

Supporting Information

High-Temperature Transparent Polymer Heater Based on n-Doped Poly(benzodifurandione)

Joseph A. Romo^{1†}, Won-June Lee^{1†}, Aalok Gaitonde², Liyan You¹, Benjamin Cerjan³, Lucas Q. Flagg⁴, Daniel Sunday⁴, Chad R. Snyder⁴, Dean M. DeLongchamp⁴, Amy M. Marconnet², Jianguo Mei^{1*}

¹ James Tarpo Jr. and Margaret Tarpo Department of Chemistry, Purdue University, West Lafayette, IN 47907, United States

² Birck Nanotechnology Center and School of Mechanical Engineering, Purdue University, West Lafayette, IN 47907, United States

³ Jonathan Amy Facility for Chemical Instrumentation, Purdue University, West Lafayette, IN 47907, United States

⁴ Material Measurement Laboratory, National Institute of Standards and Technology, Gaithersburg, MD 20899, United States

[†] These authors contributed equally to this study.

* Corresponding author: E-mail: jgmei@purdue.edu

This PDF file includes:

Notes S1 to S9

Figures S1 to S46

Tables S1 to S13

Supporting Information References

TABLE OF CONTENTS

Supporting Information.....	1
Note S1. Materials and Methods.....	8
1.1 Reagents and Chemicals.....	8
1.2 Conductive Polymer Ink.....	8
1.3 Substrates.....	8
1.4 Benchmark Material Fabrication and Validation	8
1.5 EtOH-based <i>n</i> -PBDF Ink Formulation.....	9
1.6 Preparation of <i>n</i> -PBDF Films.....	10
1.6.1 Substrate Cleaning.....	10
1.6.2 Conductive Polymer Film Deposition.....	10
1.7 Doping Level Control of Prepared Films	12
1.8 Film-based Characterizations	12
1.8.1 Electrical Properties	12
1.9 Film Thickness and Surface Morphology	13
1.9.1 Atomic Force Microscopy (AFM)	13
1.9.2 Stylus Profilometry	13
1.10 Optical Properties	13
1.11 X-Ray Reflectivity.....	14
1.12 Mechanical Bending (Fatigue) Testing	14
1.13 Grazing-incidence Wide-angle X-ray Scattering (GIWAXS).....	15
1.14 Data Reliability and Reproducibility.....	16
Note S2. Specific Heat Capacity and Thermal Stability.....	17
1.1 Differential Scanning Calorimetry (DSC).....	17
1.1.1 Preliminary Modulated DSC (MDSC®) Analysis.....	17
1.1.2 Definitive Heat Capacity Measurement	17
1.2 Thermogravimetric Analysis (TGA)	18
Note S3. In-plane and Cross-plane Thermal Conductivity (κ)	19
1.1 In-plane Thermal Conductivity (κ_x and κ_y)	19
1.1.1 Measurement Principle and Technique	19
Experimental Setup.....	19

1.1.2	Data Analysis	20
1.2	Cross-plane Thermal Conductivity (κ_z).....	20
1.2.1	Measurement Principle and Technique	20
1.2.2	Experimental Setup and Sample Preparation	20
1.2.3	Data Analysis	21
Note S4.	Comprehensive Optical Modeling	22
1.1	Material Model and Software	22
1.2	Substrate Model Development	22
1.3	Model Validation via Monte Carlo Analysis.....	23
1.4	Extraction of Optical Constants.....	23
1.5	Calculation of The Absorption and Extinction Coefficient.....	23
1.5.1	Experimental Determination	24
1.5.2	Data Normalization and Analysis.....	24
1.6	Comparison of Methods and Analysis of Absorbance Calculation.....	26
Note S5.	Visible Light Transmittance (VLT)	27
1.1	Visible Light Transmittance (VLT).....	27
Note S6.	Characterization and Modeling of Thermal Behaviors.....	28
1.1	Theory Behind the Observed Joule Heating Response	28
1.2	Detailed Derivation of a Simple Thermal Model	29
1.2.1	Lumped Capacitance Model.....	29
1.2.2	Transient Analysis (Further Details)	29
1.2.3	Steady-state Analysis (Further Details).....	32
1.3	Detailed Derivation of a Temperature Coefficient of Resistance (TCR)-aware Thermal Model 33	
1.4	Comparative Analysis of the Models (Steady-state vs. Transient, and TCR-aware).....	36
1.4.1	Extraction of Thermal Constants Alpha (α) and Tau (τ).....	36
1.4.2	Steady-state Approach.....	36
1.4.3	Standard Transient Approach.....	37
1.4.4	TCR-aware Transient Approach	37
1.5	Analysis of Extracted α and τ	38
1.5.1	Interpretation and Contextualization of α and τ	39

1.6	Comparison to Other Heater Systems and Justification of The Model Fit.....	41
1.7	Scaling of Performance Metrics with Heater Device Size	42
1.7.1	Scaling Analysis of α and τ	42
1.7.2	Device Size and Geometric Trends	42
	Edge Effects	42
	Natural Convection Efficiency.....	43
1.8	Scaling of Performance Metrics with Film Thickness	44
	Film Thickness (n-PBDF) Dependent Scaling of τ	44
Note S7.	Joule Heater Characterization.....	45
1.1	Experimental Setup and Equipment	45
1.2	Preparation of Devices for Testing.....	46
1.3	Heating Measurement Protocol	47
Note S8.	Transparent Conductor Figure of Merit (FOM).....	48
1.1	Fundamental Principles of Transparent Conductors (TCs)	48
1.2	Empirical-based FOMs (Fraser–Cook; Haacke)	48
1.3	Physics-based Optoelectronic FOMs (Dressel–Grüner; De–Coleman)	50
1.3.1	Dressel and Grüner (2002)	50
1.3.2	Limitations of Bulk Electrical Conductivity Assumptions	52
1.3.3	The Importance of Percolation in TCs	52
1.3.4	De and Coleman (2009)	53
1.3.5	Application of Percolation Models in This Work	54
1.3.6	Contreras et al. FOM.....	54
1.3.7	Literature Survey of Transparent Conductive Materials.....	55
Note S9.	Data Analysis and Robustness of In-plane Thermal Conductivity Measurements.....	56
1.1	Frequency-dependent Extraction of Thermal Conductivity	56
1.2	Sensitivity Analysis of the Convective Heat Transfer Coefficient.....	56
1.3	Consistency with Joule Heating Thermal Analysis.....	57
	Supporting Figures.....	58
	Supporting Tables (S9 to S13).....	104
	Supporting Information References.....	117

TABLE OF FIGURES

- Figure S1.** Atomic force microscopy (AFM) surface morphology (5×5) μm^2 scans
- Figure S2.** Atomic force microscopy (AFM) surface morphology (2×2) μm^2 scans
- Figure S3.** Spatial mapping of sheet resistance
- Figure S4.** Relative deviation maps of sheet resistance
- Figure S5.** Spatial mapping of electrical conductivity
- Figure S6.** Relative deviation of electrical conductivity
- Figure S7.** Model fitting of transient Joule heating profiles (3×3) cm^2 devices
- Figure S8.** Dynamic heating rate profiles (3×3) cm^2 devices
- Figure S9.** Steady-state temperature vs. areal power density (3×3) cm^2 devices
- Figure S10.** Model fitting of transient Joule heating profiles (5×5) cm^2 devices
- Figure S11.** Dynamic heating rate profiles (5×5) cm^2 devices
- Figure S12.** Steady-state temperature vs. areal power density (5×5) cm^2 devices
- Figure S13.** Electrical resistance vs. steady-state temperature for TCR determination
- Figure S14.** Statistical distribution of the Temperature Coefficient of Resistance (TCR)
- Figure S15.** Time-dependent current response during Joule heating
- Figure S16.** Representative voltage control profiles for electrothermal characterization
- Figure S17.** Steady-state temperature vs. applied current
- Figure S18.** Steady-state temperature vs. applied voltage
- Figure S19.** Current–Voltage (I–V) characteristics
- Figure S20.** Maximum heating rate vs. applied current
- Figure S21.** Maximum heating rate vs. steady-state areal power density
- Figure S22.** Comparative Joule heating performance of *n*-PBDF relative to PEDOT:PSS
- Figure S23.** Wavelength-dependent transmittance, absorptance, and reflectance (line plots)
- Figure S24.** Wavelength-dependent transmittance, absorptance, and reflectance (stacked area charts)
- Figure S25.** Transmittance vs. film thickness for *n*-PBDF and PEDOT:PSS
- Figure S26.** Relationship between VLT, film thickness, and electrical conductivity
- Figure S27.** Relationship between film thickness and color hue for *n*-PBDF and PEDOT:PSS
- Figure S28.** Quantitative analysis and reproducibility of CIELAB color space values

Figure S29. Optical characterization and modeling of the glass substrate

Figure S30. Complex dielectric function and refractive index from optical modeling

Figure S31. Comparison of experimental and modeled optical spectra

Figure S32. Analysis of absorption and extinction coefficients

Figure S33. Optoelectronic Figure of Merit (FOM) analysis for *n*-PBDF films

Figure S34. X-ray reflectivity (XRR) measurement for film density determination

Figure S35. Temperature-dependent specific heat capacity of *n*-PBDF

Figure S36. Response time ($t_{90\%}$) vs. applied voltage (3×3) cm² devices

Figure S37. Response time ($t_{90\%}$) vs. applied voltage (5×5) cm² devices

Figure S38. Transparent heater Figure of Merit (TH FOM) benchmark

Figure S39. Flexible *n*-PBDF transparent heaters and demonstration of practical applications

Figure S40. Thermogravimetric analysis (TGA) of *n*-PBDF

Figure S41. Summary and validation of extracted thermal parameters (τ and α)

Figure S42. Frequency-dependent in-plane thermal conductivity

Figure S43. Comparison of the molecular packing structure of *n*-PBDF films processed from ethanol- and DMSO-based ink formulations

Figure S44. Radar chart comparison of *n*-PBDF and PEDOT:PSS performance metrics at a matched film thickness of ≈ 71 nm

Figure S45. Photos showing a representative *n*-PBDF heater and the experimental testing setup

Figure S46. Photos showing the Graphical User Interface (GUI) of the custom-made LabVIEW® program

TABLE OF TABLES

Table S1. Optimized spray-coating conditions for glass and PET substrates

Table S2. Cross-validation of *n*-PBDF film thickness measurements (on glass substrate). Comparison of thickness values obtained via Atomic Force Microscopy (AFM) step-height analysis and stylus profilometry

Table S3. Summary of extracted GIWAXS parameters for *n*-PBDF films

Table S4. Comparison of Monte Carlo analysis results for a 72 nm *n*-PBDF film using two different substrate models

Table S5. Representative dataset for (3×3) cm² samples of *n*-PBDF derived from SST analysis

Table S6. Alpha and Tau values for small and large-area devices

Table S7. Calculation of contribution to alpha from various modes of heat transfer

Table S8. Comparison of in-plane thermal conductivities from different convective heat transfer coefficient treatments

Table S9. Various Figures of Merit (FOMs) of the reported transparent conducting film materials

Table S10. Literature survey of thermal conductivity of materials

Table S11. Literature survey of Figure of Merit (FOM) for transparent Joule heating (TH) materials

Table S12. Side-by-side values used for the radar chart comparison of *n*-PBDF and PEDOT:PSS

Table S13. Comparison of steady-state temperature (SST) for the two most comparable (3×3) cm² PEDOT:PSS-based heaters fabricated and measured in this work

Note S1. Materials and Methods

1.1 Reagents and Chemicals

Anhydrous ethanol (EtOH, 200 proof, $\geq 99.5\%$), dimethyl sulfoxide (DMSO, anhydrous, 99.9 %), and tetramethyl hydroquinone (TMHQ, 98 %) were purchased from Fisher Scientific, Sigma-Aldrich, and ChemScene, respectively. Deionized water with a resistivity of $18.2\text{ M}\Omega\cdot\text{cm}$ was produced using a Millipore Direct-Q® 3 UV water purification system (Merck Millipore). Fast-drying silver paint (Electrodag® 1415M, Catalog No. 1640-30) was purchased from Ted Pella, Inc.

1.2 Conductive Polymer Ink

The n-doped poly(benzodifurandione) (*n*-PBDF) was synthesized following a previously published procedure.¹ The resulting *n*-PBDF ink in DMSO was dialyzed against DMSO using a cellulose membrane (10K MWCO, SnakeSkin™) to achieve a final molecular mass of $>10\text{ kDa}$. This purified ink was subsequently used to formulate the ethanol-based conductive ink, as detailed in **Note S1.5**.

1.3 Substrates

Microscope glass slides composed of low-iron soda-lime glass ($75\text{ mm} \times 50\text{ mm} \times 1\text{ mm}$, Corning Incorporated, Catalog No. 2947-75 $\times$ 50) were cut to the required dimensions using a tungsten-carbide cutting wheel. Heat-stable poly(ethylene terephthalate) (PET) films (Melinex® STS505HS1; $125\text{ }\mu\text{m}$ thickness) were purchased from Tekra LLC and cut to size using a Cricut® Maker 3 computer-controlled cutting machine.

1.4 Benchmark Material Fabrication and Validation

Thin films of the benchmark *p*-type conducting polymer, poly(3,4-ethylenedioxythiophene):poly(styrene sulfonate) (PEDOT:PSS) (Clevios™ PH 1000), were prepared and characterized alongside those of *n*-PBDF films to provide a direct, state-of-the-art comparison. This approach was necessary to enable performance evaluations under precisely matched thickness and transmittance conditions not fully available in the existing literature.

The PEDOT:PSS films were fabricated following the high-performance methods detailed by Gueye et al.². The resulting optoelectronic and heater performance characteristics of our fabricated PEDOT:PSS films were found to be in close agreement with their reported values. A detailed comparison of key performance metrics for both *n*-PBDF and PEDOT:PSS samples, including sheet resistance, conductivity, and thermal properties at similar thicknesses is provided in **Tables S9** and **S10**, confirming the validity and high quality of our benchmark devices.

1.5 EtOH-based *n*-PBDF Ink Formulation

The final ethanol-based conductive ink was prepared from an *n*-PBDF/DMSO stock solution via a co-solvent precipitation method. The entire formulation process was performed under ambient atmospheric conditions without using surfactants or other stabilizing additives.

The procedure was as follows:

1. The concentration of the stock *n*-PBDF/DMSO ink was adjusted to (5 to 7) mg mL⁻¹.
2. In a separate beaker, deionized water (the primary co-solvent) was stirred vigorously with a magnetic stir bar to form a vortex.
3. The *n*-PBDF/DMSO ink was added dropwise to the vortex. The mixture was stirred for 2 h, resulting in a stable dark-colored *n*-PBDF dispersion.
4. Finally, anhydrous ethanol was added dropwise to the dispersion, and the mixture was stirred gently for 30 min to yield a homogeneous and stable ternary solvent-based conductive ink.

The optimal volumetric ratio of DMSO to water to ethanol was determined to be 1:2:4. This ternary solvent system was selected because (1) water and ethanol act as effective co-solvents for *n*-PBDF, facilitating stable nano-colloidal formation; (2) all three solvents are fully miscible, ensuring a homogeneous final product; and (3) the combination maintains a polar solvent environment. The resulting ink exhibited excellent stability and remained homogeneous for over two weeks under ambient storage conditions. Further details regarding the physical chemistry, colloidal stability, and solvent interactions of this ternary ink system have been recently reported by our group.³

The properties of our ink can be readily tuned for specific applications, and the final polymer concentration can be controlled by adjusting the amount of ethanol added. Ethanol is an ideal final solvent because of its relatively low surface energy and boiling point, which are critical parameters for achieving uniform films during coating or printing. GIWAXS experiments proved that the EtOH-based ink formulation gave films with the same morphology as films prepared with DMSO-based ink (see **Figure S43** and **Table S3** for a comparison). Moreover, for substrates requiring enhanced wetting, small amounts of other low-surface-energy alcohols, such as 1-butanol or isopropyl alcohol, can be optionally incorporated into the formulation.

1.6 Preparation of *n*-PBDF Films

1.6.1 Substrate Cleaning

The substrates were prepared using methods specific to their material types. Glass substrates were cleaned by sequential 15 min sonication steps in each: **(1)** a detergent solution (0.5 % v/v Micro90® in deionized water), **(2)** deionized water, **(3)** acetone, and finally **(4)** isopropanol. PET substrates were gently hand cleaned using a non-abrasive cleanroom wipe soaked in the detergent solution described above, followed by rinsing with deionized water, and finally ethanol.

After cleaning, all substrates were dried under a gentle stream of nitrogen and stored in sealed containers to prevent recontamination. Immediately prior to coating, the glass substrates were treated with UV-ozone (UVO) (JELIGHT 144AX UVO Cleaner) for 10 min to remove organic residues and enhance surface wettability.

1.6.2 Conductive Polymer Film Deposition

The *n*-PBDF conductive ink was deposited onto the prepared substrates using an automated ultrasonic spray coating (USSC) system (ExactaCoat™, Sono-Tek, USA) equipped with a spray nozzle (Impact™). The deposition process was performed under ambient conditions, with distinct parameters optimized for the glass and PET substrates, as detailed in **Table S1**.

The full substrate area was coated in multiple, separate cycles, allowing 45 s between passes for the individual layers to dry. The total number of cycles was adjusted to achieve the desired film thickness and surface morphology.

Table S1. Optimized spray-coating conditions for glass and PET substrates.

Parameter	Glass substrates	PET substrates
Nozzle frequency (kHz)	120	120
Power (Ratio)	1.7	1.7
Stage temperature (°C)	40	55
Shaping gas	N ₂	N ₂
Shaping gas flow level (arb.)	0.35	0.35
Nozzle-to-substrate distance* (mm)	45.5	45.5
Ink flow rate (mL min ⁻¹)	0.5	0.4
Coating speed (mm s ⁻¹)	70	70

Note: *A recipe-set ‘z-height’ value of 25 corresponds to an approximate nozzle-to-substrate distance of 45.5 mm.

Table S2. Cross-validation of *n*-PBDF film thickness measurements (on glass substrate). Comparison of thickness values obtained via Atomic Force Microscopy (AFM) step-height analysis and stylus profilometry. Both measurement methods show strong agreement and linear correlation (Adj. $R^2 = 0.99$). Relative difference calculated as $(|d_{\text{AFM}} - d_{\text{Prof}}| / d_{\text{Prof}}) \cdot 100$.

Coating cycles (#)	AFM thickness (nm)	Profilometer thickness (nm)	Relative difference (%)
1	3.81 ± 0.34	—	—
2	6.75 ± 0.59	5.33 ± 0.34	26.7
3	9.04 ± 0.41	8.53 ± 0.26	5.9
4	11.42 ± 0.68	10.71 ± 0.27	6.6
5	15.48 ± 0.42	15.19 ± 0.12	1.9
6	19.99 ± 0.57	19.21 ± 0.32	4.1
7	25.92 ± 0.52	25.63 ± 0.38	1.1
8	30.06 ± 0.37	29.56 ± 0.35	1.7
9	34.92 ± 0.50	34.51 ± 0.51	1.2
10	41.37 ± 0.67	40.34 ± 0.36	2.6
12	51.06 ± 0.73	50.55 ± 0.62	1.0
14	59.13 ± 0.74	59.81 ± 0.45	1.1
16	71.70 ± 0.48	71.37 ± 0.24	0.5

1.7 Doping Level Control of Prepared Films

To establish a consistent baseline for all experiments, the as-coated PBDF films with unknown initial doping levels were subjected to a controlled re-doping procedure. This process was performed in a nitrogen-filled glove box to prevent oxidation.

A re-doping solution was prepared by dissolving TMHQ (5 mmol) in anhydrous ethanol in a nitrogen-filled glove box. TMHQ was selected because it is an effective proton-coupled electron transfer agent for this polymer system. The films were fully immersed in the TMHQ solution for (1 to 2) min, which was determined to be sufficient time to fully saturate the polymer and restore a consistent, maximally n-doped state. This method ensured that all films possessed a reliable and reproducible doping level prior to characterization and subsequent analyses. After re-doping, the films were then rinsed with a gentle stream of ethanol to remove the excess/residual dopant, after which they were dried under a gentle stream of nitrogen.

1.8 Film-based Characterizations

All characterizations were performed at room temperature ($\approx(20$ to $23)$ °C) under ambient conditions (≈ 30 % relative humidity (RH)), unless otherwise specified.

1.8.1 Electrical Properties

The sheet resistance (R_s) was measured using a Filmetrics® R50-4PP contact four-point probe system having automated mapping capabilities and equipped with a KLA-Tencor™ Type I probe head (0.5 mm (20.0 mil) radius, 100 g loading, tungsten carbide, 0.6 mm (25 mil) spacing). The electrical conductivity (σ) was calculated using the measured sheet resistance and film thickness (d) through the following equation, where ρ denotes the electrical resistivity:

$$\sigma = \frac{1}{\rho} = \frac{1}{(R_s \cdot d)} . \quad \text{Eq. S1}$$

1.9 Film Thickness and Surface Morphology

The film thickness and surface morphology were characterized using both atomic force microscopy (AFM) and stylus profilometry for cross-validation (see **Table S2**). The data were processed and analyzed using NanoScope® Analysis (v.3.0), Gwyddion (v.2.67), and Vision64® (v.5.51) software.

1.9.1 Atomic Force Microscopy (AFM)

Topographical analysis was performed using a Bruker Dimension Icon® in the soft tapping mode. Images were acquired from $(2 \times 2) \mu\text{m}^2$ and $(5 \times 5) \mu\text{m}^2$ areas using a μMasch HQ:NSC18/Al BS probe (resonant frequency (f_0): 75 kHz, spring constant (k): 2.8 N m^{-1} , tip radius (r): $\approx 8 \text{ nm}$) at a scan rate of 0.200 Hz.

1.9.2 Stylus Profilometry

Film thickness was verified using a Bruker DektakXT™ surface profilometer with a $2 \mu\text{m}$ tip radius and 3 mg stylus force.

1.10 Optical Properties

Transmittance, absorbance, and reflectance spectra were collected over a wavelength range of (380 to 1700) nm using a Filmetrics® F10-RT-EXR reflectometer.

The optical haze and Commission Internationale de l'Eclairage L^* , a^* , b^* (CIELAB) color coordinates of the samples were measured using a Konica Minolta CM5 spectrophotometer equipped with a light-integrating sphere, capable of quantifying the scattered (diffuse) transmittance relative to the total transmitted light. The data were subsequently analyzed using SpectraMagic™ NX software.

In this study, the haze was measured in accordance with the ASTM D1003 standard. This method defines haze as the percentage of transmitted light that deviates by more than 2.5° from the incident direction, with lower values corresponding to higher optical clarity. The haze percentage was calculated as follows:

$$\text{Haze (\%)} = \left(\frac{T_{\text{diffuse}}}{T_{\text{total}}} \right) \cdot 100 \quad \text{Eq. S2}$$

where T_{diffuse} is the diffuse transmittance, and T_{total} is the total transmittance. Optical haze, which describes the milky or cloudy appearance of a transparent material, is a key performance parameter for applications where high clarity is required, such as packaging, LED diffusers, and automotive components. This is caused by light scattering from features such as surface roughness, bulk inhomogeneities, porosity, or impurities in the material.

1.11 X-Ray Reflectivity

The density of the *n*-PBDF thin film was determined using X-ray Reflectivity (XRR). For this measurement, a sample was prepared by spin-coating an approximately 50 nm thick film of *n*-PBDF onto a cleaned silicon substrate within a nitrogen-filled glovebox. The as-prepared film was then annealed under vacuum at room temperature for 24 h to ensure the complete removal of any residual solvent.

XRR measurements were performed using a Rigaku SMARTLAB® diffractometer. The raw data were first corrected for the X-ray beam footprint on the sample. Subsequently, the reflectivity curve was fitted using the REFNX data analysis package for Python. The structure was modeled as a single *n*-PBDF layer on a native silicon oxide (SiO_x) layer over a silicon substrate (SiO_2/Si). During the fitting process, the densities of the substrate layers were fixed to their known literature values, allowing the density of the *n*-PBDF layer to be determined with a high precision.

1.12 Mechanical Bending (Fatigue) Testing

To evaluate the mechanical robustness of the *n*-PBDF films for flexible applications, a cyclic bending test was performed on a heater device fabricated on a flexible PET substrate. The test was conducted using a custom-built, automated linear rail bending apparatus. The flexible heater samples were mounted onto rail brackets, which cyclically moved the sample between two states: A near-fully extended, flat position, and a bent position (10 mm bending radius). Each full back-and-forth motion constituted a single bending cycle.

The performance of the heater was monitored by periodically measuring its sheet resistance (R_s). Measurements were taken at frequent intervals for the first several thousand cycles (e.g., every 5000 cycles) to observe any initial changes and then continued at longer intervals for the duration of the test. The total test was run for 60 000 cycles. The change in electrical performance

was quantified by comparing the sheet resistance at a given cycle number to the initial, pristine sheet resistance.

The *n*-PBDF heater demonstrated excellent mechanical durability. After 60 000 bending cycles to a 10 mm radius, the device retained over 80 % of its initial performance. This degree of robustness of our spray-coated *n*-PBDF films under extensive mechanical deformation highlights its suitability for demanding flexible electronic applications. The results of this test are highlighted in **Figure 6f (Main Text)**.

