increasing the number of percolation paths and lowering the resistive barrier to transport of charge carriers along them. Increasing conduction across domains has been shown to increase the electrical conductivity of PEDOT:PSS.[32]

### 2.4. Thermoelectric Performance of Sheared PEDOT:PSS

Measured Seebeck coefficients, electrical conductivities, and power factor values of individual films are shown in Figure 5A. As observed with other PEDOT derivatives,[3,14] the Seebeck coefficient initially increases with increasing electrical conductivity. The initial increase in \(S\) with \(\sigma\) is attributed to improvement to the transport coefficient, \(\sigma_{\text{tr}}\), by increasing contact area and increased dopant effectiveness.

![Figure 4](image)

**Figure 4.** X-ray characterization of chain-scale structural changes in PEDOT:PSS films. A) 2D GIWAXS plots of solution- and solvent-sheared (Shear/Shear) films oriented parallel (top) and perpendicular (bottom) to the direction of shearing. B) Integrated intensities at the horizon (0°–20°) for parallel and perpendicular samples subject to different treatment conditions. C) PSS (Q ≈ 1.2 Å) and PEDOT (Q ≈ 1.8 Å) peak height ratios for films subjected to different treatment conditions, aligned parallel (red) and perpendicular (black) to the direction of the treatment.

![Figure 5](image)

**Figure 5.** Thermoelectric performance of sheared PEDOT:PSS films. A) Seebeck coefficient and B) power factor versus electrical conductivity of sheared PEDOT:PSS films subjected to different postdeposition solvent treatments. Each data point represents an individual sample with error bars calculated from repeated measurements on each.
the connectivity of PEDOT-rich domains and enlarging the percolating network. With mixed solvent shearing, transport is no longer percolation-dominated, and the traditional inverse relation between $S$ and $\sigma$ is observed. The resulting power factor values peaked at the optimized point before the PEDOT:PSS films become metallically conductive (Figure 5B). The highest value obtained in this work is $823 \mu W m^{-1} K^{-2}$, nearly double previously reported values for solution-processed PEDOT:PSS.

### 2.5. Cross-Plane Thermal Conductivity of Sheared PEDOT:PSS

Full evaluation of the thermoelectric performance of these highly conductive PEDOT:PSS thin films requires measurement of the thermal conductivity of the films. The $3\omega$ technique was used to measure the properties of a drop-cast thick-film PEDOT:PSS sample, which yielded isotropic, bulk thermal conductivity $\kappa = 0.44 W m^{-1} K^{-1}$, and a heat capacity, $C_v = 2.2 \times 10^6 J m^{-3} K^{-1}$. This establishes a baseline for comparison to thin-film processing of the same polymer. Cross-plane thermal conductivity ($\kappa_z$) was measured via time-domain thermoreflectance (TDTR).

A plot showing representative TDTR data and best fit, along with ±10% perturbations in $\kappa_z$ about the best fit value, is shown in Figure 6. Solution-sheared PEDOT:PSS thin films exhibit $\kappa_z = 0.31 \pm 0.03 W m^{-1} K^{-1}$ and $C_v = (1.9 \pm 0.3) \times 10^6 J m^{-3} K^{-1}$. These extracted values are in good agreement with reports for PEDOT:PSS films in literature. Using this value for the thermal conductivity results in an upper bound for the room temperature $zT$ of 0.81 for the thin films; however, given the highly anisotropic electrical transport, we expect a higher in-plane thermal conductivity than the value used here. Although PEDOT:PSS systems have not exhibited the same interdependence between electrical and thermal conductivities as PEDOT:tosylate, the unprecedented electrical conductivity of these PEDOT:PSS thin films merits further study of their anisotropic thermal transport. Nevertheless, the nearly twofold improvement in power factor over previously reported PEDOT:PSS films establishes a new standard for thermoelectric performance of scalable, solution-processable organics. We expect this work to stimulate further refinement of processing techniques for improving the conductivity and Seebeck coefficient of organic material systems.

### 3. Conclusion

We report a scalable solvent-shearing technique to improve the alignment and relative percentage of conductive PEDOT domains in thin films of PEDOT:PSS. The key feature of this processing technique is its ability to achieve high power factor and high throughput; the shearing deposition and solvent treatment are readily integrable into a high-throughput roll-to-roll process. The sheared films exhibit anisotropically aligned PEDOT-rich domains in the direction of shearing, resulting in a record-high room temperature electrical conductivity of $8500 \pm 400 S cm^{-1}$ and a power factor of over $800 \mu W m^{-1} K^{-2}$.