1.13 Grazing-incidence Wide-angle X-ray Scattering (GIWAXS)

Ex-situ GIWAXS measurements were performed at the Complex Materials Scattering (CMS, 11-BM) beamline at the National Synchrotron Light Source II (NSLS-II), Brookhaven National Laboratory. For this measurement, films of DMSO-based and EtOH-based ink formulations were prepared by spin-coating an approximately 50 nm thick film of each *n*-PBDF onto a cleaned silicon substrate. The incident X-ray energy was 13.5 keV ($\lambda = 0.9184 \text{ \AA}$). The data were collected using a Dectris Pilatus® 800K area detector, with the sample-to-detector distance calibrated to 257.3 mm using a silver behenate (AgBH) standard. To maximize the q -range coverage and eliminate gap effects, two detector images were collected at vertically offset positions and stitched together. The films were measured at an incidence angle of 0.14° with respect to the substrate, with an exposure time of 10 s. Data reduction and analysis were performed using the Nika software package for WaveMetrics® Igor Pro®.⁴ Out-of-plane profiles were extracted using 10° wide sector averages centered at 90° , while in-plane profiles were obtained via horizontal line integration (3-pixel width) with a vertical offset of 9 pixels from the horizon. See **Table S3** and **Figure S43** for a comparison. The crystallographic d -spacings and crystalline coherence lengths (L_c) were calculated using the relations $d = 2\pi/q_0$ and $L_c = 2\pi K/\Delta q$ (Scherrer approximation, using a standard shape factor of $K = 0.9$), respectively.⁵ Because the peaks were modeled using Gaussian fits $\left(y = y_0 + A \cdot \exp\left(-\left(\frac{x-x_0}{w}\right)^2\right)\right)$ in the Nika software package, the full-width at half-maximum (FWHM) of the scattering peak (Δq) was analytically converted from the fitted width parameter (w) using the relation $\Delta q = 2\sqrt{\ln 2} \cdot w$.

Table S3. Summary of extracted GIWAXS parameters for *n*-PBDF films. The table compares the peak position (q), Gaussian width parameter, and intensity for the out-of-plane lamellar stacking and the in-plane π - π stacking reflections. Data corresponds to the line-cut profiles shown in **Figure S43**.

Sample	Direction	Reflection	Position (q) ($\text{\AA}^{-1}$)	Fit parameter (w) ($\text{\AA}^{-1}$)	Intensity (A) (a.u.)	d -spacing ($\text{\AA}$)	Coherence length, L_c ($\text{\AA}$)
DMSO- based <i>n</i>-PBDF	Out-of- plane	(100)	0.5980 ± 0.0003	0.0558 ± 0.0008	2193 ± 22	10.51 ± 0.01	61 ± 1
		(200)	1.1516 ± 0.0008	0.0671 ± 0.0047	122 ± 8	5.46 ± 0.01	51 ± 4
		(300)	1.7696 ± 0.0002	0.0828 ± 0.0007	131 ± 1	3.55 ± 0.01	41 ± 1
		(400)	2.3485 ± 0.0012	0.0985 ± 0.0073	10 ± 1	2.68 ± 0.01	34 ± 3
	In-plane	(010)	1.8776 ± 0.0005	0.0619 ± 0.0012	127 ± 2	3.35 ± 0.01	55 ± 1
Ethanol- based <i>n</i>-PBDF	Out-of- plane	(100)	0.6044 ± 0.0003	0.0572 ± 0.0007	2584 ± 22	10.40 ± 0.01	59 ± 1
		(200)	1.1512 ± 0.0012	0.0784 ± 0.0103	106 ± 16	5.46 ± 0.01	43 ± 6
		(300)	1.7687 ± 0.0005	0.0835 ± 0.0022	104 ± 2	3.55 ± 0.01	41 ± 1
		(400)	2.3786 ± 0.0010	0.1138 ± 0.0081	12 ± 1	2.64 ± 0.01	30 ± 2
	In-plane	(010)	1.8923 ± 0.0005	0.0656 ± 0.0013	166 ± 2	3.32 ± 0.01	52 ± 1

1.14 Data Reliability and Reproducibility

To ensure the reproducibility of the fabrication process, all measurements were performed at multiple distinct locations and on replicate samples. For each film, at least five distinct AFM measurements and no fewer than ten profilometry measurements were performed. The results are reported as average values with corresponding uncertainties.

Note S2. Specific Heat Capacity and Thermal Stability

1.1 Differential Scanning Calorimetry (DSC)

The temperature-dependent specific heat capacity (C_p or c_1) of *n*-PBDF was determined for use in subsequent thermal modeling. The procedure involved initial measurements that revealed the hygroscopic nature of the material, a refined temperature modulated DSC analysis to confirm this and establish a drying protocol, and a final high-precision measurement to obtain the intrinsic heat capacity of the dry material.

1.1.1 Preliminary Modulated DSC (MDSC®) Analysis

Initial measurements, conducted on a Discovery™ 2500 DSC (TA Instruments, USA), revealed that the *n*-PBDF material is hygroscopic, absorbing approximately 1 % water by mass under ambient conditions (≈ 20 % relative humidity (RH)). This moisture content confounds the heat capacity measurement due to the added thermal effect of moisture loss. To address this and develop a robust measurement protocol, a refined MDSC® analysis with an in-situ drying step was performed.

A sample (10.239 mg) was sealed in a standard non-hermetic aluminum pan and subjected to a two-segment procedure:

1. In-situ Drying: The sample was first dried directly within the DSC cell by holding it at an isothermal temperature of 140 °C for 40 min.
2. MDSC® Measurement: Immediately following the drying step, the MDSC® experiment was performed. The sample was equilibrated at -120 °C, held isothermally for 5 min, and subsequently heated to 145 °C at an underlying ramp rate of 3 °C min⁻¹ with a temperature modulation amplitude of ± 1 °C. The analysis confirmed that the in-situ drying step was essential for removing absorbed water and obtaining accurate measurements of the intrinsic thermal properties of *n*-PBDF.

1.1.2 Definitive Heat Capacity Measurement

Based on the findings from the MDSC® analysis, the definitive measurements were performed using a DSC 8500 equipped with a CLN2 liquid nitrogen chiller (PerkinElmer Inc.,

USA), using StepScan mode (heating rate of 150 K min^{-1} , steps of 1 K , and isotherm times of 60 s) and employing the calibration methods described elsewhere.^{6,7} To ensure reproducibility, samples from two independently synthesized batches of *n*-PBDF were analyzed in this study. The resulting temperature-dependent C_p (or c_1) data and the corresponding linear fit are presented in **Figure S35**.

The procedure for each sample was as follows: the sample was sealed in a non-hermetic aluminum DSC pan and loaded into the instrument. A rigorous in-situ drying step was performed by holding the sample at $140\text{ }^{\circ}\text{C}$ for approximately 40 min under a high-purity helium purge. Immediately following this, and without breaking the inert atmosphere, the heat capacity measurement was performed under the same dry helium purge.

The two resulting data sets were found to be in excellent agreement. These values were then averaged, and the final temperature-dependent specific heat capacity was determined by fitting the averaged data to a linear model, yielding the equation $C_p(T) = (0.0029859 \pm 0.000027)\text{ J g}^{-1}\text{ }^{\circ}\text{C}^{-2} \cdot T + (0.75341 \pm 0.0016)\text{ J g}^{-1}\text{ }^{\circ}\text{C}^{-1}$. The values extracted through this fit were used in all subsequent thermal models and calculations.

1.2 Thermogravimetric Analysis (TGA)

The thermal stability of *n*-PBDF was characterized by using a Q500 thermogravimetric analyzer (TA Instruments, USA). A sample of dried *n*-PBDF powder (approximately 5 mg to 10 mg) was loaded into a platinum TGA pan for analysis.

The analysis was conducted using a High-Resolution Dynamic Heating method at a heating rate of $40\text{ }^{\circ}\text{C min}^{-1}$ with a resolution setting of 4.0 . The sample was heated from room temperature to $800\text{ }^{\circ}\text{C}$ under a high-purity nitrogen atmosphere. Upon reaching $800\text{ }^{\circ}\text{C}$, the carrier gas was switched to air to enable the combustion of any remaining char.

The remaining mass percentage and its first derivative (derivative thermogravimetry, DTG) were recorded as a function of temperature and time. The onset temperature of decomposition was determined from the TGA curve using the tangent intersection method via the instrument's analysis software (TA TRIOSTM). This analysis defined the thermal degradation profile of *n*-PBDF under both inert and oxidative conditions. These results established the upper temperature limit for the Joule heating experiments, ensuring that device testing was conducted below the primary decomposition threshold of *n*-PBDF.

Note S3. In-plane and Cross-plane Thermal Conductivity (κ)

1.1 In-plane Thermal Conductivity (κ_x and κ_y)

1.1.1 Measurement Principle and Technique

The in-plane thermal conductivities (κ_x and κ_y) of a free-standing, 73 μm thick *n*-PBDF film were measured using an advanced, two-dimensional extension of the classic Ångström method, as recently developed and detailed by Gaitonde et al.^{8–11}

The core principle of the technique is to periodically heat a single spot at the center of a suspended thin-film sample and use a high-speed infrared (IR) camera to map the resulting two-dimensional, oscillating temperature field on the sample's surface. The key advantage of this method is that the thermal conductivities in the two in-plane orthotropic directions (κ_x and κ_y) can be extracted simultaneously from a single measurement.

Experimental Setup

A custom-built experimental setup, illustrated schematically in **Figure 5e (Main Text)**, was used to perform the measurements. A free-standing 73 μm thick *n*-PBDF film was suspended over a circular aperture in a temperature-controlled heat sink and clamped by a copper holder.

A thin aluminum disk cut from adhesive-backed aluminum tape and coated with a thin layer of graphite (PELCO® Colloidal Graphite, Ted Pella, Inc, Cat. No. 16053) was attached at the center of the bottom-side sample surface to function as a laser absorber and transducer—ensuring uniform, circular heating of the sample, and protecting the IR detector from direct laser radiation.

The sample was heated from the bottom using a fiber-coupled diode laser (BWTek BWF2, 980 nm, 5 W max). The laser's output was modulated into a square wave at a set frequency (50 to 400) mHz using a function generator. To ensure precise and repeatable alignment, the laser's output fiber was rigidly secured to the mounting plate with a sub-miniature version-A (SMA) adapter, centering the laser spot on the absorber disk. An infrared microscope (Infrascopes™, Quantum Focus Instruments Corporation) was positioned above the sample to record the transient temperature distribution. For this work, a 1/6 times magnification infrared lens was used, providing a spatial resolution of $\approx 75 \mu\text{m}/\text{pixel}$ over a $\approx (77 \times 77) \text{ mm}^2$ field of view.

1.1.2 Data Analysis

The data analysis was performed in the frequency domain. The raw spatiotemporal data, which consisted of a series of IR thermal images over time, was first processed using a Fourier transform at each pixel within the imaging area into its amplitude and phase lag (first harmonic). An inverse fitting algorithm was then used to determine κ_x and κ_y . This algorithm compares the experimentally measured 2D maps of amplitude and phase to a thermal diffusion model and finds the unique values of κ_x and κ_y that best match the experimental data. Notably, this method does not require precise knowledge of the laser power, boundary conditions at the edge of the sample, or the through-plane thermal conductivity, which significantly reduces sources of experimental uncertainty. The full derivation of the governing equations, the detailed data analysis workflow, and the validation of the technique are presented in the original works by Gaitonde et al.^{8–10} A detailed analysis of the robustness of this extraction, including a sensitivity analysis of the model parameters and a reconciliation with the Joule heating results, is provided in **Note S9**.

1.2 Cross-plane Thermal Conductivity (κ_z)

1.2.1 Measurement Principle and Technique

The cross-plane (or through-plane) thermal conductivity (κ_z) of a bulk *n*-PBDF film was measured using a steady-state, one-dimensional heat flux method based on the conventional reference bar method (ASTM D5470), as detailed by Gaitonde et al.⁸ The principle is to create a steady 1D heat flux through a multi-layer stack—where the sample with unknown conductivity is sandwiched between reference materials with known conductivity—and measure the resulting temperature gradient across the sample to determine its thermal conductivity via Fourier's Law.

1.2.2 Experimental Setup and Sample Preparation

The experimental setup is illustrated schematically in **Figure 5a (Main Text)**. Here, a 1D heat flow is established across a sample stack that is clamped between heated and cooled aluminum reference bars by applying a temperature gradient. During the steady state, an IR microscope then maps the temperature profile along the polished cross-section of this stack. The specific sample preparation for the *n*-PBDF film was a critical, multi-step process:

1. **Stack Assembly:** A 1 cm² piece of the free-standing, 73 μm thick *n*-PBDF film was sandwiched between two equally sized squares of 1 mm thick black poly(tetrafluoroethylene) (PTFE), which serve as the thermal reference bars.
2. **Encapsulation and Polishing:** This PTFE | *n*-PBDF | PTFE stack was encapsulated in a cold-mounting epoxy (QC Epoxy, Leco Corporation). After curing, a cross-sectional surface was meticulously wet polished on a lapidary wheel (Leco® SS1000) using a sequence of SiC pads (progressing sequentially from 400 to 2000 grit). This was followed by polishing with 3 μm and 1 μm diamond pastes and Microid Extender on a Red Felt cloth, and a final polish with a colloidal silica slurry (812-121-300, Leco Corporation) on an Ultra Silk cloth. This created the optically flat, mirror-like surface required for high-resolution IR imaging.
3. **Final Preparation:** Excess epoxy was carefully ground away from the outer faces of the PTFE layers. A thin layer of silver-thermal paste was then applied to these exposed faces to ensure excellent thermal contact with the heated and cooled aluminum reference bars of the measurement setup before the sample was clamped in place.

1.2.3 Data Analysis

During the experiment, an IR microscope captured a high-resolution 2D thermal map of the polished cross-section (**Figure 5b, Main Text**). This map was spatially averaged to create a 1D temperature profile along the direction of heat flow (**Figure 5c, Main Text**).

For the calculation of heat flux (q''), the temperature gradient (dT/dx) within the known PTFE references were measured. Using Fourier's Law ($q'' = -\kappa_{\text{ref}} \cdot (dT/dx)_{\text{ref}}$), the heat flux through the stack was determined. Additionally, the temperature gradient across the *n*-PBDF sample, $(dT/dx)_{\text{sample}}$ was measured and recorded. With this data in hand, the through-plane thermal conductivity (κ_z) was then calculated as $\kappa_z = -q''/(dT/dx)_{\text{sample}}$. By plotting the calculated heat flux against the sample's temperature gradient for multiple heating powers, a linear relationship was obtained (**Figure 5d, Main Text**), where the slope provided a robust, averaged value of κ_z for *n*-PBDF, where the uncertainty represents the standard error of the fitted slope.

Note S4. Comprehensive Optical Modeling

1.1 Material Model and Software

The optical constants of the *n*-PBDF films were determined by analyzing the experimental transmittance and reflectance spectra using the WVASE® software package (J. A. Woollam Co.). The optical response of the film was modeled using a general oscillator material model (GENOSC, J. A. Woollam Co.), which combines Gaussian oscillators to represent interband electronic transitions and a Drude oscillator to account for the free-carrier contribution in the conductive polymer.

1.2 Substrate Model Development

A precise optical model of the substrate is critical for accurately extracting the properties of the film. It was observed that the UV-ozone (UVO) treatment, used to clean and prepare the substrate surface, slightly altered its optical properties. Accurately accounting for this alteration is crucial, particularly for thin films, where the substrate significantly influences the total optical response. Therefore, two competing models were developed and tested:

1. Single-Layer Substrate: The *n*-PBDF film was modeled on a simple, unmodified 'BK_7g' substrate.
2. Two-Layer Substrate: The *n*-PBDF film was modeled on a custom "UVO-Glass" substrate. This model consisted of the base 'BK_7g' layer plus an additional thin surface layer with modified optical oscillators to account for the effects of UVO treatment.

The two-layer substrate model was found to provide a more robust and accurate fit to the experimental data. Consequently, this refined "UVO-Glass" model was adopted for all subsequent analyses, ensuring that the extracted parameters were decoupled from substrate influences and accurately represented the *n*-PBDF material itself.

1.3 Model Validation via Monte Carlo Analysis

A Monte Carlo (MC) analysis was performed to validate the stability and quantify the confidence limits of the fitted parameters (**Table S4**). This statistical method repeatedly fits the model to the data, each time using a randomly resampled subset of the data points (with replacement). This process rigorously assessed the stability of the solution and provided a statistical basis for the uncertainty of each parameter.

The MC analysis confirmed that the two-layer substrate model was robust and yielded well-defined parameters with low uncertainty. The final fit was considered acceptable when the Mean Squared Error (MSE) was minimized, achieving an average value of approximately 0.1206.

Table S4. Comparison of Monte Carlo analysis results for a 72 nm *n*-PBDF film using two different substrate models. The analysis was performed using five repeated fits.

Parameter	Model w/o UVO Layer	Model w/ UVO Layer
n_{fit}	35	36
n_{data}	2536	2536
Fit iterations	1000	1000
MSE	0.1212 ± 0.0026	0.1206 ± 0.0026
RMSE	0.348 ± 0.004	0.347 ± 0.004

Note: RMSE is Root mean-square error.

1.4 Extraction of Optical Constants

From the validated and optimized fits using the two-layer substrate model, the following optical constants for the *n*-PBDF films were extracted: the refractive index (*n*), extinction coefficient (*k*), real (ϵ_1) and imaginary (ϵ_2) components of the dielectric function, and absorption coefficient (α).

1.5 Calculation of The Absorption and Extinction Coefficient

The absorption coefficient (α) of the *n*-PBDF films was determined using two complementary methods: an experimental approach based on substrate-normalized data and the Beer–Lambert law, and an analytical approach using the results from optical modeling (as described above).

1.5.1 Experimental Determination

A series of n-PBDF films with varying thicknesses was prepared. The raw optical transmittance (T_{sample}) and reflectance (R_{sample}) for each film, as well as for a bare reference substrate (T_{glass} and R_{glass}), were measured using a Filmetrics® F10-RT reflectometer. To improve the signal-to-noise ratio and increase statistical power, at least five scans were averaged for each measurement. The instrument calculates the total absorptance of a sample as:

$$A_{\text{sample}} = 100 - R_{\text{sample}} - T_{\text{sample}} \quad \text{Eq. S3}$$

which includes contributions from both the film and substrate.

1.5.2 Data Normalization and Analysis

To isolate the intrinsic optical properties of the *n*-PBDF film, a normalization procedure was performed on the raw experimental transmittance (T) and reflectance (R) data to eliminate the influence of the glass substrate. The substrate-normalized transmittance (T_{film}) was calculated as follows:

$$T_{\text{film}} = \frac{T_{\text{sample}}}{T_{\text{glass}}} \cdot 100 \quad \text{Eq. S4}$$

with its propagated uncertainty given by:

$$\delta T_{\text{film}} = T_{\text{film}} \cdot \sqrt{\left(\frac{\delta T_{\text{sample}}}{T_{\text{sample}}}\right)^2 + \left(\frac{\delta T_{\text{glass}}}{T_{\text{glass}}}\right)^2} \quad \text{Eq. S5}$$

The substrate-normalized reflectance (R_{film}) was calculated as follows:

$$R_{\text{film}} = \frac{R_{\text{sample}} - R_{\text{glass}}}{1 - \frac{R_{\text{glass}}}{100}} \quad \text{Eq. S6}$$

with its propagated uncertainty given by:

$$\delta R_{\text{film}} = \left| \frac{R_{\text{sample}} - R_{\text{glass}}}{1 - \frac{R_{\text{glass}}}{100}} \right| \cdot \left(\frac{\sqrt{\delta R_{\text{sample}}^2 + \delta R_{\text{glass}}^2}}{R_{\text{sample}} - R_{\text{glass}}} \right)^2 + \left(\frac{\frac{\delta R_{\text{glass}}}{100}}{1 - \frac{R_{\text{glass}}}{100}} \right)^2 \quad \text{Eq. S7}$$

A negative value indicated that the sample appeared to reflect slightly less than the bare glass. Because negative reflectance is not physical, this result suggests that, within the measurement uncertainties, the reflectance of the film is essentially zero (or similarly low). The substrate-normalized absorptance (A_{film}) was then calculated from the normalized values:

$$A_{\text{film}} = 100 - T_{\text{film}} - R_{\text{film}} \quad \text{Eq. S8}$$

with its propagated uncertainty given by:

$$\delta A_{\text{film}} = \sqrt{(\delta T_{\text{film}})^2 + (\delta R_{\text{film}})^2} . \quad \text{Eq. S9}$$

After normalization, the Beer–Lambert law was applied. Assuming negligible reflectance (justified by the low values of R_{film} after normalization), the substrate-normalized transmittance ($T_{\text{film}} \%$) was converted to absorbance (Abs):

$$\text{Abs} = 2 - \log_{10}(T_{\text{film}} \%) \quad \text{Eq. S10}$$

A Beer–Lambert plot of absorbance versus film thickness was constructed for each wavelength of interest ($\lambda_{550 \text{ nm}}$). The absorption coefficient (α) was then determined from the slope of this plot. The relationship between these variables and the subsequent calculation of the extinction coefficient (k) is given by:

$$\alpha(\lambda) = \frac{2.303 \cdot \text{Abs}(\lambda)}{\text{film thickness (cm)}} \quad \text{Eq. S11}$$

$$k(\lambda) = \frac{\alpha(\lambda) \cdot \lambda}{4\pi} . \quad \text{Eq. S12}$$

The uncertainties in the calculated values were determined using the following standard error propagation formulas:

$$\delta \alpha = \alpha \sqrt{\left(\frac{\delta \text{Abs}}{\text{Abs}}\right)^2 + \left(\frac{\delta \text{film thickness}}{\text{film thickness}}\right)^2} \quad \text{Eq. S13}$$

$$\delta k = k \sqrt{\left(\frac{\delta \alpha}{\alpha}\right)^2 + \left(\frac{\delta \lambda}{\lambda}\right)^2} . \quad \text{Eq. S14}$$

1.6 Comparison of Methods and Analysis of Absorbance Calculation

The absorption coefficients derived from the experimental method and optical model were found to be in good agreement in the visible spectral range (spanning $\approx(400$ to $700)$ nm). In this region, the substrate-normalized reflectance (R_{film}) is low for all film thicknesses (typically $<10\%$), making the assumptions of the Beer–Lambert law reasonably valid.

However, a significant and systematic deviation between the two methods appears in the near-infrared (NIR) range, particularly for films thicker than ≈ 25 nm. We attribute this to the free-carrier (Drude) response of the conductive polymer, which leads to a sharp increase in reflectance in the NIR, with values approaching 50% for the thickest films. This high reflectance violates the core assumption of the Beer–Lambert law, which incorrectly attributes all light loss to absorption.

This deviation highlights the superiority of the WVASE® optical model, which correctly decouples the effects of absorption and reflectance, providing a physically accurate value for the absorption coefficient, even in spectral regions where the reflectance is high. Within the experimental analysis, the simplified absorbance formula was compared with the more rigorous reflection-corrected formula:

$$\text{Abs}(\lambda) = 2 - \log_{10} \left(\frac{T_{\text{film}}}{100 - R_{\text{film}}} \cdot 100 \right) \quad \text{Eq. S15}$$

Given that the Beer–Lambert model is strictly applicable only in the low-reflectance visible region, a simplified formula was adopted. In this regime, the correction term from R_{film} was found to be negligible (within the measurement uncertainty). Thus, including this term introduced unnecessary measurement noise without providing a more accurate result. While this simplified Beer–Lambert analysis provided an important experimental validation in the visible range, it became more unreliable in the high-reflectance NIR region. Consequently, we determined that the WVASE® optical model provides a more representative measure of the optical constants (n and k) and absorption coefficient for n -PBDF across the entire experimental spectral window.

Note S5. Visible Light Transmittance (VLT)

1.1 Visible Light Transmittance (VLT)

Visible Light Transmittance (VLT), also known as luminosity or photopic transmission, is a standard metric that quantifies the perceived brightness of an object to a human observer. In this study, the VLT was calculated in accordance with the CIE Color Specification System (CIE 2019, CIE spectral luminous efficiency for photopic vision, International Commission on Illumination (CIE), Vienna, AT).

This method integrates the object's transmission spectrum across the visible range (defined as 380 nm to 780 nm), weighted at each wavelength by the human eye's spectral sensitivity (the photopic response function). Mathematically, the VLT is represented as the ratio of the transmitted visible light flux to the incident visible light flux:

$$\frac{\int_{380}^{780} T(\lambda)V(\lambda)d\lambda}{\int_{380}^{780} V(\lambda)d\lambda} \quad \text{Eq. S16}$$

where $T(\lambda)$ is the measured transmittance of the sample and $V(\lambda)$ is the dimensionless luminous efficiency function (photopic response). In **Eq. S16**, the numerator represents the weighted transmittance integral, which adjusts the total light transmitted through the sample to prioritize wavelengths according to human visual perception. The denominator serves as a normalization factor, representing the total integrated photopic response across the visible spectrum. The final VLT value is a dimensionless ratio between 0 (no visible light transmitted) and 1, which is commonly expressed as a percentage ((0 to 100) %).

Note S6. Characterization and Modeling of Thermal Behaviors

1.1 Theory Behind the Observed Joule Heating Response

The primary function of a transparent heater is to convert electrical energy into heat through Joule heating. Under a constant applied voltage (V), a current (I) flows through the device, and the power (P) is dissipated into the surroundings. The dissipated power is given by:

$$\text{Power} = P = IV = \frac{V^2}{R} = I^2 R \quad \text{Eq. S17}$$

and over a period of time (Δt), the total amount of heat dissipated through the system is represented by:

$$\text{Energy} = Q = P \cdot \Delta t = IV \cdot \Delta t = \frac{V^2}{R} \cdot \Delta t = I^2 R \cdot \Delta t. \quad \text{Eq. S18}$$

Consequently, films with lower electrical resistance (R) draw more current, dissipate more power, and achieve higher steady-state temperatures. This may seem counterintuitive, as one might associate higher resistance with more "friction" and thus more heat. However, for a voltage-controlled device, the inverse relationship between power and resistance ($P \propto 1/R$) is dominant.

The resulting temperature evolution reflects a balance between (1) the inflow of electrical energy and (2) the outflow of heat via conduction, convection, and radiation. Of the dissipated heat, some raises the temperature of the active material thin film and substrate (conduction), while the rest is lost to the environment (primarily via convection and radiation, through both the coated (film–air) and uncoated surface (substrate–air) interfaces). For some materials, such as graphene, radiative losses are often considered negligible due to their low emissivity.¹² However, this assumption does not apply to all transparent conducting materials (TCMs). As our analysis shows, both convection and radiation are significant heat loss pathways in the *n*-PBDF system (substrate + film).

To quantitatively link the observed Joule heating behavior with the thermal dissipation pathways, we first employed a lumped-capacitance energy balance model (Sorel et al.)¹³ and applied it to both transient and steady-state analyses. This framework provides the simplest physical description of the system, yielding initial definitions for the effective heat transfer coefficient (α) and thermal time constant (τ).

1.2 Detailed Derivation of a Simple Thermal Model

1.2.1 Lumped Capacitance Model

This model assumes that the instantaneous temperature is spatially uniform across the heater and that the losses through the electrical contacts are negligible. The energy balance is given by the following differential equation, **Eq. S19**:

$$\underbrace{\frac{V^2/R}{\text{Dissipated Electrical Power}}}_{\text{Dissipated Electrical Power}} = \underbrace{\frac{(m_1 c_1 + m_2 c_2) dT(t)/dt}{\text{Fraction of Power Used to Increase Temperature of Substrate and Film}}}_{\text{Fraction of Power Used to Increase Temperature of Substrate and Film}} + \underbrace{\frac{A(h_1 + h_2)(T(t) - T_0)}{\text{Approximate Losses via Convection}}}_{\text{Approximate Losses via Convection}} + \underbrace{\frac{\sigma A(\varepsilon_1 + \varepsilon_2) \cdot (T(t)^4 - T_0^4)}{\text{Approximate Losses via Radiation}}}_{\text{Approximate Losses via Radiation}}.$$

Here, subscripts 1 and 2 refer to the *n*-PBDF film and substrate, respectively. *m* is mass, *c* is specific heat capacity, *h* is the convective heat transfer coefficient, *ε* is emissivity (needed for both sides of the sample), *A* is the area of the film (assumed equal to substrate area), *σ* is the Stefan-Boltzmann constant ($5.67 \cdot 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$), *T*(*t*) is the instantaneous temperature, and *T*₀ is the ambient temperature.

Because this equation lacks a simple analytical solution, we made two key simplifications (described in detail below). To convert **Eq. S19** into a more usable form: **(1)** we linearized the *T*⁴ radiative term and **(2)** combined all convective and radiative loss terms into a single effective heat transfer coefficient, *α* (**Eq. S22**), which afforded an energy balance equation in the form of a first-order linear ordinary differential equation (**Eq. S23**). The solutions to this model give rise to a definition of the system's thermal time constant, *τ*, and describe the temperature evolution during heating (*t* < *t*_{off}; **Eq. S27**) and cooling (*t* > *t*_{off}; **Eq. S32**) processes.

1.2.2 Transient Analysis (Further Details)

Assuming small temperature changes, the *T*⁴ radiation term can be linearized (approximately) using a Taylor expansion, as follows:

$$T(t)^4 - T_0^4 \approx 4T_0^3(T(t) - T_0). \quad \text{Eq. S20}$$

Substituting **Eq. S20** into **Eq. S19** affords an approximate form of the energy balance equation, as follows:

$$(m_1 c_1 + m_2 c_2) \frac{dT(t)}{dt} + A[(h_1 + h_2) + 4T_0^3 \sigma(\varepsilon_1 + \varepsilon_2)](T(t) - T_0) - \frac{V^2}{R} \approx 0. \quad \text{Eq. S21}$$

Given that the mass of the *n*-PBDF films is significantly less than that of the substrate ($m_1 \ll m_2$), we considered the conduction term and heat capacity for *n*-PBDF to be negligible. To ensure high experimental reliability, the glass substrate thickness and mass were tightly controlled across all samples ((1.016 ± 0.006) mm; mass within ± 1 %). This allowed the substrate heat capacity ($m_2 c_2$) to be treated as constant, offering further simplification, as it made the mass and heat capacity of the substrate the primary determinants of the thermal response of the heaters. Furthermore, the earlier linearization of the radiative term (**Eq. S20**) allows us to factor out the temperature difference and combine all convective and radiative loss terms into a single effective heat transfer coefficient, α , as follows:

$$\alpha = (h_1 + h_2) + 4T_0^3 \sigma(\varepsilon_1 + \varepsilon_2). \quad \text{Eq. S22}$$

Having consolidated all heat dissipation pathways into a single value, the simplified energy balance now simplifies to a first-order linear ordinary differential equation, where $P = V^2/R$ is the input power, as follows:

$$m_2 c_2 \frac{dT(t)}{dt} + \alpha A(T(t) - T_0) = P \quad \text{Eq. S23}$$

$$\frac{dT(t)}{dt} + \frac{\alpha A}{m_2 c_2} (T(t) - T_0) = \frac{P}{m_2 c_2}. \quad \text{Eq. S24}$$

To solve this equation, we define the system's thermal time constant, τ , which represents the characteristic time required to reach thermal equilibrium, as follows:

$$\tau = \frac{m_2 c_2}{\alpha A} = \frac{C}{\alpha A} = \frac{\rho A d c}{\alpha A} = \frac{\rho d c}{\alpha} \quad \text{Eq. S25}$$

where C , ρ , and d are the heat capacity, the density, and the thickness of the substrate, respectively. Substituting τ (**Eq. S25**) into **Eq. S24** gives:

$$\frac{dT(t)}{dt} + \frac{1}{\tau} (T(t) - T_0) = \frac{P}{m_2 c_2}. \quad \text{Eq. S26}$$

Rearranging and simplifying **Eq. S26** provides a straightforward solution for describing the temperature evolution during the heating process ($t < t_{\text{off}}$), as follows:

$$T(t) = T_0 + \frac{P}{\alpha A} \left(1 - e^{-\frac{t}{\tau}}\right). \quad \text{Eq. S27}$$

This equation can be expressed in terms of the fundamental experimental parameters (e.g. V , R) by substituting $P = V^2/R$ and $\tau = m_2 c_2 / \alpha A$:

$$T(t) = T_0 + \frac{V^2}{\alpha A R} \left(1 - e^{-\frac{\alpha A}{m_2 c_2} t}\right)$$

or

$$T(t) = T_0 + \frac{1}{\alpha} \frac{V^2}{A R} \left(1 - e^{-\frac{\alpha A}{m_2 c_2} t}\right). \quad \text{Eq. S28}$$

Similarly, we can describe the heater's behavior during the cooling process ($t > t_{\text{off}}$), when the input power is turned off ($P = 0$). **Eq. S23** then simplifies to:

$$m_2 c_2 \frac{dT(t)}{dt} + \alpha A (T - T_0) = 0. \quad \text{Eq. S29}$$

Rearranging **Eq. S29** into standard differential form gives:

$$\frac{dT(t)}{dt} + \frac{\alpha A}{m_2 c_2} (T(t) - T_0) = 0. \quad \text{Eq. S30}$$

By substituting the definition of the thermal time constant, τ (from **Eq. S25**), we get:

$$\frac{dT(t)}{dt} + \frac{1}{\tau} (T(t) - T_0) = 0. \quad \text{Eq. S31}$$

Rearranging and simplifying **Eq. S31** provides a straightforward solution describing the temperature evolution (exponential decay) during the cooling process ($t > t_{\text{off}}$), as follows:

$$T(t) = T_0 + (T_{\text{off}} - T_0) e^{-\frac{t - t_{\text{off}}}{\tau}} \quad \text{Eq. S32}$$

where T_0 is the ambient temperature, and $T_{\text{off}} = T(t_{\text{off}})$ is the temperature of the heater at the moment in which the power is turned off.

1.2.3 Steady-state Analysis (Further Details)

Finally, we analyze the steady state condition. At the steady-state temperature, T_{sat} , the system is in thermal equilibrium, and the temperature no longer changes with time ($\frac{dT(t)}{dt} = 0$). This is represented by setting the time derivative in the approximate energy balance equation (Eq. S23) to zero, giving that the temperature rise depends solely on the areal power density ($\frac{V^2}{AR}$) and the effective heat transfer coefficient (α). This yields a general equation for the absolute steady-state temperature as follows:

$$T_{\text{sat}} = T_0 + \frac{P}{\alpha A}. \quad \text{Eq. S33}$$

This relationship can be expressed in alternative forms, depending on the electrical parameters used:

$$T_{\text{sat}} = T_0 + \frac{I^2 R}{\alpha A} = T_0 + \frac{I^2 R_s}{\alpha w^2} = T_0 + \frac{V^2}{\alpha AR} = T_0 + \frac{V^2}{\alpha l^2 R_s}. \quad \text{Eq. S34}$$

From this, the steady-state temperature rise, ΔT_{max} is given by:

$$\Delta T_{\text{max}} = T_{\text{sat}} - T_0 = \frac{V^2}{\alpha AR} = \frac{V^2}{\alpha l^2 R_s} \quad \text{Eq. S35}$$

where R can be written in terms of sheet resistance, R_s , as $R = R_s \cdot \frac{l}{w}$ and $A = l \cdot w$, with l and w being the length and the width of the film, respectively. This steady-state relationship is fundamental, as it provides a direct method for experimentally extracting the effective heat transfer coefficient, α .

By rearranging the core equation, it can be shown that ΔT_{max} is linearly proportional to the input power (α is the ratio of the input areal power density to the temperature rise; $\alpha \propto P$):

$$\alpha = \frac{P}{A \Delta T_{\text{max}}} = \frac{VI}{A \Delta T_{\text{max}}}. \quad \text{Eq. S36}$$

Therefore, α can be obtained directly by plotting the measured steady-state temperature (or ΔT_{max}) as a function of the applied areal power density. This yields a straight line with an intercept of T_0 (or 0), and the heat transfer coefficient can be extracted from the reciprocal of the slope (slope =

$1/\alpha$). We further note that since power is supplied by a voltage source ($P = V^2/R$), one can alternatively plot $\Delta T_{\max}$ versus V^2 (or $1/\Delta T_{\max}$ versus $1/V^2$) which yields a slope of $1/\alpha AR$ (or αAR).

1.3 Detailed Derivation of a Temperature Coefficient of Resistance (TCR)-aware Thermal Model

A key assumption in the lumped-capacitance model is that the electrical resistance of the heater (and thus power) is invariant with temperature. However, the electrical resistance of many materials is often temperature dependent, a behavior described by the Temperature Coefficient of Resistance (TCR or β), denoted as:

$$R = R_0(1 + \beta(T(t) - T_0)) \text{ or } R = R_0(1 + \beta\Delta T) \quad \text{Eq. S37}$$

where a positive TCR indicates that R increases with T .

In such a case, when heating under a fixed applied voltage (V), the input power dynamically decays ($P = V^2/R$) as the device heats. As a result of standard models not explicitly accounting for this, the observed slower temperature rise that results can be misattributed as being caused by changes in the material's inherent thermal transport properties, leading to a systematic overestimation of both α and τ . Therefore, in addition to the lumped-capacitance model and unlike most analogous reports in the Joule heating literature, we additionally applied the TCR-aware transient model (which explicitly accounts for resistance drift during heating; based on Ji et al.¹⁴) to our data, to assess its significance and impact on our system, in comparison with the former.

In contrast to the heating process, the cooling curve should be nominally independent of R (power is no longer applied). Therefore, the decay in temperature should reflect only passive thermal dissipation via conduction, convection, and radiation.

To obtain a 'TCR-aware' energy balance model, we substituted the temperature-dependent resistance (**Eq. S37**) into the standard transient heating equation (**Eq. S23**) to add the non-constant power delivery term (as demonstrated by Ji et al.¹⁴). However, rather than expressing the equation in terms of constant power (P), we instead used $\frac{V^2}{R}$ to more clearly track the impact of resistance changes as a function of the applied voltage and the material's initial electrical resistance (R_0 ; at T_{initial}), as follows:

$$m_2 c_2 \frac{dT(t)}{dt} = \frac{V^2}{R_0[1+\beta(T(t)-T_0)]} - \alpha A(T(t) - T_0). \quad \text{Eq. S38}$$

Given the non-linear denominator, we used a first-order Taylor expansion to approximate $1/R$ (assuming small/modest $\beta(T(t) - T_0)$), as follows:

$$\frac{1}{1+\beta(T(t)-T_0)} \approx 1 - \beta(T(t) - T_0). \quad \text{Eq. S39}$$

Substituting the approximation (**Eq. S39**) into **Eq. S38** yielded:

$$m_2 c_2 \frac{dT(t)}{dt} = \frac{V^2}{R_0} [1 - \beta(T(t) - T_0)] - \alpha A(T(t) - T_0). \quad \text{Eq. S40}$$

After expanding and grouping the $(T-T_0)$ terms together, we obtained a linearized form as:

$$\begin{aligned} m_2 c_2 \frac{dT(t)}{dt} &= \frac{V^2}{R_0} - \left(\frac{V^2 \beta}{R_0} + \alpha A \right) (T(t) - T_0) \\ \frac{dT(t)}{dt} &= \frac{V^2}{m_2 c_2 R_0} - \frac{1}{m_2 c_2} \left(\frac{V^2 \beta}{R_0} + \alpha A \right) (T(t) - T_0) \end{aligned} \quad \text{Eq. S41}$$

which matched the form of a standard ordinary differential equation (ODE) of the type:

$$\frac{dT(t)}{dt} = K_1 - K_2(T(t) - T_0). \quad \text{Eq. S42}$$

This gave rise to the constants:

$$K_1 = \frac{V^2}{m_2 c_2 R_0} \text{ and } K_2 = \frac{1}{m_2 c_2} \left(\frac{V^2 \beta}{R_0} + \alpha A \right). \quad \text{Eq. S43}$$

Inserting the constants from **Eq. S43** into an exponential approach-to-equilibrium solution of the form:

$$T(t) = T_0 + \frac{K_1}{K_2} (1 - e^{-K_2 t}) \quad \text{Eq. S44}$$

and substituting the expressions for K_1 and K_2 yielded the full solution for the TCR-aware model, as:

$$T(t) = T_0 + \frac{\frac{V^2}{m_2 c_2 R_0}}{\frac{1}{m_2 c_2} \left(\frac{V^2 \beta}{R_0} + \alpha A \right)} \left(1 - e^{-\left(\frac{1}{m_2 c_2} \left(\frac{V^2 \beta}{R_0} + \alpha A \right) \right) t} \right)$$

$$T(t) = T_0 + \frac{V^2/R_0}{\left(\frac{V^2 \beta}{R_0} + \alpha A \right)} \left(1 - e^{-\left(\frac{1}{m_2 c_2} \left(\frac{V^2 \beta}{R_0} + \alpha A \right) \right) t} \right). \quad \text{Eq. S45}$$

Next, we defined a new TCR-corrected equation for τ by using the terms from within the exponent. This enabled us to preserve the similar exponential form of the standard model which contained the ‘ $1 - e^{-t/\tau}$ ’ term as:

$$\tau = \frac{m_2 c_2}{\frac{V^2 \beta}{R_0} + \alpha A} = \frac{\rho d c}{\alpha + \underbrace{\frac{V^2 \beta}{A R_0}}_{\text{Corrective Term (K)}}}. \quad \text{Eq. S46}$$

Lastly, we obtained the final expression for the ‘TCR-aware’ heating process as:

$$T(t) = T_0 + \frac{V^2/R_0}{\left(\frac{V^2 \beta}{R_0} + \alpha A \right)} \left(1 - e^{-\frac{t}{\tau}} \right). \quad \text{Eq. S47}$$

To apply the TCR-aware model to our data, we experimentally determined the average value of β for *n*-PBDF. We recorded the resistance (R) at different steady-state temperatures (T_{SST}) during Joule heating experiments and plotted the data as R vs. SST (R vs. T_{sat}). We performed a linear fit on the data, which produced a line in the form $y = R_0 + R_0 \beta(x)$ having slope $R_0 \cdot \beta$. After comparing all fit results, we found good agreement between the samples and extracted a mean TCR value of $\beta = (0.585 \pm 0.138) \% \text{ } ^\circ\text{C}^{-1}$ (**Figures S13 and S14** for additional details).

1.4 Comparative Analysis of the Models (Steady-state vs. Transient, and TCR-aware)

1.4.1 Extraction of Thermal Constants Alpha (α) and Tau (τ)

To quantitatively and thoroughly assess the thermal performance of our heaters, we extracted the effective heat transfer coefficient (α) and thermal response time constant (τ) using three distinct methods: (1) a steady-state (SST) energy balance (adapted from Sorel et al.¹³), (2) a standard (non-TCR) dual-region transient fit, and (3) a TCR-aware transient fitting approach. The extracted values for both (3×3) cm² and (5×5) cm² devices were plotted as a function of film transmittance in **Figure S38**.

1.4.2 Steady-state Approach

In the SST approach, α was extracted by linear regression of the steady-state temperature rise (ΔT_{max}) versus areal power density (P/A), based on the energy balance equation from Sorel et al.¹³

$$\Delta T_{\text{max}} = \frac{V^2}{\alpha AR} . \quad \text{Eq. S48}$$

This method provides an estimate of α under equilibrium conditions, integrating all modes of heat loss (conduction, convection, and radiation) and assumes constant resistance and steady input power (see above **Eq. S36**).

Table S5. Representative dataset for $(3 \times 3) \text{ cm}^2$ samples of *n*-PBDF derived from SST analysis. Data was obtained by fitting a line of the form $y = a + bx$ to the steady state temperature vs. areal power density plotted data for each film thickness. The SI unit was calculated from the slope value as (SI Unit = $1/(\text{slope} \cdot 0.1) = 10/\text{slope}$).

Film thickness (nm)	Slope value from fitting ($^{\circ}\text{C cm}^2 \text{ mW}^{-1}$)	SI unit* ($\text{W m}^{-2} \text{ K}^{-1}$)
71.70	0.31 ± 0.01	32.26 ± 1.04
59.13	0.35 ± 0.01	28.57 ± 0.82
51.05	0.34 ± 0.01	29.41 ± 0.87
41.37	0.40 ± 0.01	25.00 ± 0.63
34.92	0.33 ± 0.01	30.30 ± 0.92
30.06	0.38 ± 0.01	26.32 ± 0.69
25.92	0.36 ± 0.01	27.78 ± 0.77
19.99	0.41 ± 0.01	24.39 ± 0.59
15.48	0.44 ± 0.01	22.73 ± 0.52
11.42	0.41 ± 0.01	24.39 ± 0.59
9.04	0.43 ± 0.01	23.26 ± 0.54
6.75	—	—
3.81	—	—

Note: ‘*’ denotes SI Unit, which is a standard unit of measurement within the international system of units (metric system).

1.4.3 Standard Transient Approach

Here, the full set of transient heating and cooling curves from the Joule heating experiments were independently fitted to **Eq. S27** and **Eq. S32**, respectively. This allowed for the extraction of both α and τ . However, this method does not consider TCR effects during the heating phase.

1.4.4 TCR-aware Transient Approach

In the standard SST and uncorrected transient model, it is assumed that the resistance of the heater remains constant during Joule heating. However, as described previously this assumption is flawed: resistance increases (power decreases) with temperature due to the positive Temperature Coefficient of Resistance (TCR). This leads to a dynamic reduction in input power during heating, which violates this assumption. Similarly, Ji et al. analyzed this effect in detail and described that neglecting TCR leads to overestimation of α , due to inflated apparent power input (especially at high voltage), and by inference, an overestimation of τ , as the delayed system response from decreasing power would be misattributed to slower thermal transport.¹⁴

Additionally, our interest in exploring this more rigorous model was also motivated by a slight hysteresis we observed between the α and τ values extracted from the heating versus the cooling curves in the basic model. While Ji et al.¹⁴ did not explicitly quantify the error in τ , their analysis and fit results implied that assuming constant resistance caused the early-stage heating response to appear slower than it truly was. This would lead to an overestimation of τ in non-TCR models, a conclusion that is supported by our own data and comparative fits.

$$\alpha_{\text{measured}} = \alpha_{\text{true}} + \beta \cdot \frac{V^2}{AR_0}. \quad \text{Eq. S49}$$

Here, the full set of transient heating curves from the Joule heating experiments were fitted to **Eq. S47**, using the experimentally determined value of β . This allowed for the simultaneous extraction of both α and τ .

1.5 Analysis of Extracted α and τ

While the simpler SST and non-TCR transient methods yielded results for α and τ that were in close agreement (within $\approx 5\%$), a direct comparison of the models confirmed that neglecting the TCR leads to a systematic overestimation of both the thermal time constant (τ) and the heat transfer coefficient (α).

The impact was most pronounced for the thermal time constant, τ . For the $(3 \times 3) \text{ cm}^2$ devices, the TCR-aware model yielded an average τ of 89.2 s. This represents a reduction of $\approx (10 \text{ to } 13)\%$ compared to the values obtained from the SST method (99.6 s) and the non-TCR transient fits (100.1 s to 102.4 s). A similar trend was observed for the $(5 \times 5) \text{ cm}^2$ devices, where the TCR-aware τ of 128.5 s was $\approx (8 \text{ to } 14)\%$ lower than the values obtained through the SST (139.7 s) and non-TCR (143.3 s to 149.2 s) methods.

Likewise, the TCR-corrected heat transfer coefficient (α) values were consistently lower than those derived from the SST and non-TCR model. For the $(3 \times 3) \text{ cm}^2$ devices, the TCR-corrected α was $20.9 \text{ W m}^{-2} \text{ K}^{-1}$, approximately 5% lower than the SST value of $21.9 \text{ W m}^{-2} \text{ K}^{-1}$, and $\approx (1 \text{ to } 2)\%$ lower than the non-TCR range ($(21.1 \text{ to } 21.2) \text{ W m}^{-2} \text{ K}^{-1}$). The effect was most pronounced for the larger $(5 \times 5) \text{ cm}^2$ devices, where the TCR-corrected α of $15.3 \text{ W m}^{-2} \text{ K}^{-1}$ was approximately 12% lower than the SST value of $17.3 \text{ W m}^{-2} \text{ K}^{-1}$. In this case, the TCR-corrected

value was comparable to the upper end of the range determined from the non-TCR method (14.5 to 15.2) $\text{W m}^{-2} \text{K}^{-1}$.

This systematic overestimation, more pronounced in the larger (5×5) cm^2 devices, is fully consistent with the theoretical model, which predicts that the error term scales with the square of the applied voltage (V^2), a value that is necessarily higher for larger-area heaters to achieve a given power density.

The accuracy of the TCR-aware model is further validated by the close agreement between its extracted parameters and those derived from the cooling-only regime, where TCR effects are absent (**Figure S38**). Therefore, while simpler methods provide a reasonable first-order approximation, these findings underscore that TCR-aware analysis is essential for accurate performance evaluation and rational heater design, especially when comparing different device geometries or operating at high power levels.

Table S6. Alpha and Tau values for small and large-area devices.

Alpha ($\text{W m}^{-2} \text{K}^{-1}$)	(3×3) cm^2 device	(5×5) cm^2 device
SST	21.9	17.3
non-TCR	21.1 to 21.2	14.5 to 15.2
TCR	20.9	15.3
Tau (s)	(3×3) cm^2 device	(5×5) cm^2 device
SST	99.6	139.7
non-TCR	100.1 to 102.4	143.3 to 149.2
TCR	89.2	128.5

1.5.1 Interpretation and Contextualization of α and τ

The experimentally extracted values for the effective heat transfer coefficient (α) for the *n*-PBDF-coated glass substrates fall within the range of $\approx(15$ to $25) \text{ W m}^{-2} \text{K}^{-1}$, depending on film thickness and device geometry. These experimental values can be contextualized and validated by estimating the theoretical contributions from the two primary heat loss mechanisms: convection and radiation. From our thermal model derivation, the linearized, combined heat transfer coefficient (α) for a device with two distinct surfaces is given by **Eq. S22**:

$$\alpha = (h_1 + h_2) + 4T_0^3 \sigma (\varepsilon_1 + \varepsilon_2).$$

Using standard assumptions and material properties at the experimental ambient temperature ($T_0 \approx 297 \text{ K}$; 24°C) we estimated the theoretical contributions (and thus α) for the *n*-PBDF on glass system in **Table S7**.

Table S7. Calculation of contribution to alpha from various modes of heat transfer.