### 4. Experimental Section

#### 4.1. Preparation of Films

PH1000 PEDOT:PSS was purchased from Heraeus. All other chemicals were purchased from Sigma–Aldrich and used as received. Some batch-to-batch variation of the PH1000 was observed. It is critical for film performance to store PH1000 at 5–10 °C when not in use. Solution shearing and solvent treatment: PEDOT:PSS films were deposited onto SiO$_2$-covered (300 nm) silicon and glass substrates. Substrates were washed with acetone and isopropyl alcohol and exposed to O$_2$ plasma at 150 W for at least 2 min. The shearing blade consisted of a rectangular piece of silicon, functionalized on the blade surface and blade edge with a monolayer of octadecltrichlorosilane. The monolayer quality and cleanliness of the blade are critical for film performance. Films were deposited at various substrate temperatures, ranging from 85 to 90 °C at a blade height of ~100 mm relative to the substrate. Coating speeds ranged from 0.5 to 4 mm s$^{-1}$, producing films between 20 and 200 nm in thickness. Samples were kept on a hot plate at 130 °C in air until treated with solvent. Solvent treatments were consisted of two types: 1) “drop” wherein solvent was directly drop-coated via pipette onto the sample, and 2) “shear” wherein solvent was applied to the samples via the shearing blade. The conditions for solvent treatments, unless otherwise noted, are listed in Table 2. Each sample was submerged in MeOH and gently swirled for at least 10 s directly following solvent treatment. Samples were stored in a dry environment when not in active use.

#### 4.2. Morphological and Chemical Characterization

UV–vis spectra were obtained with a Cary 6000i spectrophotometer through an aperture of 1.3 × 0.4 cm on films prepared as described above on quartz substrates. Film thickness and topology were measured with tapping-mode atomic force microscopy (AFM) from Nanoscope III (Digital Instruments/Veeco.
Metrology Group) and with an interferometer (Filmetric F 201R). All thickness values were the average of at least three measurements in different areas of the film. IR absorbance measurements were taken with a Nicolet iS50 FT/IR spectrometer using an attenuated total reflectance (ATR) accessory.

Both GISAXS and GIWAXS were performed at the Stanford Synchrotron Radiation Lightsource (SSRL) of the SLAC National Accelerator Laboratory on beamlines 1–5 and 11–3, respectively. The sample-to-detector distance was calibrated using an in-line thiosulfate standard was used for energy calibration. The cross-plane thermal conductivity and specific heat of PEDOT:PSS film. The thicknesses of Al and PEDOT:PSS were measured by AFM to be 77 ± 1 and 38 ± 4 nm, respectively. The thermal conductivity and specific heat of Al were taken from literature. The thermal conductivity of Al was measured via four-probe electrical measurements and using the Wiedemann–Franz law, κ_{Al} = 160 W m⁻¹ K⁻¹.[39] The thermal boundary conductance at the Al–PEDOT:PSS interface was fixed at 100 MW m⁻² K⁻¹. Note that although the PEDOT:PSS is expected to be anisotropic with a different thermal conductivity in- and cross-plane, the TDTR measurement is insensitive to the in-plane value as the thermal penetration depth (at 4 MHz, ~100 nm) is significantly smaller than the laser spot size. This leaves the cross-plane conductivity and volumetric specific heat of PEDOT:PSS as the only unknown parameters, which are extracted through a simultaneous fit of the model to the data. Error bars in the reported data were calculated by propagating uncertainties in the fixed parameters, namely Al thickness (~1 nm), PEDOT:PSS thickness (~4 nm), and rms spot size (~3%), and adding them up in quadrature along with the uncertainty due to spot-to-spot measurement variability on the sample (which was ~3% for κ and ~8% for C). The accuracy of this setup and measurement procedure was validated by performing experiments on a 300 nm SiO₂/Si witness sample that had undergone Al evaporation alongside the PEDOT:PSS.
samples. This sample gave a thermal conductivity for SiO$_2$ of 1.4 ± 0.1 W m$^{-1}$ K$^{-1}$, which was in agreement with literature.

The cross-plane, bulk thermal conductivity of the PEDOT:PSS samples was measured by the 3ω method. The 3ω method is a frequency-domain electrothermal measurement technique used to characterize the thermal properties of thin films and bulk materials.[40,41] In brief, the 3ω method utilizes a single-patterned metal line driven by a current source at frequency $\omega$ to provide Joule heating and subsequent temperature oscillations at frequency 2$\omega$. Due to the temperature coefficient of resistance of the metal, the resistance of the line is also perturbed at frequency 2$\omega$, leading to an overall voltage oscillation at frequency 3$\omega$, which is detected using a lock-in amplifier. PEDOT:PSS films were deposited onto microfabricated substrates that contained electrically isolated metal heater/thermometer lines. Under periodic heating, the temperature oscillations in the metal line are proportional to the thermal properties in the surrounding materials. The thermal conductivity and heat capacity of the polymer were then extracted by fitting the thermal frequency response to the heat conduction equation.

Acknowledgements
A.C.H. and S.C.A. contributed equally to this work. A.C.H. acknowledges support from the National Science Foundation Graduate Research Fellowship under Grant No. DGE-1147474. Use of the Stanford Synchrotron Radiation Lightsource, SLAC National Accelerator Laboratory, is supported by the U.S. Department of Energy, Office of Science, Office of Basic Energy Sciences under Contract No. DE-AC02-76SF00515. M.T.D. and M.T.B. were supported by the National Defense Science, Office of Basic Energy Sciences, Division of Material Science and Engineering, Program on Physical Behaviors of Materials(DE-SC0016523).

Conflict of Interest
The authors declare no conflict of interest.

Data Availability Statement
The full X-ray dataset can be obtained free of charge at Mendeley DOI:10.17632/mds8frh9rn.1

Keywords
energy harvesting, organic electronic, PEDOT, PEDOT:PSS, power factor, thermoelectrics

Received: December 3, 2020
Revised: December 27, 2020
Published online: January 27, 2021