Parameter	Value
Convective heat transfer coefficient (h) for Glass	$\approx 10 \text{ W m}^{-2} \text{ K}^{-1}$ (a typical value for natural convection from a small, flat plate in air)
Convective heat transfer coefficient (h) for PET	$\approx 14 \text{ W m}^{-2} \text{ K}^{-1}$
Emissivity of <i>n</i> -PBDF (ϵ_{film} ; 1)	≈ 0.8 (based on measurements of the bulk material)
Emissivity of glass (ϵ_{glass} ; 2a)	≈ 0.84
Emissivity of PET (ϵ_{PET} ; 2b)	≈ 0.90
Stefan-Boltzmann Constant (σ)	$5.67 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$
Considering Pure Substrate Only (Glass, 2a)	
Contribution From Radiation, 2a (One Side)	$5 \text{ W m}^{-2} \text{ K}^{-1}$
Contribution From Convection, 2a (One Side)	$10 \text{ W m}^{-2} \text{ K}^{-1}$
Total Alpha (One side)	$15 \text{ W m}^{-2} \text{ K}^{-1}$
Radiation (Both sides)	$10 \text{ W m}^{-2} \text{ K}^{-1}$
Convection (Both sides)	$20 \text{ W m}^{-2} \text{ K}^{-1}$
Total Alpha (Both sides)	$30 \text{ W m}^{-2} \text{ K}^{-1}$
Considering Pure Substrate Only (PET, 2b)	
Contribution From Radiation, 2b (One Side)	$5.4 \text{ W m}^{-2} \text{ K}^{-1}$
Contribution From Convection, 2b (One Side)	$14 \text{ W m}^{-2} \text{ K}^{-1}$
Total Alpha (One side)	$19.4 \text{ W m}^{-2} \text{ K}^{-1}$
Radiation (Both sides)	$10.7 \text{ W m}^{-2} \text{ K}^{-1}$
Convection (Both sides)	$28 \text{ W m}^{-2} \text{ K}^{-1}$
Total Alpha (Both sides)	$38.7 \text{ W m}^{-2} \text{ K}^{-1}$

The radiative component for a single, uncoated glass surface was calculated as:

$$\alpha_{\text{rad,glass}} = 4T_0^3 \sigma \epsilon_{\text{glass}} = 4(297.15)^3 (5.67 \times 10^{-8}) (0.84) \approx 5 \text{ W m}^{-2} \text{ K}^{-1}.$$

The total heat transfer coefficient for one side is the sum of radiative and convective losses:

$$\alpha_{\text{side,glass}} = \alpha_{\text{rad,glass}} + h_2 \approx 5 + 10 = 15 \text{ W m}^{-2} \text{ K}^{-1}.$$

Given that the measured emissivity of the *n*-PBDF film ($\epsilon_{\text{film}} \approx 0.8$) is very similar to that of glass, the calculated heat loss from the coated side is nearly identical, at $\alpha_{\text{side,film}} \approx 15 \text{ W m}^{-2}$

K^{-1} . Within this value, the radiative loss is $\approx 5 \text{ W m}^{-2} \text{ K}^{-1}$ and the convective loss is $\approx 10 \text{ W m}^{-2} \text{ K}^{-1}$, indicating that convection is the dominant heat loss mechanism, accounting for roughly two-thirds of the total dissipation from each surface.

Therefore, the theoretical α_{total} for the entire device should lie between the range $\approx (15 \text{ to } 30) \text{ W m}^{-2} \text{ K}^{-1}$. Our experimentally measured values ($(15 \text{ to } 25) \text{ W m}^{-2} \text{ K}^{-1}$) are consistent with this estimated theoretical range, confirming the validity of our approach.

1.6 Comparison to Other Heater Systems and Justification of The Model Fit

These extracted α values are lower, but comparable to those previously reported for AgNW/PET systems.^{13,14} This is physically reasonable, as α is primarily governed by the substrate. For comparison, a PET substrate ($\epsilon \approx 0.9$, $h \approx 14 \text{ W m}^{-2} \text{ K}^{-1}$) would yield a theoretical α of approximately $39 \text{ W m}^{-2} \text{ K}^{-1}$, which is the same order of magnitude and reflects the same underlying physics.

The lower α values of our *n*-PBDF-on-glass system are an advantageous property. A lower heat transfer coefficient signifies better thermal insulation, which enables the device to achieve higher steady-state temperatures for a given input power, a key requirement for applications like de-icing. This difference is physically reasonable and can be attributed primarily to the different substrate used (glass vs. PET), as α is dominated by the substrate's properties (emissivity and convective heat transfer).

Additionally, this analysis importantly confirms that radiative loss ($\approx 5 \text{ W m}^{-2} \text{ K}^{-1}$) is still a significant component, accounting for roughly one-third of the total heat dissipation from each surface. This provides a crucial distinction from lower emissivity materials like graphene, where heat loss is *almost entirely* dominated by convection.^{12,13,15} Therefore, the inclusion of both convective and radiative terms in our thermal model was essential for accurately describing the behavior of the *n*-PBDF heating system.

1.7 Scaling of Performance Metrics with Heater Device Size

1.7.1 Scaling Analysis of α and τ

Beyond validating the absolute values of the thermal parameters, a key part of this work was also to understand how they scale with device geometry and film thickness and inform critical design principles for future transparent heaters.

The thermal time constant (τ) reflects the system's response time to reach thermal equilibrium. It is inversely proportional to the heat loss rate (α), as shown by the relationship $\tau = \rho dc/\alpha$ (or $\tau = mc/A\alpha$). This implies a fundamental trade-off between fast response times (low τ , high α) and high thermal output (high steady-state temperature, low α). This behavior is central to heater design; for example, applications requiring rapid heating (e.g., defogging) may favor a higher α , while those needing higher steady-state temperatures (e.g., deicing) benefit from a lower α .

1.7.2 Device Size and Geometric Trends

Consistent scaling trends with device size were observed across all analytical methods. The effective heat transfer coefficient (α) for the larger (5×5) cm² heaters was found to be (21 to 31) % lower than for the (3×3) cm² counterparts. We attribute this reduction as driven by two primary geometric factors: edge effects and natural convection efficiency.

Edge Effects

Smaller devices have a higher edge-to-area ratio, which enhances lateral heat loss through edge conduction and convection (increasing α and reducing τ), as compared to larger devices which experience weaker natural convection due to thicker thermal boundary layers and reduced effective surface cooling (especially near the center of the heater). In the case of our samples, the smaller (3×3) cm² devices have a 66 % higher edge-to-area ratio than the (5×5) cm² devices (1.33 cm^{-1} vs. 0.80 cm^{-1}) which leads to the smaller devices having greater relative heat loss from the perimeter.

Natural Convection Efficiency

Natural convection theory predicts that the convective heat transfer coefficient (h) scales with the characteristic length (L) of the heater as $h \propto L^{-1/4}$. This suggests a ≈ 12 % decrease in h when scaling from a 9 cm^2 to a 25 cm^2 device ($(\frac{5}{3})^{-\frac{1}{4}} \approx 0.88$), as buoyancy-driven airflow becomes less efficient over larger surfaces. Since convection accounts for roughly two-thirds of the total heat dissipation in the system, this effect alone contributes an estimated ≈ 8 % to the total reduction in α . These combined effects cause the experimental values for α to scale sub-linearly with area, a behavior captured in our measurements but not accounted for in idealized lumped-capacitance models.

The thermal time constant (τ) scales as a direct consequence of changes in α , increasing with device size, and follows the expected inverse relationship ($\tau \propto 1/\alpha$) predicted by the simple lumped capacitance (constant resistance) model. This means that a (21 to 31) % decrease in α , when scaling from $(3 \times 3) \text{ cm}^2$ to $(5 \times 5) \text{ cm}^2$ device, is expected to cause a $\approx (27 \text{ to } 45)$ % increase in τ ($\tau_{(5 \text{ cm} \times 5 \text{ cm})} / \tau_{(3 \text{ cm} \times 3 \text{ cm})} = 1/(1 - \delta)$, $\delta = 0.21 - 0.31$). This prediction aligns well with the results obtained from the experimental results across all methods. The SST and non-TCR methods show τ increasing from ≈ 100 s for the 3×3 device to $\approx (140 \text{ to } 149)$ s for the $(5 \times 5) \text{ cm}^2$ device (a $\approx (40 \text{ to } 49)$ % increase), while the TCR-aware model shows τ increasing from 89.2 s to 128.5 s (a ≈ 44 % increase). This self-consistent result, where the observed $\approx (40 \text{ to } 49)$ % increase in τ is explained by the $\approx (21 \text{ to } 31)$ % reduction in α , holds true across all models and reinforces the physical coupling between the thermal dissipation rate and system response time.

Furthermore, we specifically validated this scaling behavior within the context of our more rigorous TCR-aware model. This model includes a corrective term, K , in the denominator of the equation (**Eq. S46**) for τ , which could potentially alter the scaling:

$$\tau = \frac{m_2 c_2}{\frac{V^2 \beta}{R_0} + \alpha A} = \frac{\rho d c}{\alpha + \frac{\frac{V^2 \beta}{AR_0}}{\text{Corrective Term } (K)}}. \quad \text{Eq. S50}$$

A large K (from high V , low R , or reduced AR_0) would dampen the sensitivity of τ to changes in α . In contrast, when $K \ll \alpha$, the TCR-aware result naturally converges to the constant-resistance prediction ($\tau \propto 1/\alpha$). To test this, we analyzed the TCR-aware results exclusively. Our TCR-aware results show that α_{TCR} decreased by ≈ 27 % (from $(20.9 \text{ to } 15.3) \text{ W m}^{-2} \text{ K}^{-1}$) when

scaling from the $(3 \times 3) \text{ cm}^2$ to the $(5 \times 5) \text{ cm}^2$ device. Based on the simple $1/\alpha$ relationship, this would predict an $\approx 37\%$ increase in τ_{TCR} . Our experimental τ_{TCR} results show an increase of $\approx 44\%$ (89.2 s to 128.5 s).

This strong agreement between the predicted ($\approx 37\%$) and measured ($\approx 44\%$) increase confirms that, under our operating conditions, the corrective term K is negligible relative to α . Therefore, while the TCR correction is critical for determining the *absolute value* of τ , the scaling behavior with device geometry remains dominated by the fundamental inverse relationship with α .

1.8 Scaling of Performance Metrics with Film Thickness

Film Thickness (n-PBDF) Dependent Scaling of τ

To further interrogate the underlying heat loss mechanisms, we investigated how the thermal time constant (τ) scales with film thickness. According to the lumped capacitance model, the thermal time constant is governed by the total thermal mass of the system and the effective heat transfer to the environment ($\tau = m_2 c_2 / \alpha A$).

As established in **Section 1.2.2**, the mass of the *n*-PBDF films is negligible compared to the tightly controlled glass substrate. Therefore, classical thermal models predict that the thermal mass (and consequently the thermal time constant, τ) should remain effectively constant across our samples, regardless of the nanometer-scale polymer film thickness.

Our transient analysis confirms this physical expectation. As derived from our experimental heating and cooling curves (**Table S6; Figures S36 and S37**), the thermal time constant remains consistent across the entire thickness range (from $\approx (4 \text{ to } 72) \text{ nm}$). Rather than the thickness of the active layer, we found that τ is governed primarily by the device area (as detailed in **Section 1.7.2**). This confirms that the macroscopic thermal dynamics of the heaters are reliably governed by the substrate's thermal mass.

Note S7. Joule Heater Characterization

1.1 Experimental Setup and Equipment

The Joule heating experiments were controlled and monitored using a custom-built, computer-automated setup. The core components of the system were:

1. Power Source: A programmable 9140 Triple Output DC Power Supply (B&K Precision, USA) was used to apply a precise DC voltage to the heater devices. Standard slew rates (Voltage: 600 mV ms^{-1} , Current: 100 mA ms^{-1}) were used for all tests.
2. Data Acquisition System (DAQ): A DAS240 unit (Sefram, FR; B&K Precision, USA) was used to log temperature data from the thermocouples at a 1 Hz sampling rate. The DAQ was connected to a 20-channel interface module (902401000, Sefram, FR) to handle multiple simultaneous thermocouple inputs.
3. Temperature Sensor and Connections: Fast-response ($<1 \text{ s}$), micro-sized, 30-gauge, PFA-insulated Type K thermocouple with a linear range of $(-70 \text{ to } 260) ^\circ\text{C}$ were used for temperature monitoring (K1X-WBWX-30G-EX-0.25-PFXX-80-STWL, Evolution Sensors & Controls, LLC, USA). The thermocouple wires were terminated into 3-pole screw-set terminal blocks (TLPS-308, Tianli Electrical Machinery (Ningbo) Co., Ltd., CN) before being connected to the 20-channel interface module (to DAQ).
4. Electrical Leads and Device Connection: Gold-plated banana plug test leads (BU-PB72-2, Digi-Key, USA) connected the power supply to the device. Custom-made wire leads were used to interface the main test leads with the device. These were constructed using 14-AWG copper hook-up wire with a soldered female 4 mm banana connector on one end, and a smooth-jawed, copper micro-alligator clip (BU-34M, Mueller Electric) on the other. This ensured a robust mechanical connection to the heater's silver electrodes.
5. Control and Automation: The power supply and DAQ were interfaced to a computer workstation via a custom-made LabVIEW® program, allowing for the precise and automated execution of voltage and timing routines (recipes) for high throughput, systematic testing of devices.

1.2 Preparation of Devices for Testing

For the Joule heating experiments, electrical contacts were created by painting fast-drying silver paint (Electrodag® 1415M, Ted Pella, USA) on two opposing edges of the prepared *n*-PBDF films (as shown in **Figure 1a, Main Text**). The thermocouples were then carefully affixed to the center of the bottom face (uncoated side) of the substrate using a small piece of 25.4 μm thickness high-temperature polyimide tape (Kapton®, Qnity Electronics, Inc., USA) (see **Figure S45** for photos of a representative device that is ready for testing). The devices were thermally isolated from direct contact with the workbench during testing.

1.3 Heating Measurement Protocol

All Joule heating tests were conducted in a controlled laboratory environment with an ambient temperature of (23 to 24) °C and a relative humidity (RH) of $\approx$ (20 to 30) %, under quiescent conditions with no forced air circulation.

A systematic, automated voltage and timing routine was executed for each device, typically stepping through a DC voltage range from (1 to 24) V. For each voltage step in the sequence, the following three-part procedure was performed:

1. Ambient Equilibration: The device temperature was recorded for 60 s to establish a stable ambient baseline before heating. No voltage was applied during this period.
2. Heating Period: The specified voltage was applied for approximately 1500 s ($\approx$ 25 min) to ensure the device reached a full thermal steady state.
3. Cooling Period: The voltage was turned off, and the device was allowed to cool for approximately 1000 s ($\approx$ 17 min) while temperature continued to be recorded. This cool-down period was confirmed to be sufficient for the device to return fully to ambient temperature, preventing thermal cross-contamination between sequential voltage tests.

This cycle was then automatically repeated for the next voltage in the sequence. See **Figure S46** for a screenshot of our testing program.

Note S8. Transparent Conductor Figure of Merit (FOM)

1.1 Fundamental Principles of Transparent Conductors (TCs)

The primary function of a TC is to exhibit low sheet resistance (R_s) while maintaining high optical transmittance (T) in the visible spectrum (often at $T_{550\text{ nm}}$). These two properties are often in opposition due to the fundamental physics of free-electron materials, as expressed by the Drude model.

Materials require a high density of free electrons (e.g., metals, doped semiconductors, conducting polymers) to achieve high DC electrical conductivity (σ_{DC}). However, these free electrons also have a characteristic plasma frequency (ω_p) which is the natural resonant frequency of the free electron gas. The material's interaction with light is dictated by the relationship between the light's frequency (ω) and the plasma frequency:

When $\omega < \omega_p$, (typically in the infrared for TCs), the free electrons easily respond to the oscillating electric field. This strong interaction causes high reflection and absorption, and thus low transmittance.

When $\omega > \omega_p$, (typically in the visible and UV for TCs), the electrons cannot respond quickly enough to the rapid oscillations. This weak interaction results in the material appearing optically transparent.

This creates a fundamental tradeoff. Increasing the free carrier density to improve σ_{DC} also increases ω_p . If ω_p is pushed too high, it can move into the visible spectrum, compromising transparency. Therefore, a successful TC must carefully balance these two factors, and this balance is quantitatively evaluated using a Figure of Merit (FOM).^{16,17}

1.2 Empirical-based FOMs (Fraser–Cook; Haacke)

Historically, simple empirical FOMs were developed to assess the quality of inorganic TCs like indium tin oxide (ITO). While prized for its performance, ITO suffers from significant limitations, including mechanical brittleness, high processing cost, and reliance on an element with a volatile supply chain, which has driven intense research into alternatives. These early FOMs were developed to benchmark these inorganic materials, which do not exhibit percolation behavior.

Fraser and Cook (1972)¹⁸ introduced one of the first FOMs based on a simple ratio of transmittance to sheet resistance, where higher transmittance (T) and lower sheet resistance (R_s) yield a higher FOM value^{16,18,19}:

$$\Phi_{\text{TC, F\&C}} = \frac{T}{R_s}, [\Phi_{\text{TC, F\&C}}] = \frac{1}{\Omega} = \Omega^{-1}. \quad \text{Eq. S51}$$

Fraser and Cook established the physical basis for this FOM by combining the Beer–Lambert Law ($T = e^{-\alpha d}$), which relates transmittance to film thickness (d) and the absorption coefficient (α), with the definition of sheet resistance for a bulk-like film ($R_s = \frac{1}{\sigma_{DC} \cdot d}$). While straightforward, this FOM has a serious limitation: it mathematically yields a maximum value for a material with a transmittance of only $\approx 37\%$ ($1/e$), which is too low for most practical applications.

Haacke (1976)²⁰ redefined the FOM by making it dependent on T^x , placing a much stronger emphasis on high transmittance. An exponent of $x = 10$ was optimal for maximizing the FOM for films with $T \geq 90\%$, and choosing even higher exponents (e.g., $x = (20 \text{ or } 100)$) could be used to specifically select for materials having higher transmittance ($T \geq 95\%$ or $T \geq 99\%$, respectively). The standard Haacke FOM^{16,20,21} is:

$$\Phi_{\text{TC, Haacke}} = \frac{T^{10}}{R_s}, [\Phi_{\text{TC, Haacke}}] = \frac{1}{\Omega} = \Omega^{-1}. \quad \text{Eq. S52}$$

Because of the high exponent, this FOM is highly selective, and heavily penalizes materials with even slightly lower transmittance, even if they have good conductivity.

This model is the basis for the widely used transparent conductor benchmarking plots, popularized by Contreras et al., where the FOM is visualized as a color map or contour plot of Transmittance vs. Sheet resistance.²¹ The background color map in **Figure 1c (Main Text)** is based on this approach to provide a visual benchmark.

While useful, these earlier FOMs have several limitations. They were developed for inorganic, bulk-like materials like ITO, and can be overly restrictive for other classes where a more nuanced balance is needed. Nanostructured materials (e.g. carbon nanotubes (CNTs), metallic nanowires, graphene) and organic conducting polymers often exhibit complex percolation behavior,^{19,22–24} making their electrical and optical properties nonlinear. In the race to develop flexible and solution-processable alternatives to ITO, a key distinction is that the performance of these new materials is highly sensitive to the morphology and connectivity of the conductive

network. This creates the need for new FOMs that capture the unique physics of these percolative systems.

1.3 Physics-based Optoelectronic FOMs (Dressel–Grüner; De–Coleman)

The limitations of empirical FOMs, especially for nanostructured or polymeric conductors, led to the development of more physically rigorous models.

1.3.1 Dressel and Grüner (2002)

To address the limitations of empirical FOMs, Dressel and Grüner (D&G) proposed a model based more rigorously on the physics of charge transport and light interaction.²⁵ It is defined by the ratio of the DC electrical conductivity (σ_{DC}) to the optical conductivity (σ_{Op}) as:

$$\Phi_{TC,D\&G} = \frac{\sigma_{DC}}{\sigma_{Op}}, [\Phi_{TC,D\&G}] = \text{dimensionless.} \quad \text{Eq. S53}$$

The rationale is that a good transparent conductor (TC) should have a high σ_{DC} (to conduct electricity well) but a low σ_{Op} (to absorb light minimally). These two parameters are defined by the following physical relationships:

1. The DC (σ_{DC}) conductivity is defined from sheet resistance (R_s) and thickness (d) as:

$$\sigma_{DC} = \frac{1}{(R_s \cdot d)}. \quad \text{Eq. S54}$$

2. The transmittance (T) is controlled by the optical conductivity (σ_{Op}) as:

$$T = \left(1 + \frac{Z_0}{2} \sigma_{Op} d\right)^{-2} \quad \text{Eq. S55}$$

where Z_0 is the impedance of free space ($\approx 377 \Omega$) and d is the film thickness. This equation can be rearranged to solve directly for the optical conductivity as:

$$\Rightarrow \sigma_{Op} = \frac{2}{Z_0 d} \left(T^{-\frac{1}{2}} - 1\right). \quad \text{Eq. S56}$$

To create a formula that is independent of the film thickness (d), these expressions are combined. By substituting the expression for d from the σ_{DC} equation ($d = 1 / (\sigma_{DC} \cdot R_s)$) into the transmittance equation, we obtain a new expression for T that directly incorporates R_s and the conductivity ratio:

$$T = \left(1 + \frac{Z_0 \sigma_{Op}}{2R_s \sigma_{DC}}\right)^{-2}. \quad \text{Eq. S57}$$

Since the FOM is defined as $\frac{\sigma_{DC}}{\sigma_{Op}}$, this can be re-written as:

$$T = \left(1 + \frac{Z_0}{2R_s \text{FOM}}\right)^{-2}. \quad \text{Eq. S58}$$

Finally, rearranging this expression to solve for the FOM yields the direct, practical formula for calculating the dimensionless FOM from experimental data as:

$$\text{FOM} = \Phi_{TC,D\&G} = \frac{\sigma_{DC}}{\sigma_{Op}} = \frac{Z_0}{2R_s \cdot \left(T^{-\frac{1}{2}} - 1\right)}, \left[\frac{\text{S cm}^{-1}}{\text{S cm}^{-1}}\right]. \quad \text{Eq. S59}$$

It is also notable that the optical conductivity (σ_{Op}) is approximately related to the Beer–Lambert absorption coefficient (α) through the expression $\sigma_{Op} \approx 2\alpha/(Z_0 \cdot d)$, which provides a physical link between the D&G model and classical optical absorption. Crucially, the D&G model is built on two key assumptions about the material.

First, it assumes "bulk-like" behavior, where the DC conductivity (σ_{DC}) is an intrinsic, thickness-independent property. This holds true for thick, continuous films. However, for the n -PBDF films in this work at very low thickness ($d \lesssim 70$ nm), conductivity is not constant but emerges through a percolation process as the film coalesces from isolated domains into a continuous layer.

Second, it assumes that transmittance loss is dominated by absorption, not scattering. For our n -PBDF films, which exhibit exceptionally low haze, this second assumption is valid, making the D&G model's approach to optical properties highly relevant. However, because the first assumption does not hold in our system, we decided to pursue a more advanced percolation model, as discussed next.

1.3.2 Limitations of Bulk Electrical Conductivity Assumptions

In many of the FOM formulations described above, it is implicitly assumed that the bulk (thickness-independent) value of the DC conductivity (σ_{DC}) should be used.¹³ However, for nanostructured, organic-based, or composite materials, this assumption often complicates comparison across studies and can even lead to misleading assessments of performance.

It is commonly cited that a material must achieve $R_s < 100 \, \Omega \, \text{sq.}^{-1}$ and $T > 90 \, \%$ to be considered competitive with ITO.^{17,26} According to the D&G relationship, this corresponds to a $\frac{\sigma_{\text{DC}}}{\sigma_{\text{Op}}}$ ratio of approximately 35 or higher. Nevertheless, reported values as large as $\frac{\sigma_{\text{DC}}}{\sigma_{\text{Op}}} > 400$ have appeared in the literature.²⁷ Such large apparent conductivity ratios often arise when bulk values of σ_{DC} are applied to ultrathin, discontinuous, or percolative films—underscoring the need for more accurate models, such as the De–Coleman percolation framework discussed below.

1.3.3 The Importance of Percolation in TCs

The Dressel–Grüner model implicitly assumes that the bulk, thickness-independent value of σ_{DC} should be used. However, for many advanced materials—including nanostructured composites, organic-based films, and conducting polymers, this assumption can lead to misleading assessments.

The reason is that the behavior of these materials, particularly in the highly transparent regime ($T \geq 90 \, \%$) required for many applications, is not "bulk-like." Below a certain critical thickness, d_{min} , the film is not a continuous conductive sheet. Instead, its conductivity arises from the formation of a connected network of conductive domains, a phenomenon known as percolation.

Percolation occurs when conductive elements, added beyond a critical threshold, create the first continuous conductive path through a previously insulating material. As more conductive links form, additional pathways emerge, causing conductivity to rise rapidly until it stabilizes at a bulk-like level. Percolation theory explains the non-linear, power-law relationship between conductivity and thickness in these systems. This means that FOMs based on bulk properties, such as the $\frac{\sigma_{\text{DC}}}{\sigma_{\text{Op}}}$ ratio from the standard D&G model, are not appropriate for describing the material in this crucial, highly transparent regime.

1.3.4 De and Coleman (2009)

To account for the non-bulk-like behavior of advanced TCs, De and Coleman proposed a comprehensive model that extends the D&G framework by explicitly incorporating percolation physics.²⁸ This model defines two distinct conductivity regimes separated by a critical thickness, $d_{\min}$:

1. Bulk-like Regime ($d \gg d_{\min}$): The film is thick and continuous, and the conductivity stabilizes. The standard D&G relationship applies (**Eq. S57**):

$$T = \left(1 + \frac{Z_0}{2R_s} \frac{\sigma_{Op}}{\sigma_{DC}}\right)^{-2}$$

2. Percolative Regime ($d \gtrsim d_{\min}$): Just above the percolation threshold, the DC conductivity is highly thickness-dependent, following a power-law relationship where n is the percolation exponent:

$$\begin{aligned}\sigma_{DC} &\propto (d - d_{\min})^n \\ \sigma_{DC} &= \sigma_{DC, \text{bulk}}(d - d_{\min})^n.\end{aligned}\tag{Eq. S60}$$

For $d < d_{\min}$, the film is sub-threshold or insufficiently connected, so the bulk-like model does not apply and the standard percolation scaling expression is not strictly valid in the same form. In the percolative regime, the relationship between T and R_s is governed by n and a percolative Figure of Merit (Π):

$$T = \left[1 + \frac{1}{\Pi} \left(\frac{Z_0}{R_s}\right)^{\frac{1}{n+1}}\right]^{-2}.\tag{Eq. S61}$$

The parameter Π encapsulates intrinsic material properties, including the bulk $\frac{\sigma_{DC}}{\sigma_{Op}}$ ratio and film morphology. High-performing percolative conductors (those having high T and low R_s) are characterized by large Π (indicating strong intrinsic conductivity) and small n (reflecting efficient network connectivity and low disorder). Determining n , Π , and $d_{\min}$ is essential for quantitatively benchmarking TC's performance. These parameters can be extracted by fitting the experimental T vs. R_s data to the appropriate model for each regime. The transition between the two regimes ($d_{\min}$)

can be clearly visualized on a log-log plot of $T^{-1/2} - 1$ vs. R_s (or T vs. R_s), where distinct slopes appear for the two regimes. A straight line fit through each region clearly delineates the crossover thickness and provides direct insight into network connectivity.

1.3.5 Application of Percolation Models in This Work

In this work, we used this comprehensive framework to analyze the thickness-dependent electrical properties shown in **Figure 4 (Main Text)**. This rigorous analysis allowed us to understand the transition from the percolative to the bulk-like regime in our n -PBDF films. By fitting our experimental T vs. R_s data to the De–Coleman and Dressel–Grüner models, we extracted the key physical parameters that define our material's performance:

Percolation Threshold Thickness, $d_{\min} = (9.80 \pm 0.01)$ nm

Percolation Exponent, $n = (0.81 \pm 0.23)$

Percolative Figure of Merit, $\Pi = (32.22 \pm 1.20)$

Bulk DC-to-Optical Conductivity Ratio, $\sigma_{\text{DC}}/\sigma_{\text{Op}} = (15.03 \pm 0.31)$

Bulk DC Conductivity, $\sigma_{\text{DC,bulk}} = (2663 \pm 136)$ S cm⁻¹

For added thoroughness, we evaluated the consistency of the fitted value of Π ($\Pi = 32.22$) by comparing it to the value calculated directly from the other extracted parameters ($\Pi = 35.00$) and found excellent agreement. These extracted values are highly competitive and confirm the formation of an efficient, well-connected conductive network even at very low film thicknesses, justifying the use of this detailed percolation analysis.

1.3.6 Contreras et al. FOM

Cisneros-Contreras et al. (*Modification*): More recently, Cisneros-Contreras et al. proposed a “Haacke High-Resolution” Figure of Merit (FOM) to improve the sensitivity of Haacke’s original expression. They showed that the standard Haacke FOM can be inefficient for materials with lower transmittance and modified the equation to increase its resolution by up to two orders of magnitude. Their version applies a stronger weight to transmittance by incorporating a root of the sheet resistance:

$$\Phi_{\text{TC,Contreras}} = \frac{T}{n\sqrt{R_s}}, \left[\Omega^{-\frac{1}{n}} \right] \quad \text{Eq. S62}$$

where $n = 10$ is recommended, according to the authors. This modification enables higher discrimination power across a broader range of transmittance-resistance combinations, thereby improving the reliability of inter-material comparisons. We use this Contreras-modified FOM as the background color map in **Figure 1c (Main Text)** to provide a consistent visual benchmark across different transparent-conductor systems, in a similar fashion to our previous work.¹

1.3.7 Literature Survey of Transparent Conductive Materials

See **Table S9**.

Note S9. Data Analysis and Robustness of In-plane Thermal Conductivity Measurements

1.1 Frequency-dependent Extraction of Thermal Conductivity

The in-plane thermal conductivity values were extracted at five discrete periodic heating frequencies (50 to 400) mHz. The results of these individual extractions are shown in **Figure S42**. The final values reported in the **Main Text** represent the average of these frequency-dependent values. The corresponding overall uncertainty was determined by propagating the 95% confidence interval half-widths from each individual fit (at each tested frequency).

1.2 Sensitivity Analysis of the Convective Heat Transfer Coefficient

To evaluate the robustness of the extracted in-plane thermal conductivities, the analysis was performed using two distinct approaches for the convective heat transfer coefficient (h). In the first approach, κ_x , κ_y , and h were simultaneously fitted as three independent parameters. In the second approach, h was fixed to a constant value of $10 \text{ W m}^{-2} \text{ K}^{-1}$, a typical value for natural convection. The results of this comparison are detailed in **Table S8**.

The average thermal conductivities extracted from the three-parameter fit ($\kappa_x = (3.283 \pm 0.009) \text{ W m}^{-1} \text{ K}^{-1}$ and $\kappa_y = (3.415 \pm 0.009) \text{ W m}^{-1} \text{ K}^{-1}$) are in strong agreement (differing by $\approx 2\%$) with those obtained from the fixed- h fit. This strong consistency indicates that the extracted thermal conductivity values are robust and largely insensitive to the precise value or fitting method of the convective heat transfer coefficient within this experimental regime.

As shown in **Table S8**, the fitted h values exhibited a systematic non-physical dependence on the heating frequency. A true physical convective coefficient should be independent of the experimental frequency, as it is a property of the system's physical interaction with the surrounding air and should remain constant. This trend demonstrates that the experiment is not highly sensitive to the h parameter. In a multi-parameter thermal model, low sensitivity to a secondary effect (convection) confirms that the measurement is correctly dominated by the primary physical mechanism of interest, which in this case is in-plane heat diffusion (governed by κ). Therefore, this non-physical behavior of h provides additional validation that the extracted κ values are robust and physically meaningful.

Table S8. Comparison of in-plane thermal conductivities from different convective heat transfer coefficient treatments. This table presents the average values of the extracted thermal conductivities (κ_x and κ_y) and their respective uncertainties for when the convective heat transfer coefficient (h) is treated as a fitted parameter (three-parameter fit) and when held at a fixed value of $10 \text{ W m}^{-2} \text{ K}^{-1}$ (fixed- h fit). While the extracted κ values remain stable across frequencies, the fitted h values show a frequency-dependent trend. Consequently, a fitted value for h is not physically representative and is omitted from the table summary.

Periodic Heating Frequency (mHz)	κ_x ($\text{W m}^{-1} \text{ K}^{-1}$) (from fitted h)	κ_x ($\text{W m}^{-1} \text{ K}^{-1}$) (from fixed h)	κ_y ($\text{W m}^{-1} \text{ K}^{-1}$) (from fitted h)	κ_y ($\text{W m}^{-1} \text{ K}^{-1}$) (from fixed h)	Fitted h ($\text{W m}^{-2} \text{ K}^{-1}$)
50	2.467 ± 0.014	2.630 ± 0.013	2.620 ± 0.015	2.792 ± 0.014	7.95 ± 0.08
100	2.941 ± 0.014	2.871 ± 0.014	3.123 ± 0.015	3.050 ± 0.014	11.91 ± 0.12
200	3.427 ± 0.017	3.337 ± 0.017	3.559 ± 0.017	3.461 ± 0.017	16.32 ± 0.23
300	3.582 ± 0.024	3.402 ± 0.026	3.719 ± 0.024	3.537 ± 0.027	26.40 ± 0.48
400	4.000 ± 0.029	3.787 ± 0.035	4.051 ± 0.029	3.835 ± 0.035	34.55 ± 0.71
Average	3.283 ± 0.009	3.205 ± 0.010	3.415 ± 0.009	3.335 ± 0.010	—

1.3 Consistency with Joule Heating Thermal Analysis

It is essential to distinguish the convective coefficient h used in the thermal model for the in-plane conductivity measurement (**Main Text Section 2.5**) from the effective heat transfer coefficient α derived from the Joule heating experiments (**Main Text Section 2.6 and Note S6**). As defined in our Joule heating analysis, α is a lumped parameter that inherently accounts for heat loss from both convection and radiation. Conversely, the parameter, h , in the in-plane diffusion model is designed to represent only the convective component.

Despite the insensitivity of the extracted values of κ to that of h , the fitted h values (**Table S8**) were generally within a physically plausible range for natural convection. When considering the estimated radiative heat transfer component of approximately $(5 \text{ to } 6) \text{ W m}^{-2} \text{ K}^{-1}$ (as detailed in **Note S6 and Table S7**), the sum of the convective (h) and radiative (h_{rad}) components aligns well with the independently measured α values of $(15 \text{ to } 25) \text{ W m}^{-2} \text{ K}^{-1}$ from the Joule heating experiments. This cross-validation demonstrates a strong consistency across two distinct experimental methodologies and their respective thermal models, thereby reinforcing the overall confidence in the thermal characterization presented in this work.

Supporting Figures

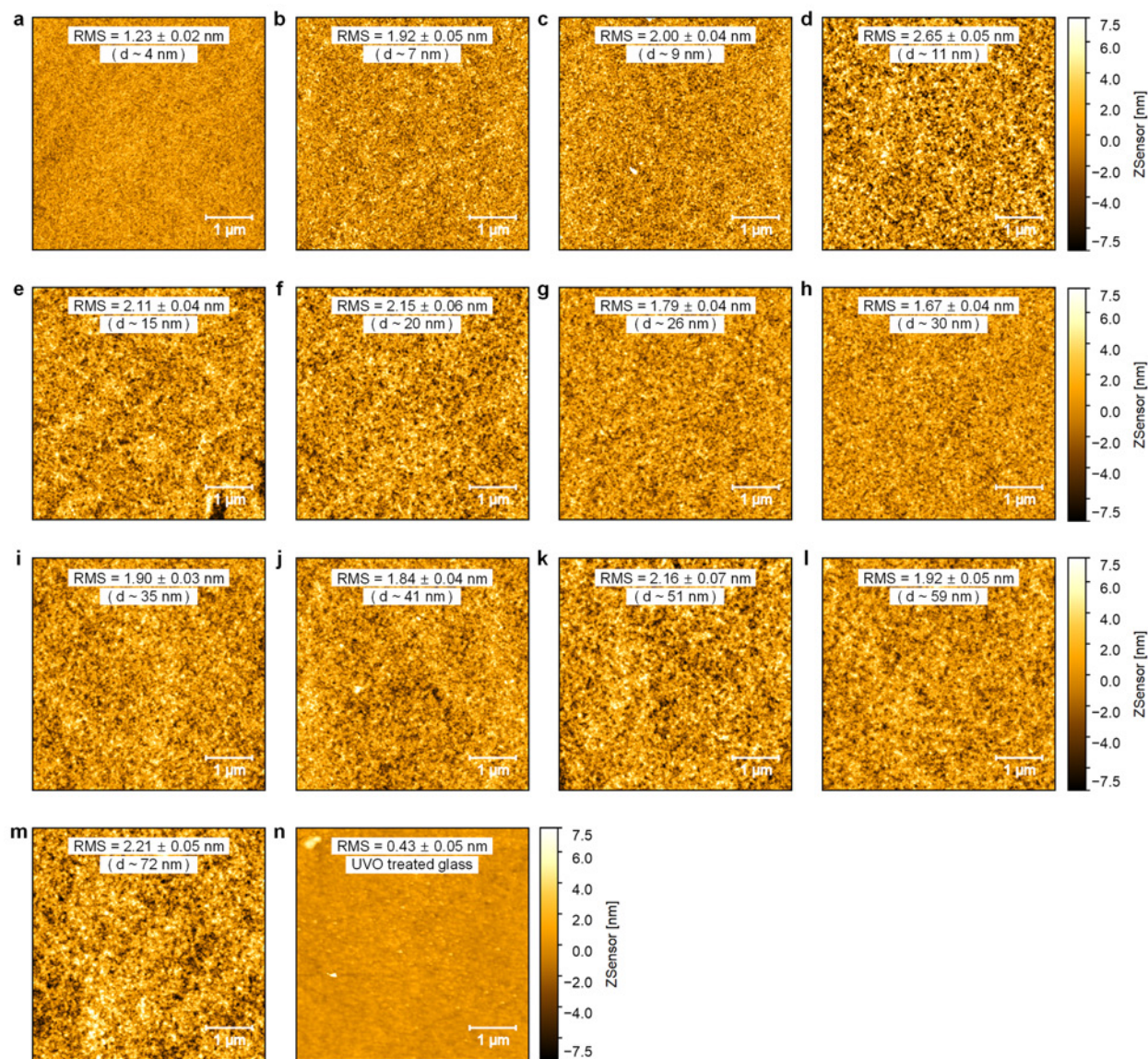


Figure S1. Atomic force microscopy (AFM) height images ($5 \times 5 \mu\text{m}^2$) showing the surface morphology of films with thicknesses from (a) $d \approx 4$ nm to (m) $d \approx 72$ nm, and that of the bare UVO-treated glass substrate (n).

The root-mean-square (RMS) roughness initially increased with thickness, reaching a maximum of (2.65 ± 0.05) nm at a film thickness of ≈ 11 nm (d). For thicker films, the roughness remained relatively stable, saturating at an RMS roughness of ≈ 1.8 nm. The substrate (n) was significantly smoother, with an RMS roughness of (0.43 ± 0.05) nm. All images share the same height scale (z-sensor height), as shown on the right.

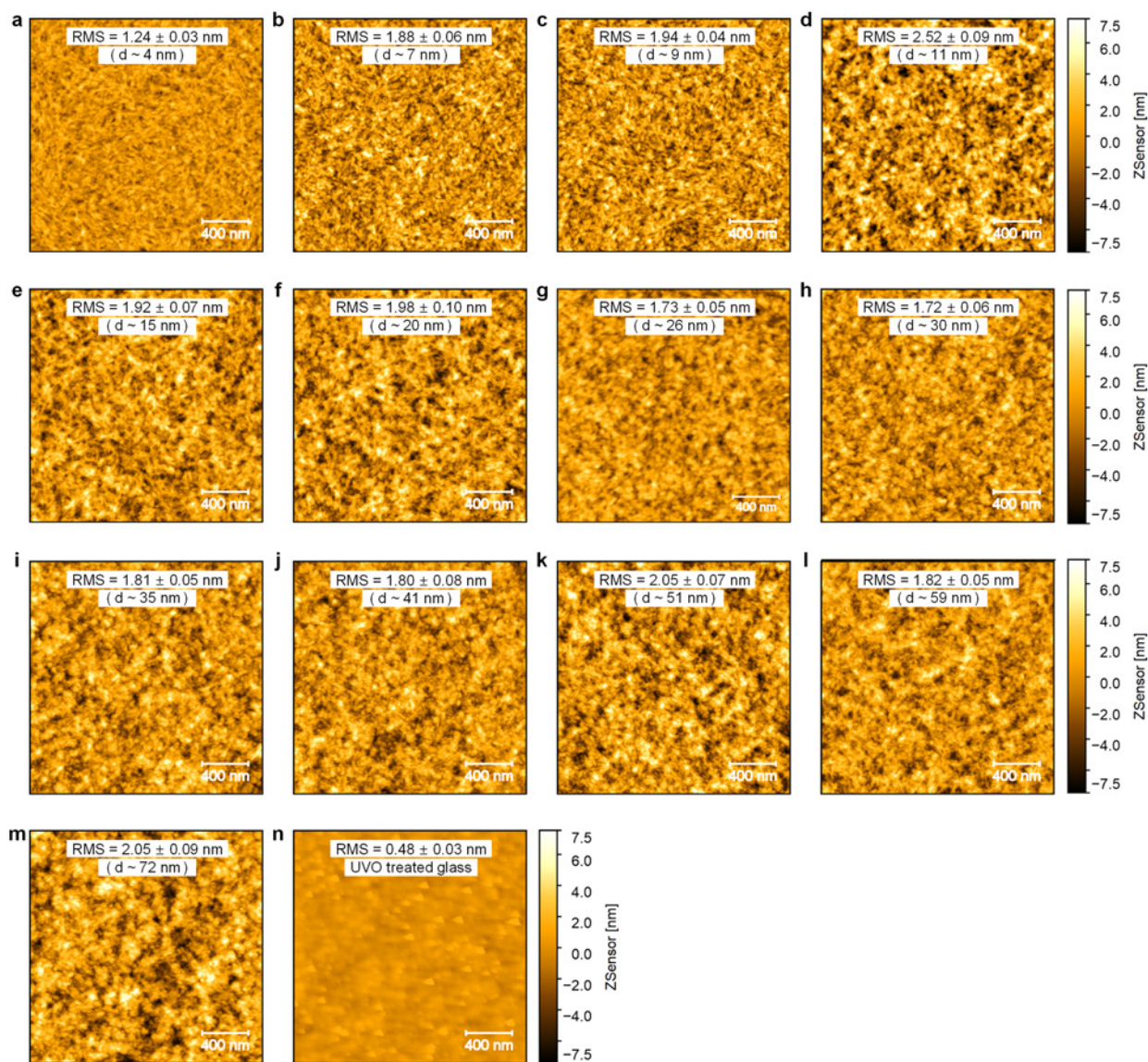


Figure S2. Atomic force microscopy (AFM) height images (2×2 μm^2) showing the surface morphology of films with thicknesses from (a) $d \approx 4$ nm to (m) $d \approx 72$ nm, and that of the bare UVO-treated glass substrate (n).

The root-mean-square (RMS) roughness initially increases with thickness, reaching a maximum of 2.65 nm at a film thickness of ≈ 11 nm (d). For thicker films, the roughness remains relatively stable, saturating at an RMS roughness of ≈ 1.8 nm. The substrate (n) is significantly smoother, with an RMS roughness of 0.48 nm. All images share the same height scale (z-sensor height), as shown on the right.

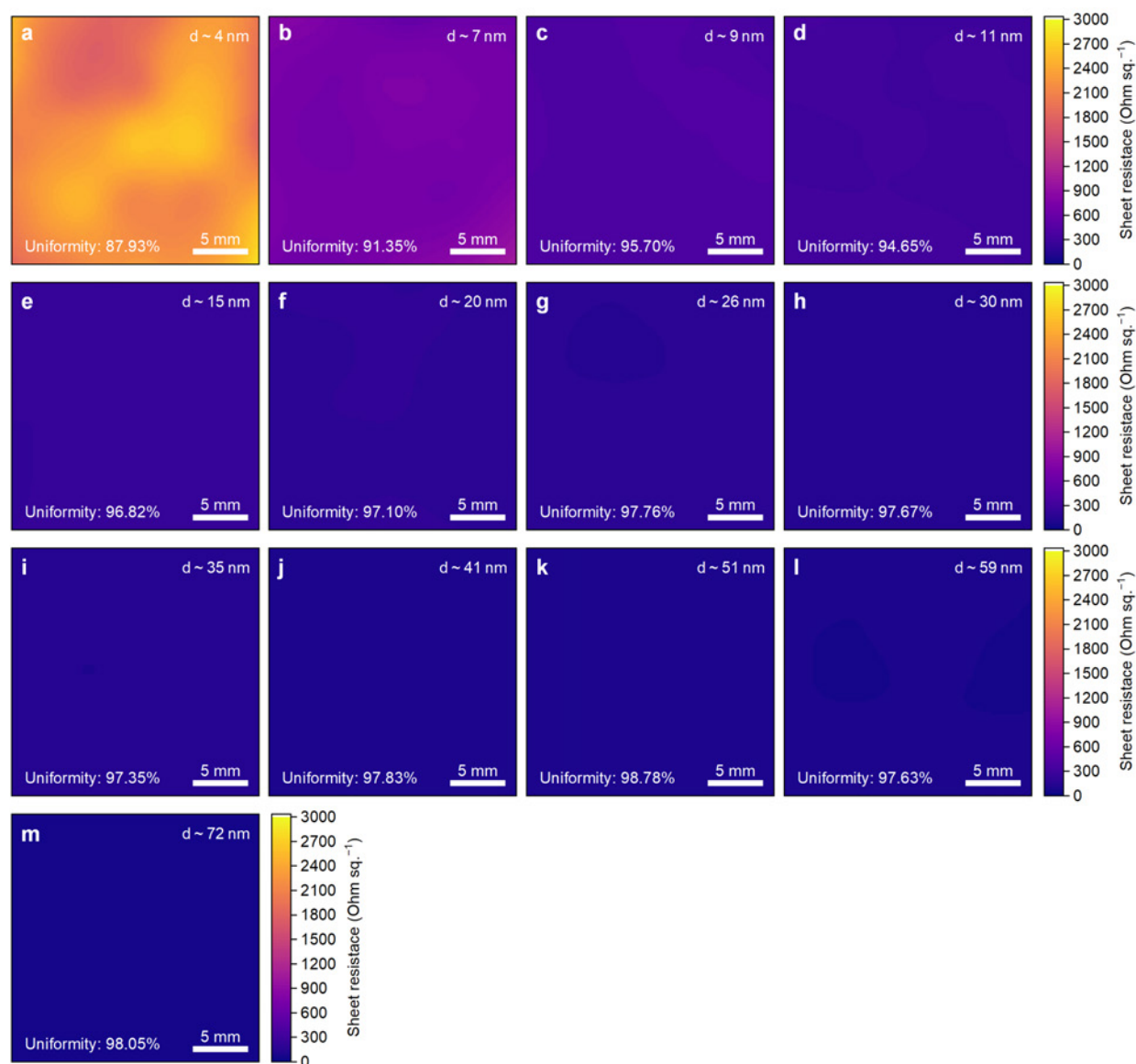


Figure S3. Spatial mapping of the sheet resistance of *n*-PBDF films with thicknesses ranging from (a) $d \approx 4$ nm to (m) $d \approx 72$ nm.

The maps were generated from automatic multipoint probe measurements across each sample. The overall uniformity, calculated from the mean (μ) and standard deviation (σ) of the sheet resistance data as $(1 - [\sigma / \mu]) \cdot 100 \%$, is indicated in each panel. The results demonstrate the high spatial uniformity of the electrical conductivity across large-area samples.

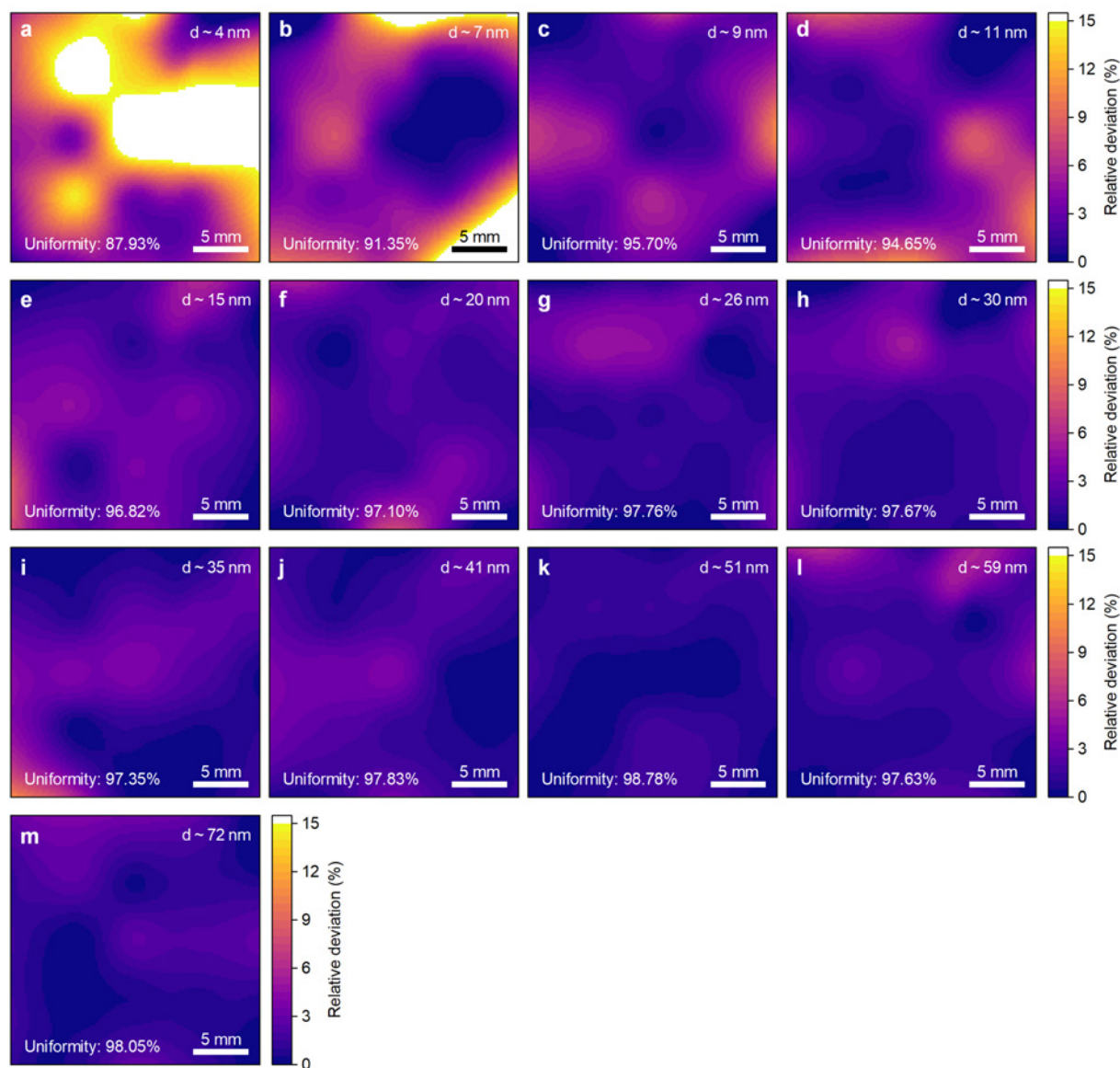


Figure S4. Spatial maps of the percent relative deviation in sheet resistance (R_s) for *n*-PBDF films with thicknesses from (a) $d \approx 4$ nm to (m) $d \approx 72$ nm.

The relative deviation at each point was calculated as $(| \text{local } R_s - \text{mean } R_s | / \text{mean } R_s) \cdot 100 \%$. These maps provide a visual representation of spatial uniformity, clearly showing that local deviations from the mean (indicated by lighter colors) are minimal.

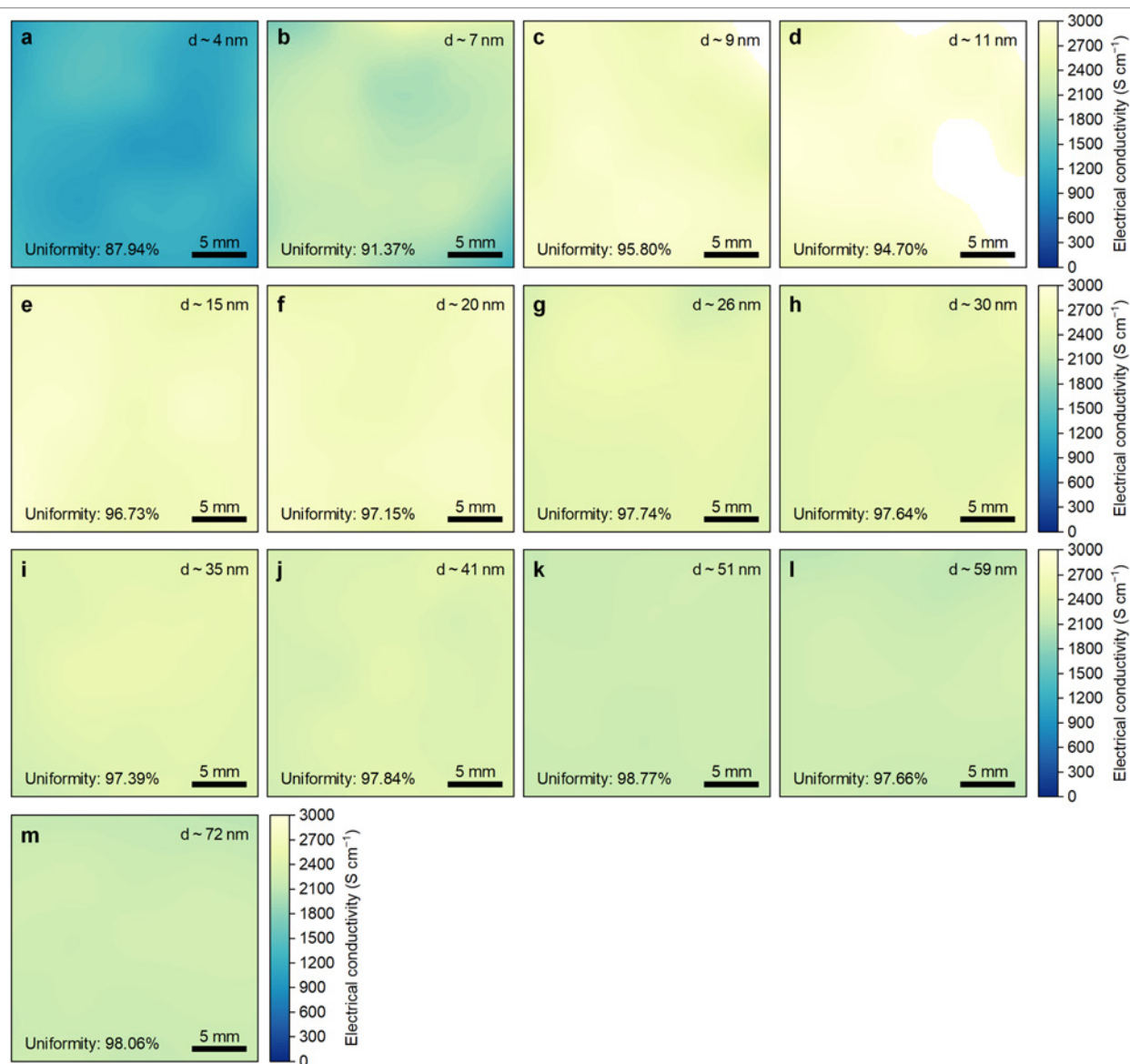


Figure S5. Spatial mapping of electrical conductivity for *n*-PBDF films with thicknesses ranging from (a) $d \approx 4$ nm to (m) $d \approx 72$ nm.

The maps were generated by calculating the local electrical conductivity from the sheet resistance measurements taken at a minimum of 25 points across each sample. The overall uniformity, calculated as $(1 - [\text{standard deviation} / \text{mean}]) \cdot 100 \%$, is indicated in each panel. The results demonstrate high spatial uniformity of the electrical conductivity across large-area samples.

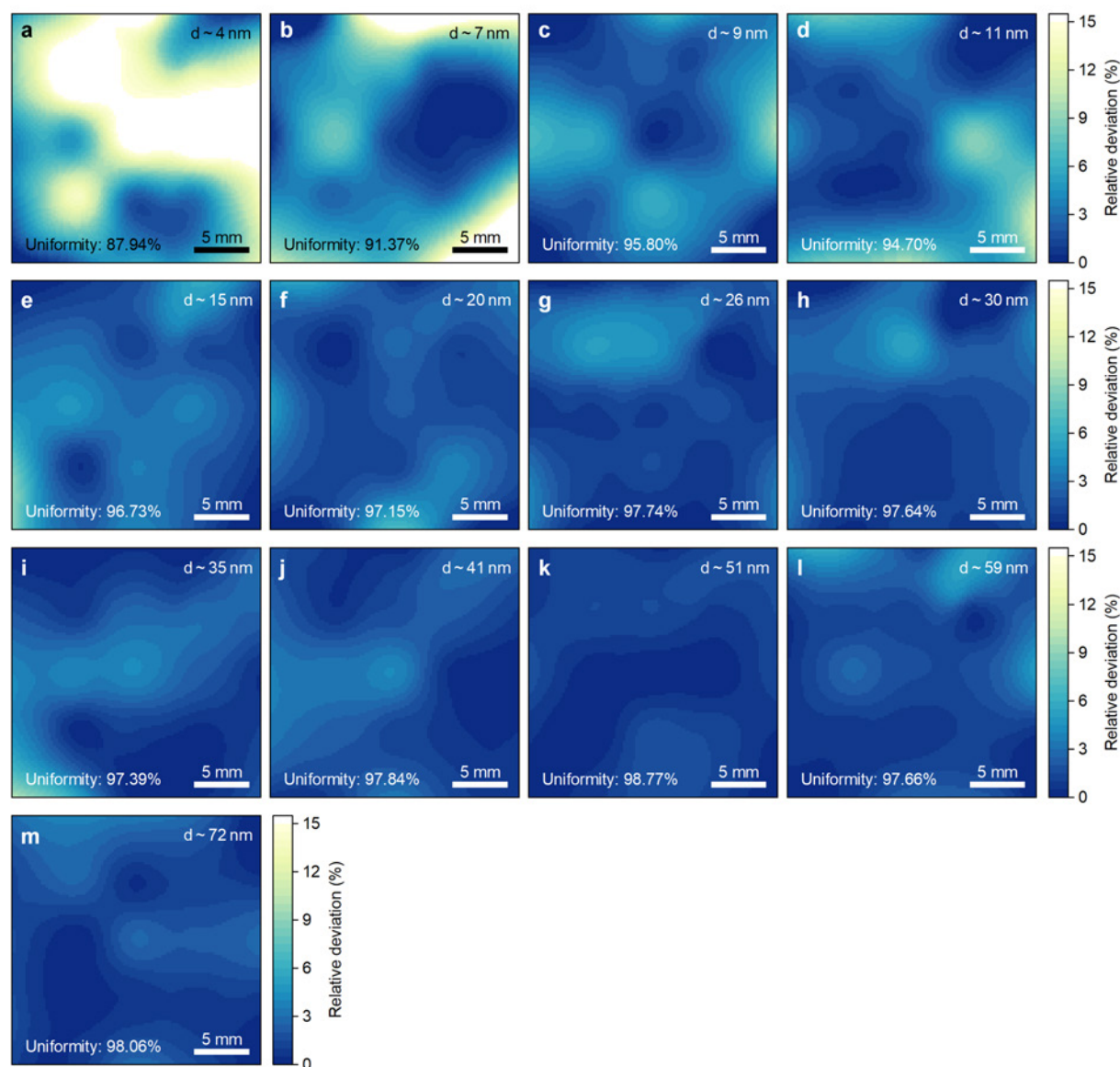


Figure S6. Spatial maps of the percent relative deviation in electrical conductivity for *n*-PBDF films with thicknesses from (a) $d \approx 4$ nm to (m) $d \approx 72$ nm.

The relative deviation at each point was calculated as $(|\text{local conductivity} - \text{mean conductivity}| / \text{mean conductivity}) \cdot 100 \%$. These maps provide a visual representation of the spatial uniformity, clearly showing that local deviations from the mean (indicated by lighter colors) are minimal.

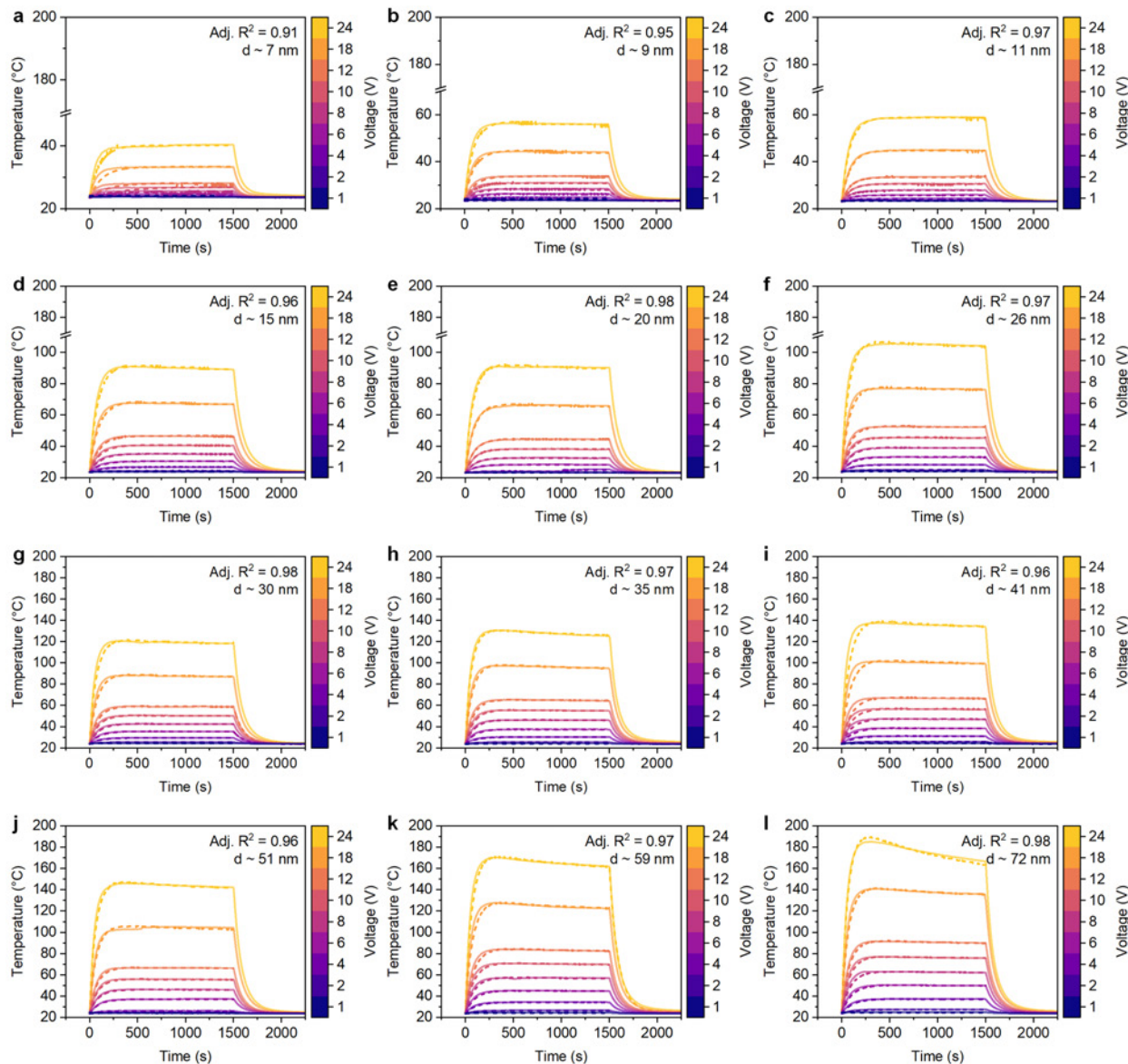


Figure S7. Model fitting of the transient Joule heating and cooling profiles of $(3 \times 3) \text{ cm}^2$ *n*-PBDF Joule heating devices.

The experimental temperature-time profiles (solid lines) for films of varying thicknesses from (a) $d \approx 7 \text{ nm}$ to (l) $d \approx 72 \text{ nm}$ are shown with the corresponding model fits (dashed lines). In the heating region, the curves were fitted using a model (adapted from Ji et al.¹⁴) that explicitly accounts for the positive Temperature Coefficient of Resistance (TCR or β) of the film. The model is described by the equation: $T(t) = T_0 + (P_0 / (\alpha A + P_0 \cdot \beta)) \cdot (1 - \exp(-t/\tau))$, where P_0 is the initial power (I^2/R_0), and the time constant τ is consequently voltage-dependent (Eq. S47). The mean TCR value of $(0.00585 \pm 0.00138) \text{ }^\circ\text{C}^{-1}$, determined from the analysis in Figures S13 and S14, was used as a fixed parameter for all fits. In the cooling region ($t \geq \approx 1500 \text{ s}$), the curves were separately fitted to a standard first-order exponential decay model. The consistently high quality of the fits ($\text{Adj. } R^2 > 0.9$) across nearly all conditions demonstrates that this comprehensive model accurately captures the physical behavior of the *n*-PBDF heaters.

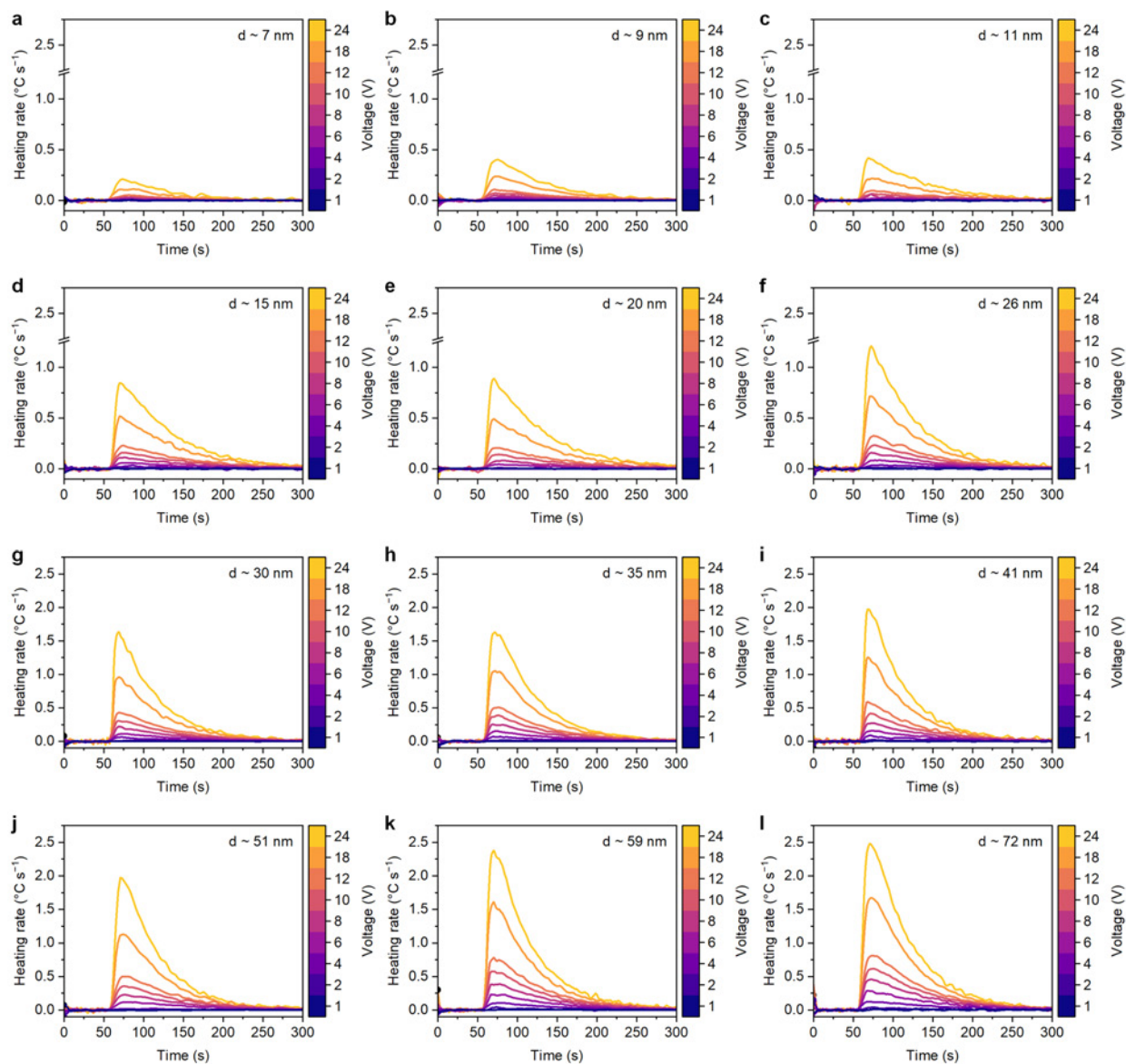


Figure S8. Dynamic thermal response of the (3×3) cm² Joule heating devices as a function of film thickness.

The heating rate is plotted against time for twelve different film thicknesses, ranging from approximately (a) 7 nm to (l) 72 nm. In each subplot, the different colored curves show the transient heating rate in response to various applied DC voltages, the magnitudes of which are indicated by the color bar. The data clearly demonstrate that the heating rate is dependent on the input voltage. The profiles show a characteristic peak heating rate immediately following the application of the voltage, which then decays as the device approaches its steady-state temperature.

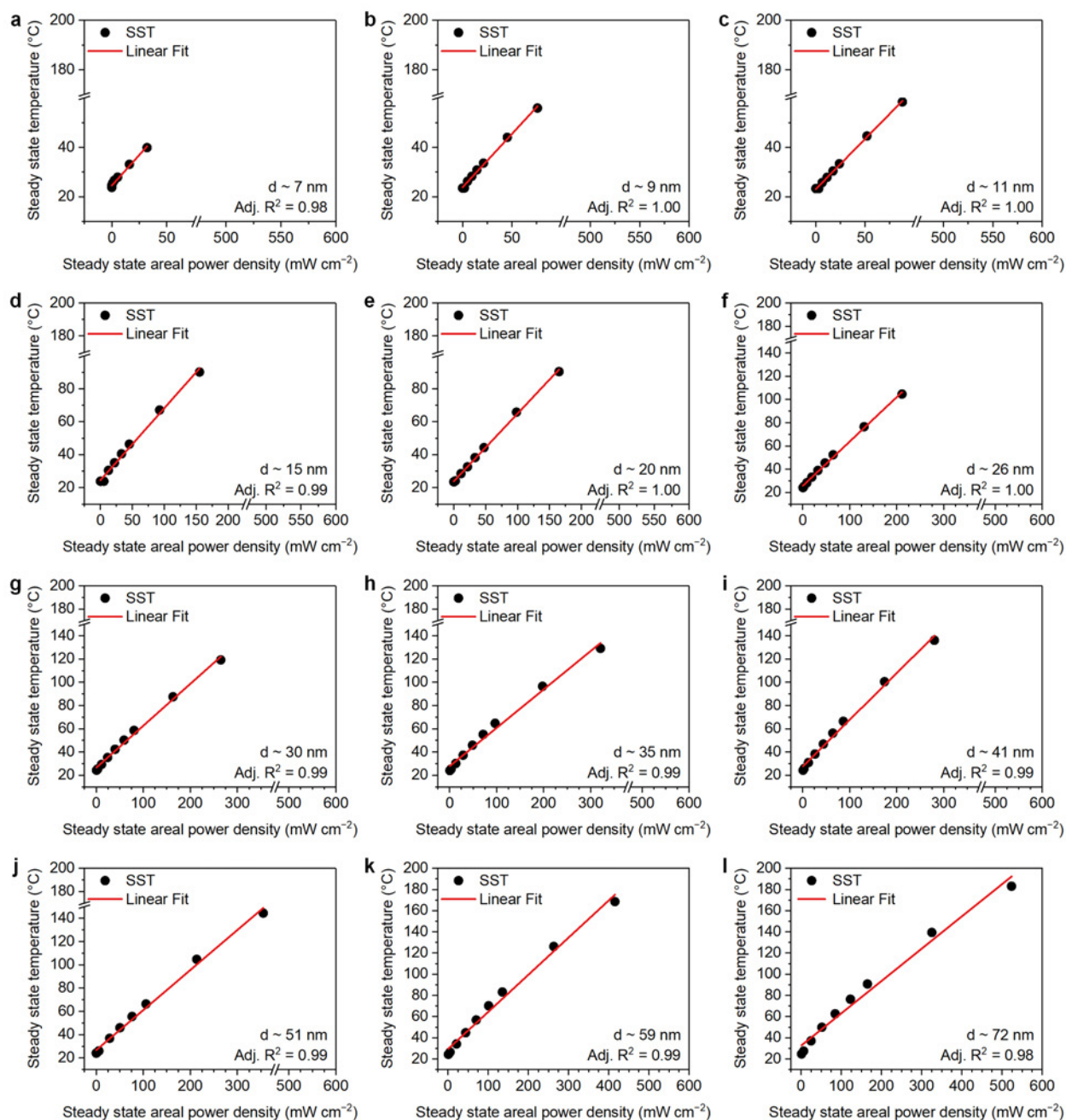


Figure S9. Characterization of the Joule heating performance of $(3 \times 3) \text{ cm}^2$ devices as a function of the film thickness.

The steady-state temperature (SST) is plotted against the input steady-state areal power density for 12 different film thicknesses, ranging from approximately (a) $d \approx 7 \text{ nm}$ to (l) $d \approx 72 \text{ nm}$. In each subplot, the black circular markers represent the measured SST, and the solid red line indicates the linear regression fit to the data, demonstrating a strong linear relationship. The adjusted R -squared (Adj. R^2) value for each linear fit is displayed, confirming the linearity of the response.

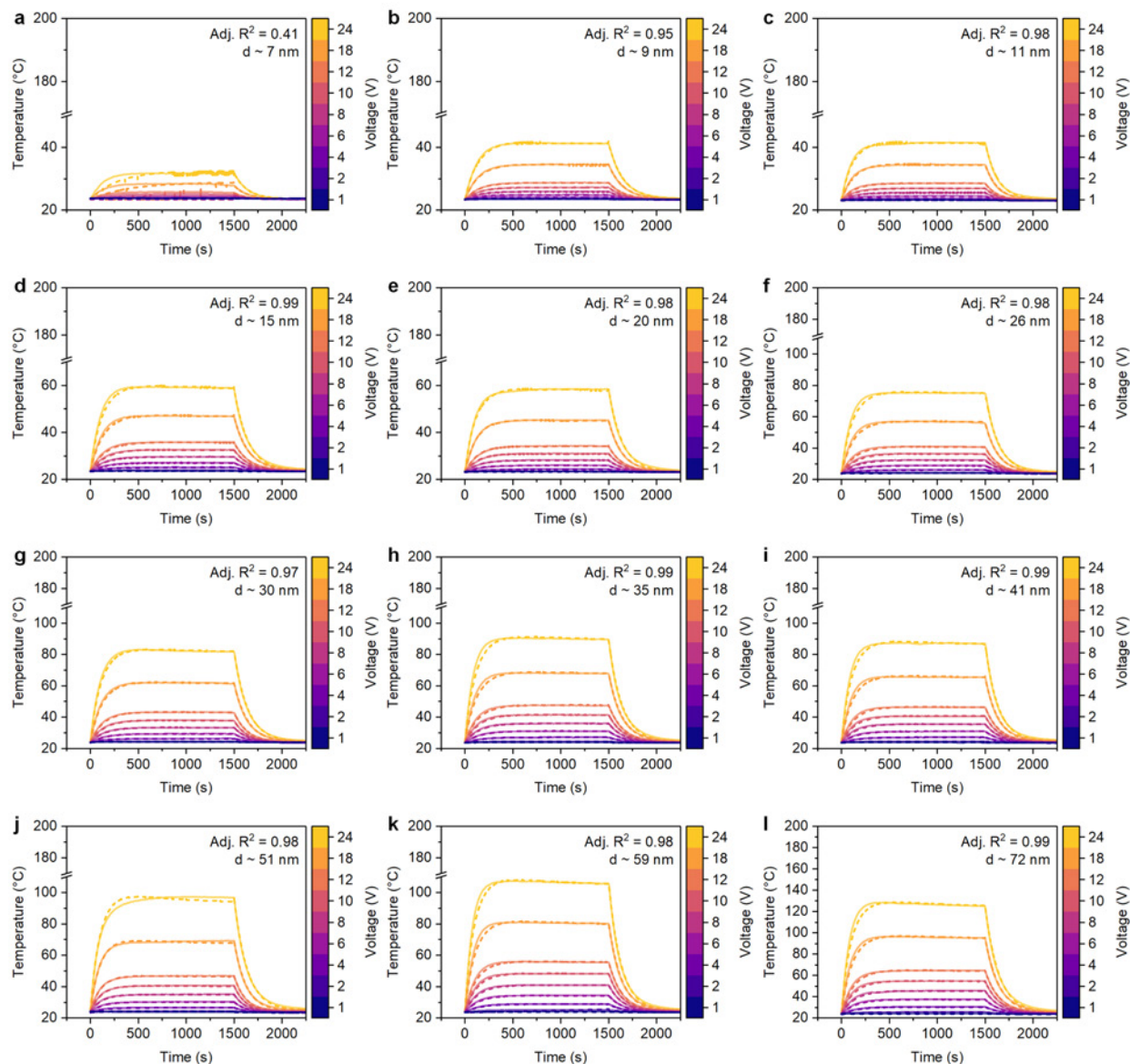


Figure S10. Model fitting of the transient Joule heating and cooling profiles of $(5 \times 5) \text{ cm}^2$ *n*-PBDF Joule heating devices.

The experimental temperature-time profiles (solid lines) for films of varying thicknesses from (a) $d \approx 7 \text{ nm}$ to (l) $d \approx 72 \text{ nm}$ are shown with the corresponding model fits (dashed lines). In the heating region, the curves were fitted using a model (adapted from Ji et al.¹⁴) that explicitly accounts for the positive Temperature Coefficient of Resistance (TCR or β) of the film. The model is described by the equation: $T(t) = T_0 + (P_0 / (\alpha A + P_0 \cdot \beta)) \cdot (1 - \exp(-t/\tau))$, where P_0 is the initial power (V^2/R_0), and the time constant τ is consequently voltage-dependent (Eq. S47). The mean TCR value of $(0.00585 \pm 0.00138) \text{ }^\circ\text{C}^{-1}$, determined from the analysis in **Figures S13 and S14**, was used as a fixed parameter for all fits. In the cooling region ($t \geq \approx 1500 \text{ s}$), the curves were separately fitted to a standard first-order exponential decay model. The consistently high quality of the fits ($\text{Adj. } R^2 > 0.9$) across nearly all conditions demonstrates that this comprehensive model accurately captures the physical behavior of the *n*-PBDF heaters.

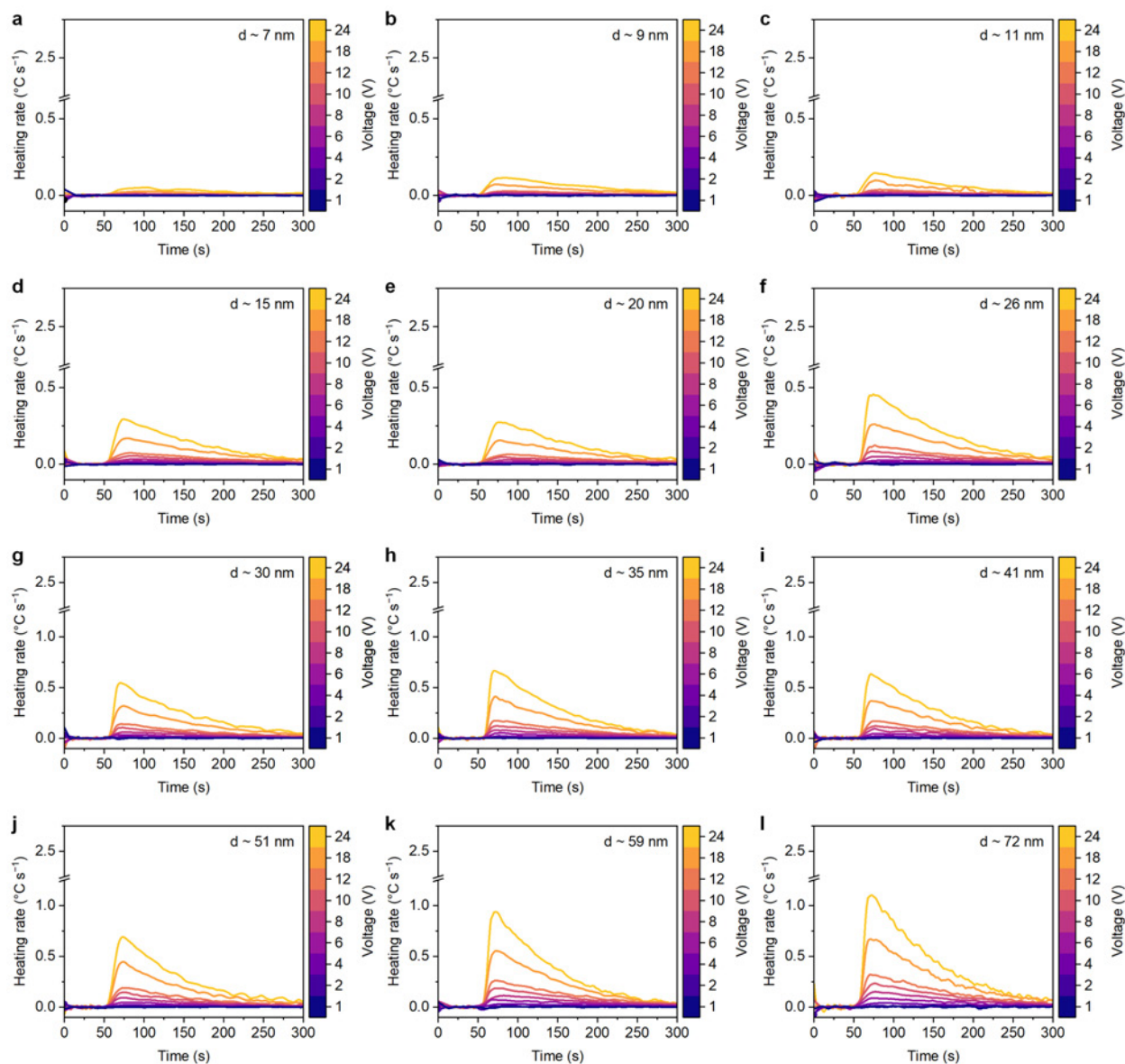


Figure S11. Dynamic thermal response of the (5×5) cm² Joule heating devices as a function of film thickness.

The heating rate is plotted against time for twelve different film thicknesses, ranging from approximately (a) $d \approx 7$ nm to (l) $d \approx 72$ nm. In each subplot, the different colored curves show the transient heating rate in response to various applied DC voltages, the magnitude of which is indicated by the color bar. The data clearly demonstrate that the heating rate is dependent on the input voltage. The profiles show a characteristic peak heating rate immediately following the application of voltage, which then decays as the device approaches its steady-state temperature.

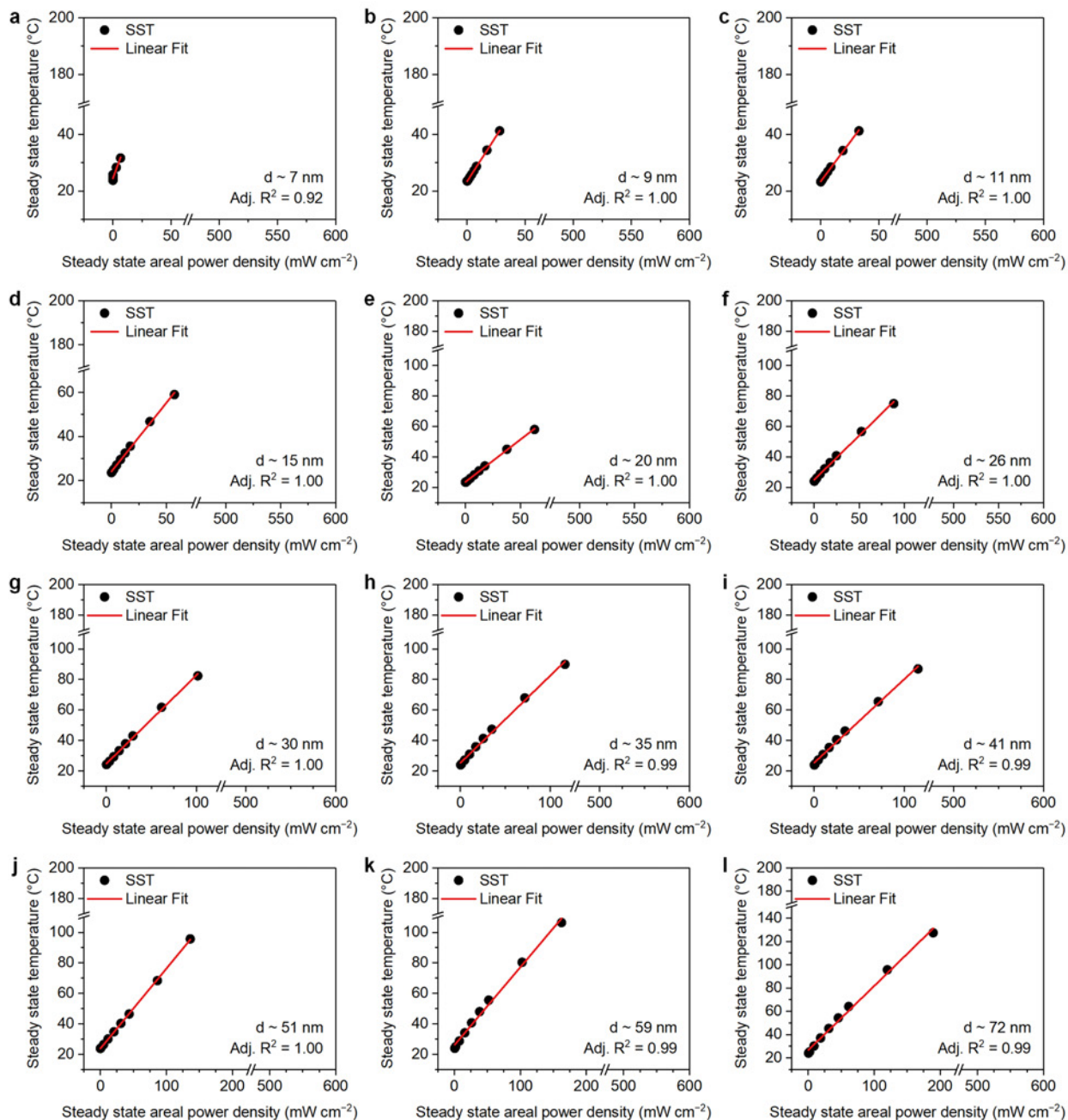


Figure S12. Characterization of the Joule heating performance of $(5 \times 5) \text{ cm}^2$ devices as a function of film thickness.

The steady-state temperature (SST) is plotted against the input steady-state areal power density for twelve different film thicknesses, ranging from approximately (a) $d \approx 7 \text{ nm}$ to (l) $d \approx 72 \text{ nm}$. In each subplot, the black circular markers represent the measured SST, while the solid red line indicates the linear regression fit to the data, demonstrating a strong linear relationship. The adjusted R -squared (Adj. R^2) value for each linear fit is displayed, confirming the linearity of the response.

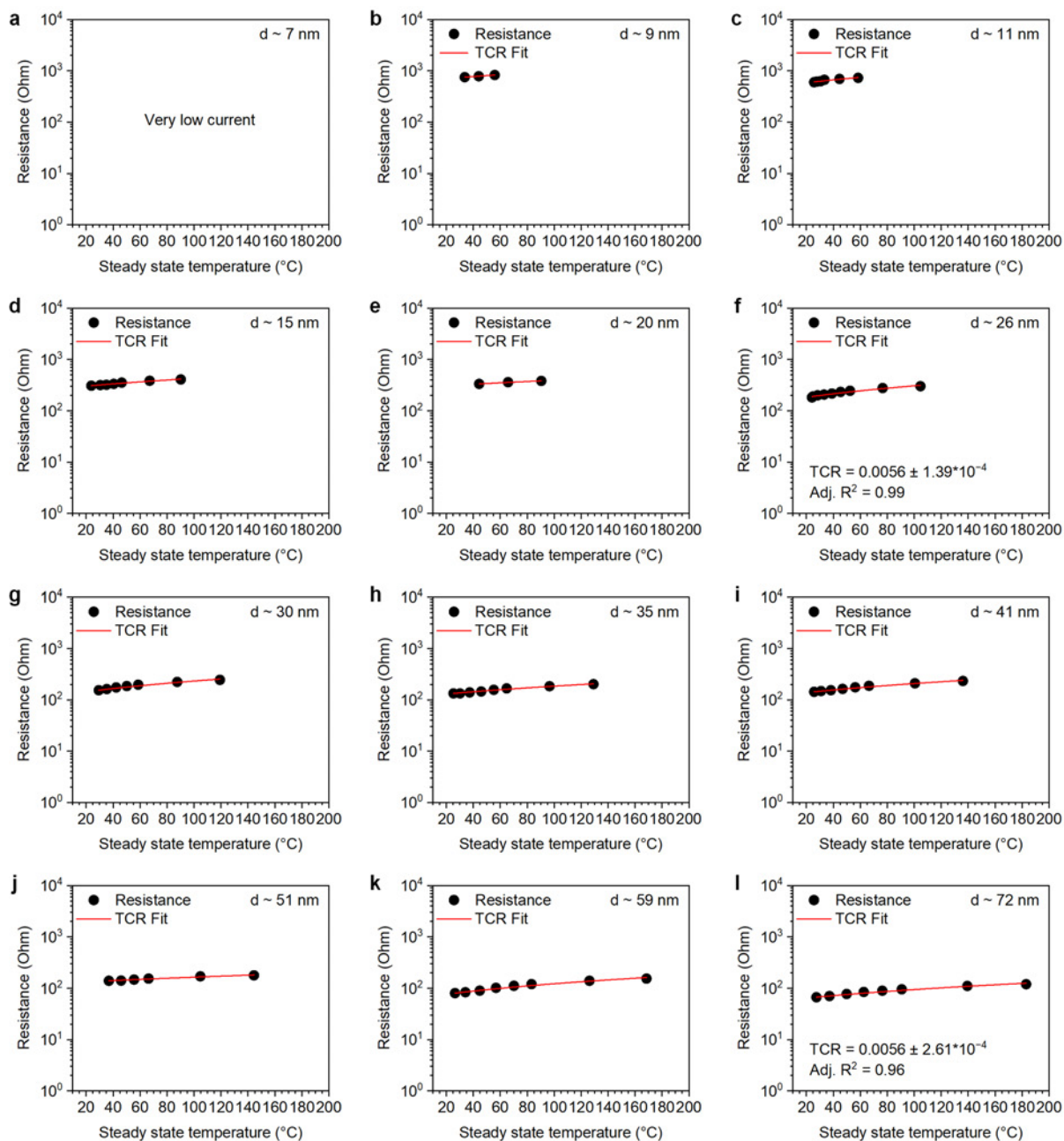


Figure S13. Quantification of the Temperature Coefficient of Resistance (TCR or β) for *n*-PBDF thin films.

Each subpanel plots the steady-state resistance of the device as a function of its steady-state temperature for a specific film thickness, ranging from approximately (a) $d \approx 7$ nm to (l) $d \approx 72$ nm. The relationship $R = R_0(1 + \beta\Delta T)$ was used to fit the data, where β is TCR. The fits show a consistent TCR of $\beta \approx (0.0056 \text{ to } 0.0059) \text{ K}^{-1}$, as representatively shown in subpanels (f) and (l). This positive TCR confirms that the resistance of the material increases with temperature, which explains the current decay observed during Joule heating. For the thinnest films (e.g., panel (a)), the very high resistance and low current prevented reliable TCR measurements across a wide temperature range.

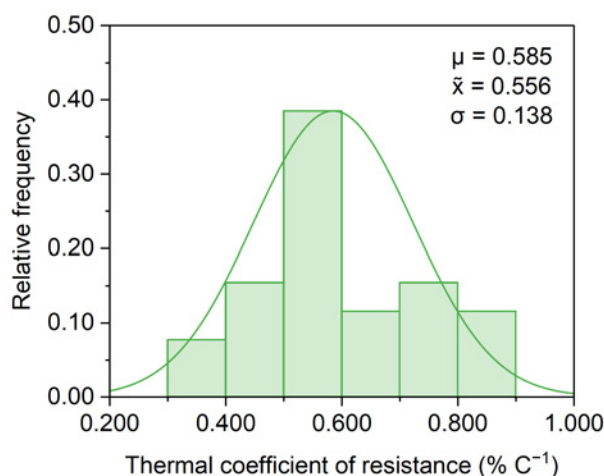


Figure S14. Quantification and statistical distribution of the Thermal Coefficient of Resistance (TCR) for *n*-PBDF.

This histogram plots the relative frequency of the individual TCR values determined from the linear fits for each device, as shown in the preceding figure (**Figure S13**). The distribution was well approximated by a normal (Gaussian) fit, indicating a consistent intrinsic material property across the various film thicknesses. The key statistical parameters, mean (μ), median ($\tilde{x}$), and standard deviation (σ), are indicated. The analysis confirmed a consistent positive Temperature Coefficient of Resistance, with a mean TCR of $\beta = (0.585 \pm 0.138) \% \text{ } ^\circ\text{C}^{-1}$. This value was subsequently used in the TCR-aware fitting of the transient heating data (**Figures S7 and S10**).

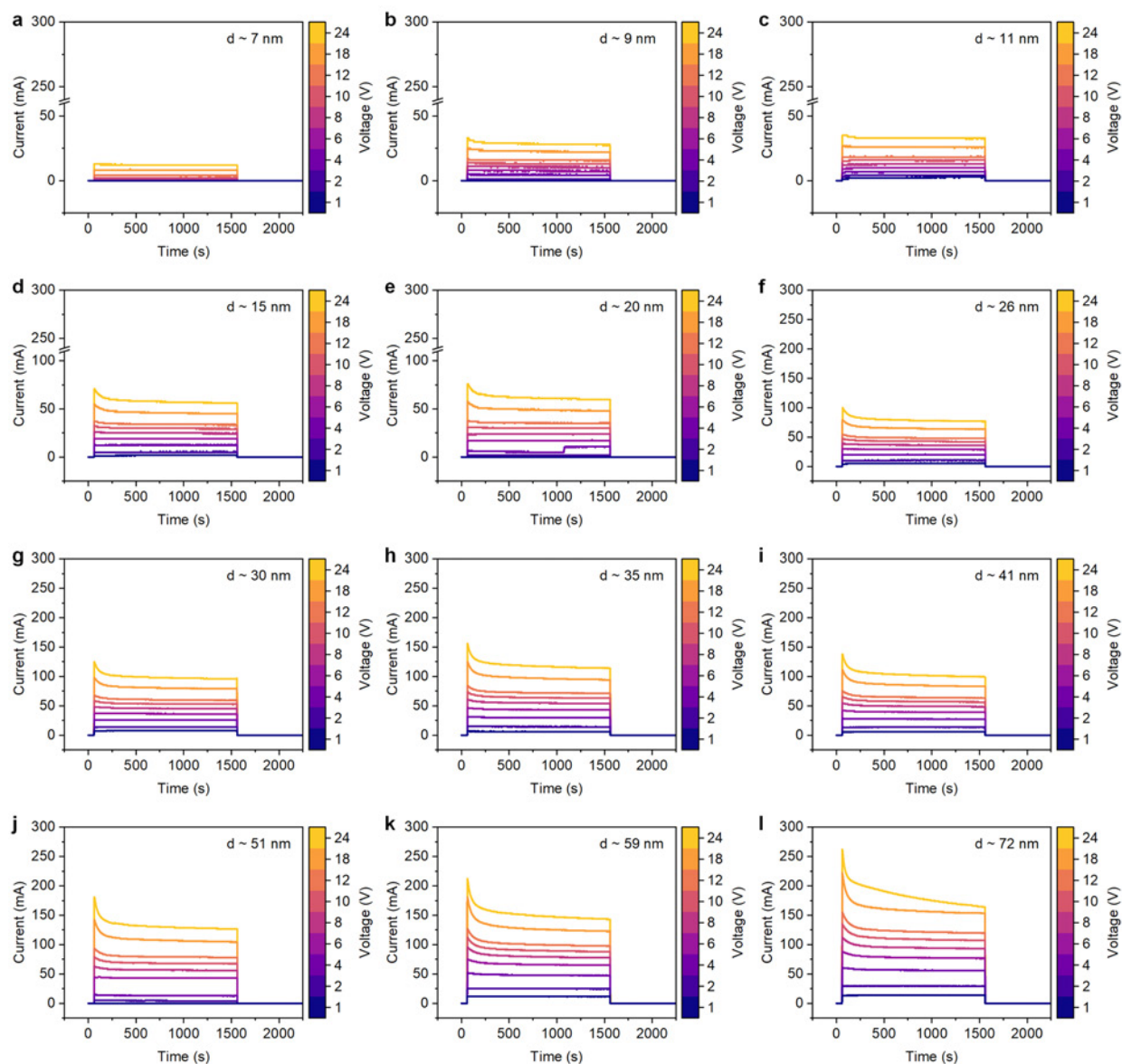


Figure S15. Time-dependent current response during Joule heating for *n*-PBDF films with thicknesses ranging from (a) $d \approx 7$ nm to (l) $d \approx 72$ nm.

For each applied voltage step, the current was initially high and then decayed over time, eventually reaching a steady-state value. This current decay is, in part, a consequence of the positive Temperature Coefficient of Resistance (TCR or β) of the material; as the film heats up, its resistance increases, causing the current to drop under a constant applied voltage. The stabilization of the current coincided with the system reaching a steady-state temperature.

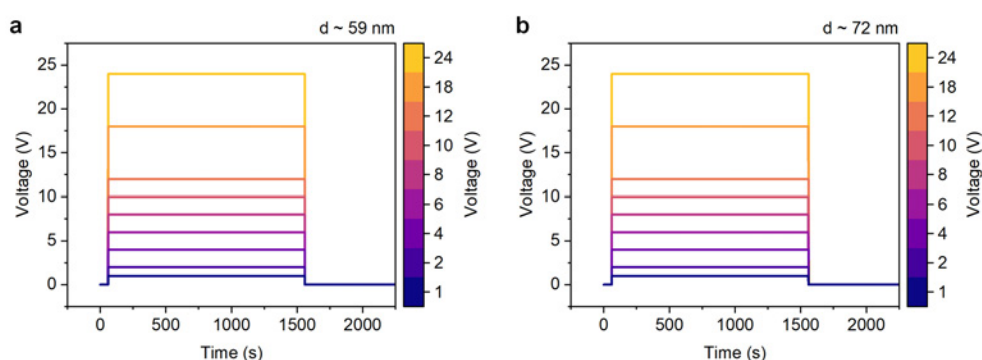


Figure S16. Time-dependent voltage control profiles for the electrothermal characterization of the prepared samples.

The profiles for the (a) $d \approx 59$ nm and (b) $d \approx 72$ nm *n*-PBDF films are shown as representative examples. This figure illustrates the precise and stable voltage profiles applied to each of the samples. Each voltage step was held constant for an extended period (≈ 1600 s) to ensure that a thermal steady state was reached, followed by a rest period during which no voltage was applied (0 V). The lack of variability during the sustained voltage period confirmed the reliability of the experimental input conditions.

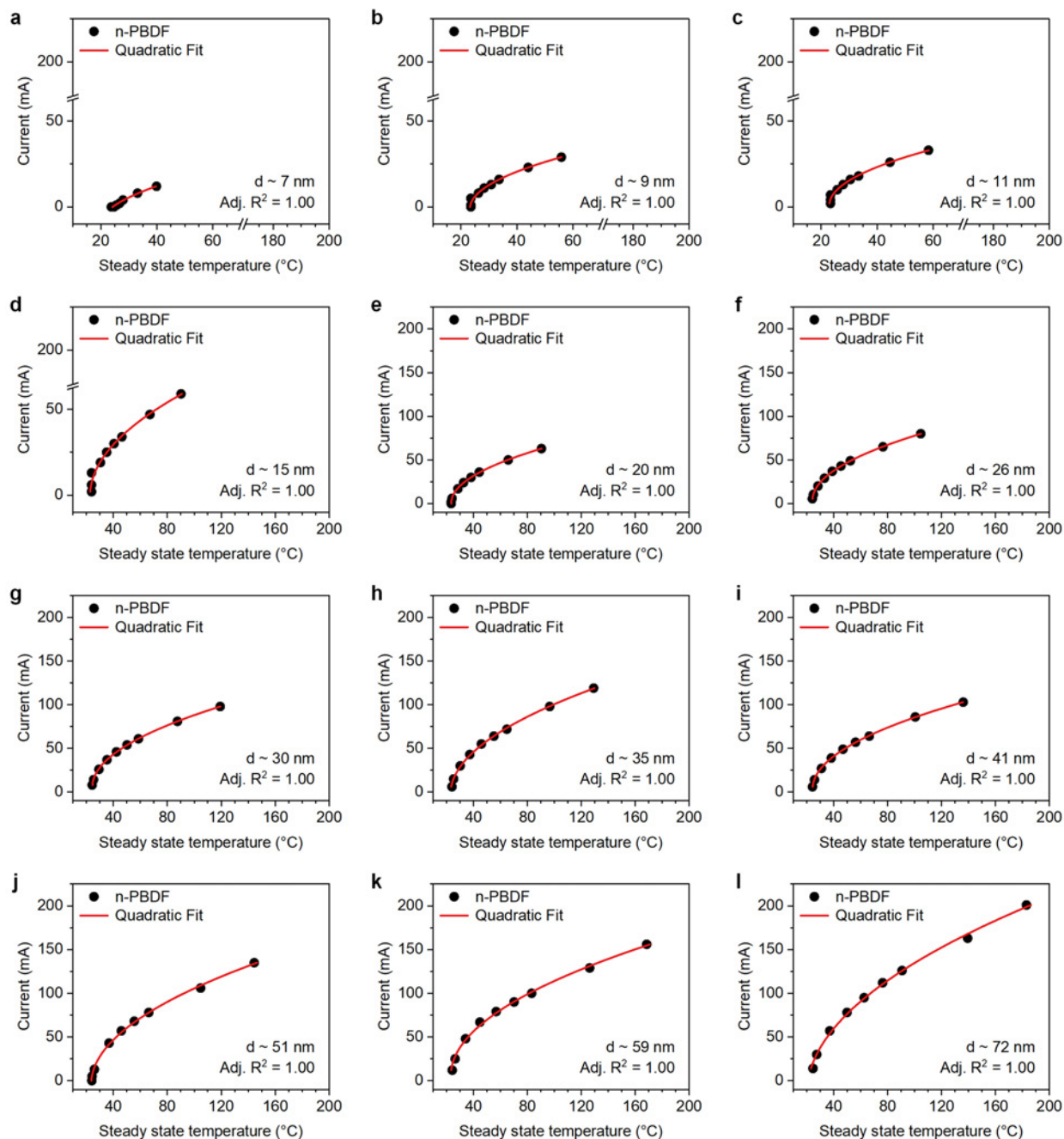


Figure S17. Characterization of the Joule heating performance of *n*-PBDF thin films.

The plots show the relationship between the applied electrical current and the measured steady-state temperature (SST) for twelve films with systematically increasing thicknesses, from (a) $d \approx 7$ nm to (l) $d \approx 72$ nm. For all film thicknesses, the relationship between the current and SST was accurately modeled using a quadratic function (red line), as confirmed by the adjusted R^2 values of 1.00. This demonstrates highly reliable electrothermal behavior, where the temperature scales predictably with the square of the current, consistent with Joule's first law ($P = I^2/R$).

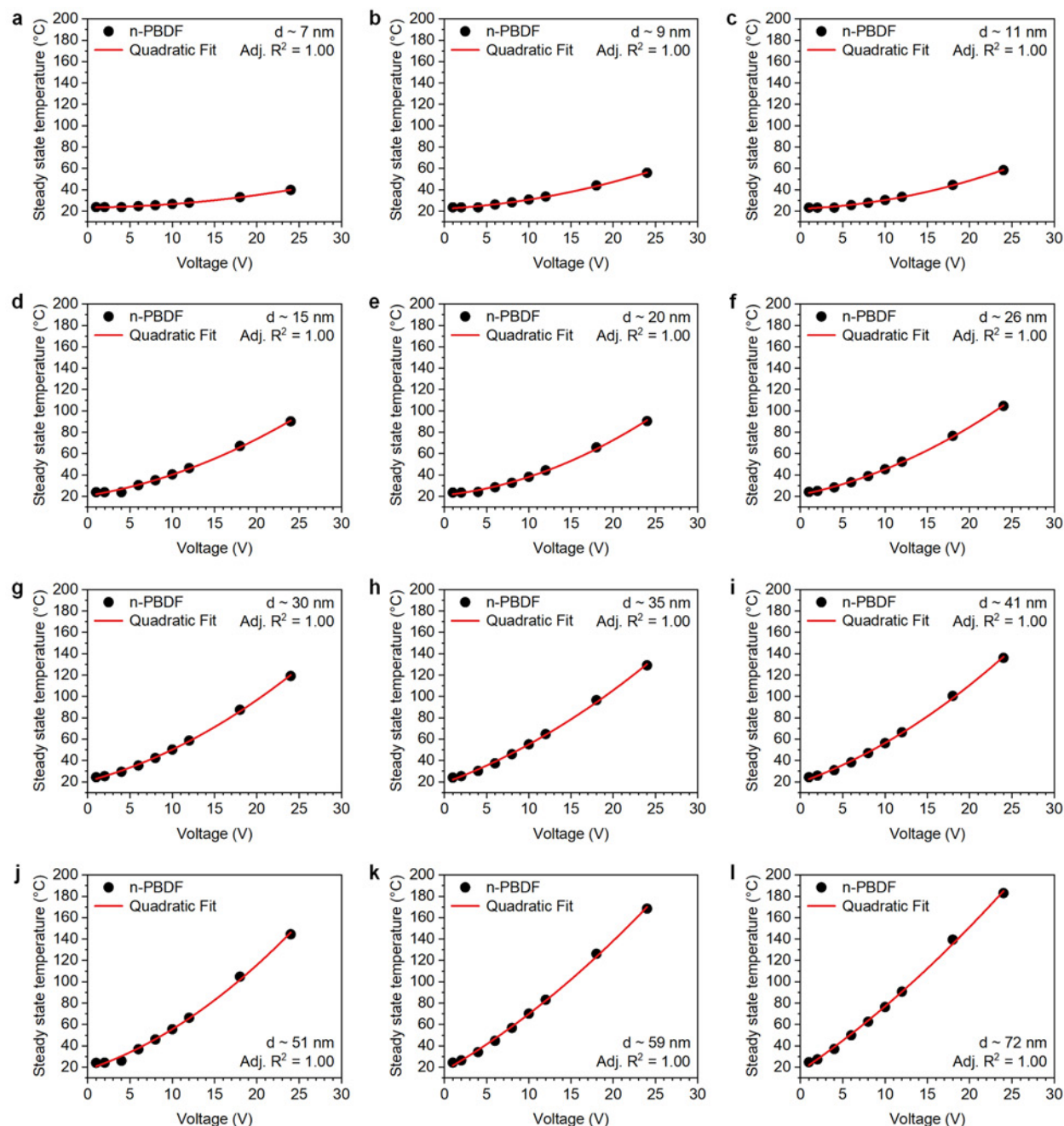


Figure S18. Characterization of the Joule heating performance as a function of the applied voltage for *n*-PBDF films.

The plots exhibit the steady-state temperature (SST) achieved for films with thickness systematically increasing from (a) $d \approx 7$ nm to (k) $d \approx 72$ nm. For all film thicknesses, the relationship between the voltage and SST was precisely modeled using a quadratic function (red line), as confirmed by the adjusted R^2 values of 1.00. This result is consistent with Joule's first law, which states that the heating power is proportional to the square of the voltage ($P = V^2/R$), demonstrating the reliable performance of the material as a transparent heater.

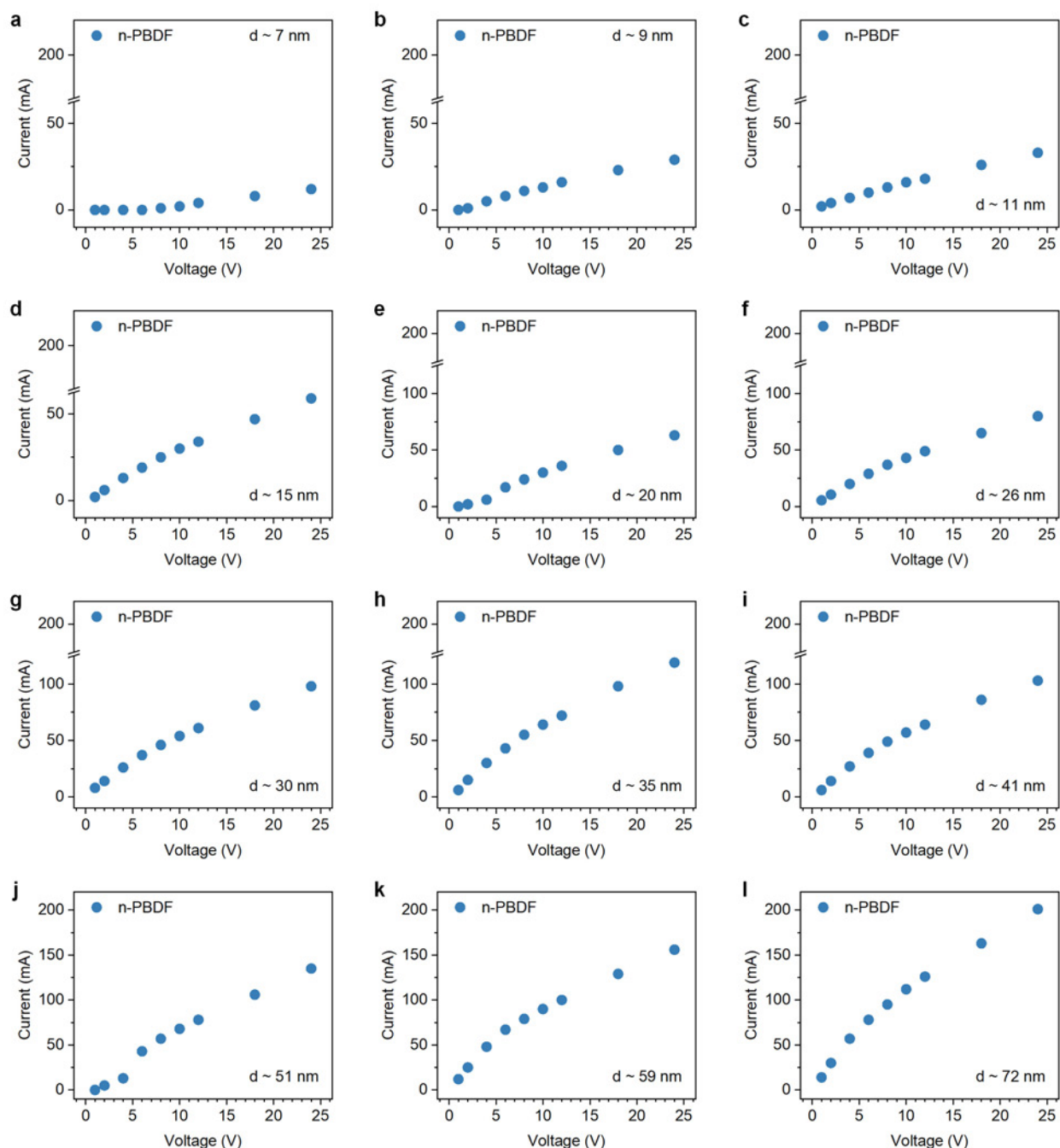


Figure S19. Electrical characterization of *n*-PBDF thin films.

The current-voltage (I-V) relationships are plotted for twelve films with systematically increasing thicknesses, from (a) $d \approx 7$ nm to (l) $d \approx 72$ nm. The I-V curves were predominantly linear, demonstrating the ohmic nature of the films. As expected, the slope of the I-V curve (conductance) increased with film thickness, which corresponds to a decrease in the overall sheet resistance of the films.

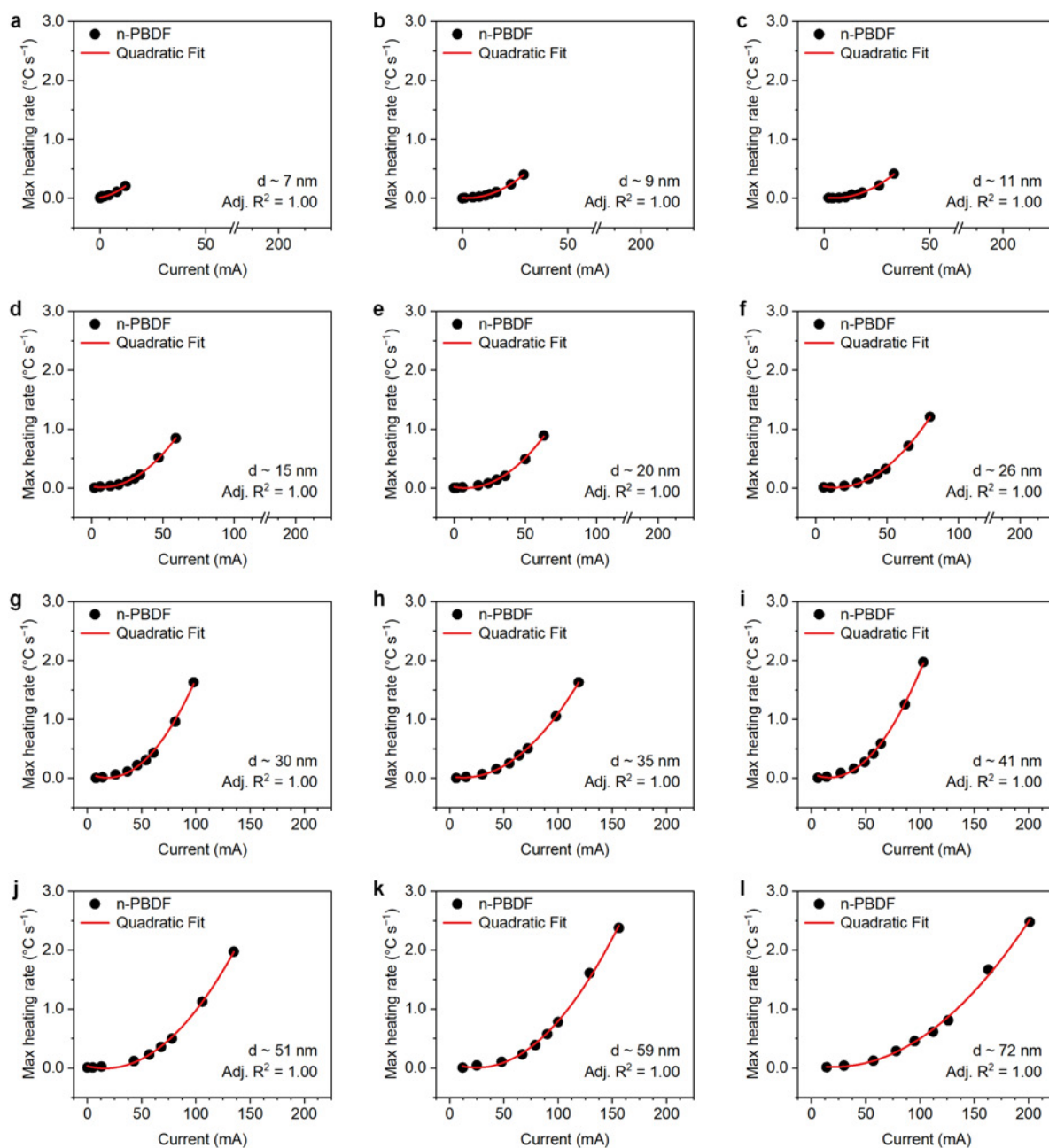


Figure S20. Characterization of the maximum heating rate of *n*-PBDF films as a function of current.

The plots show the dynamic heating response for films with thicknesses systematically increasing from (a) $d \approx 7$ nm to (l) $d \approx 72$ nm. The maximum heating rate scales with the square of the current, which is consistent with the principles of Joule heating (Power $\propto I^2$). This quadratic relationship was confirmed by the strong fit of the model (red lines) to the experimental data, with adjusted *R*² values of 1.00 for all samples.

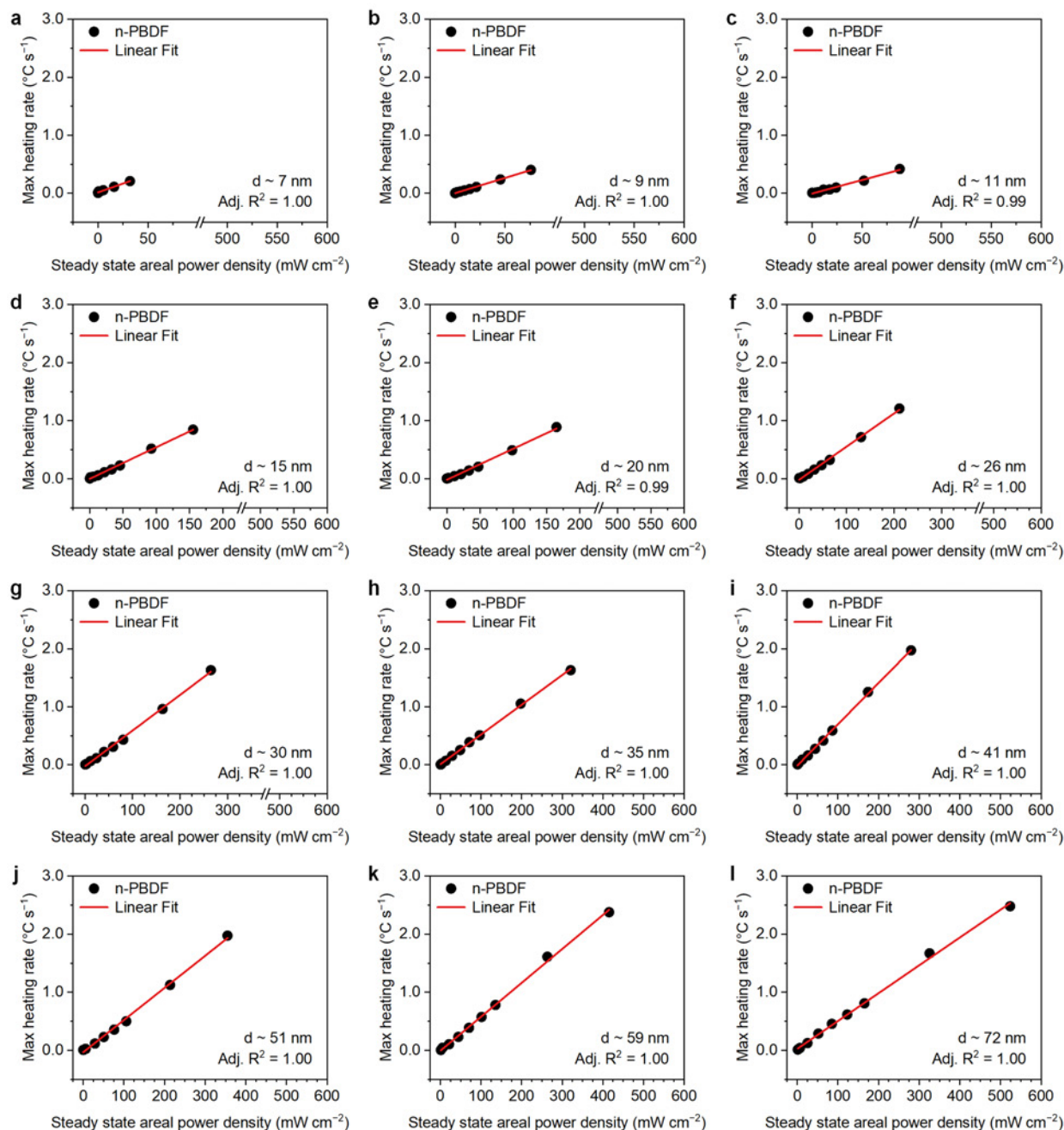


Figure S21. Maximum heating rate as a function of the steady-state areal power density for *n*-PBDF films with thicknesses ranging from (a) $d \approx 7$ nm to (l) $d \approx 72$ nm.

The data reveal a strong and consistent linear relationship for each film thickness, as indicated by the excellent linear fits ($\text{Adj. } R^2 \geq 0.99$). This linear behavior demonstrates that the dynamic heating response is directly proportional to the electrical power supplied to the device. The slope of this line is related to the effective heat capacity and heat transfer coefficient of the system, and its consistency across a wide range of film thicknesses highlights the predictable and scalable performance of the material as a thin-film heater.

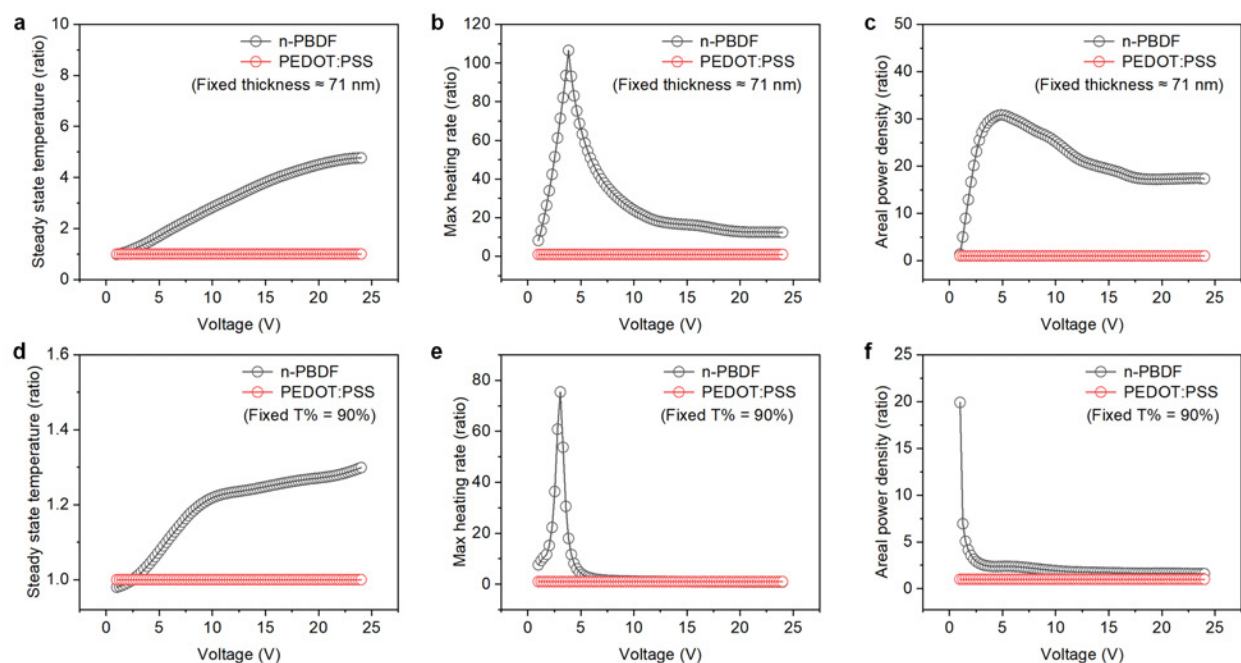


Figure S22. Performance comparison of *n*-PBDF and PEDOT:PSS Joule heaters under thickness-matched and transmittance-matched conditions.

All data were normalized to the corresponding PEDOT:PSS value, providing a direct ratio of the performance difference. (Top row) Comparison at a fixed film thickness of $d \approx 71$ nm, showing the relative increase in (a) steady-state temperature, (b) maximum heating rate, and (c) areal power density of *n*-PBDF. (Bottom row) Comparison at a fixed optical transmittance of 90 % (at 550 nm) to provide a practical, application-oriented baseline. The plots show the relative performance for (d) the steady-state temperature, (e) the maximum heating rate, and (f) the areal power density.

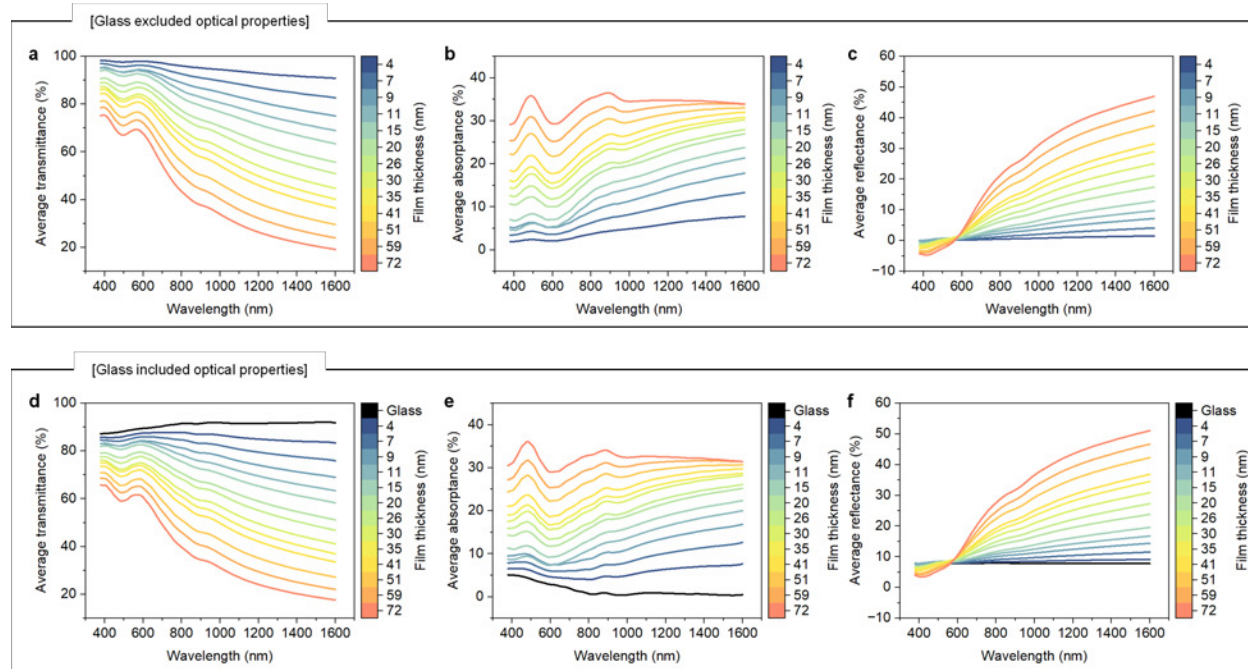


Figure S23. Wavelength-dependent optical properties of *n*-PBDF films presented as line plots.

The line color in each plot corresponds to the film thickness, as indicated by the color bar. Top row (a–c): Intrinsic optical properties of the *n*-PBDF film, calculated by mathematically subtracting the contribution of the glass substrate. These plots show the inherent (a) transmittance, (b) absorbance, and (c) reflectance of the films. Bottom row (d–f): Total measured optical properties of the final device stack (film on glass substrate). These plots show the practical (d) transmittance, (e) absorbance, and (f) reflectance. The spectrum of a bare glass substrate is included for reference.

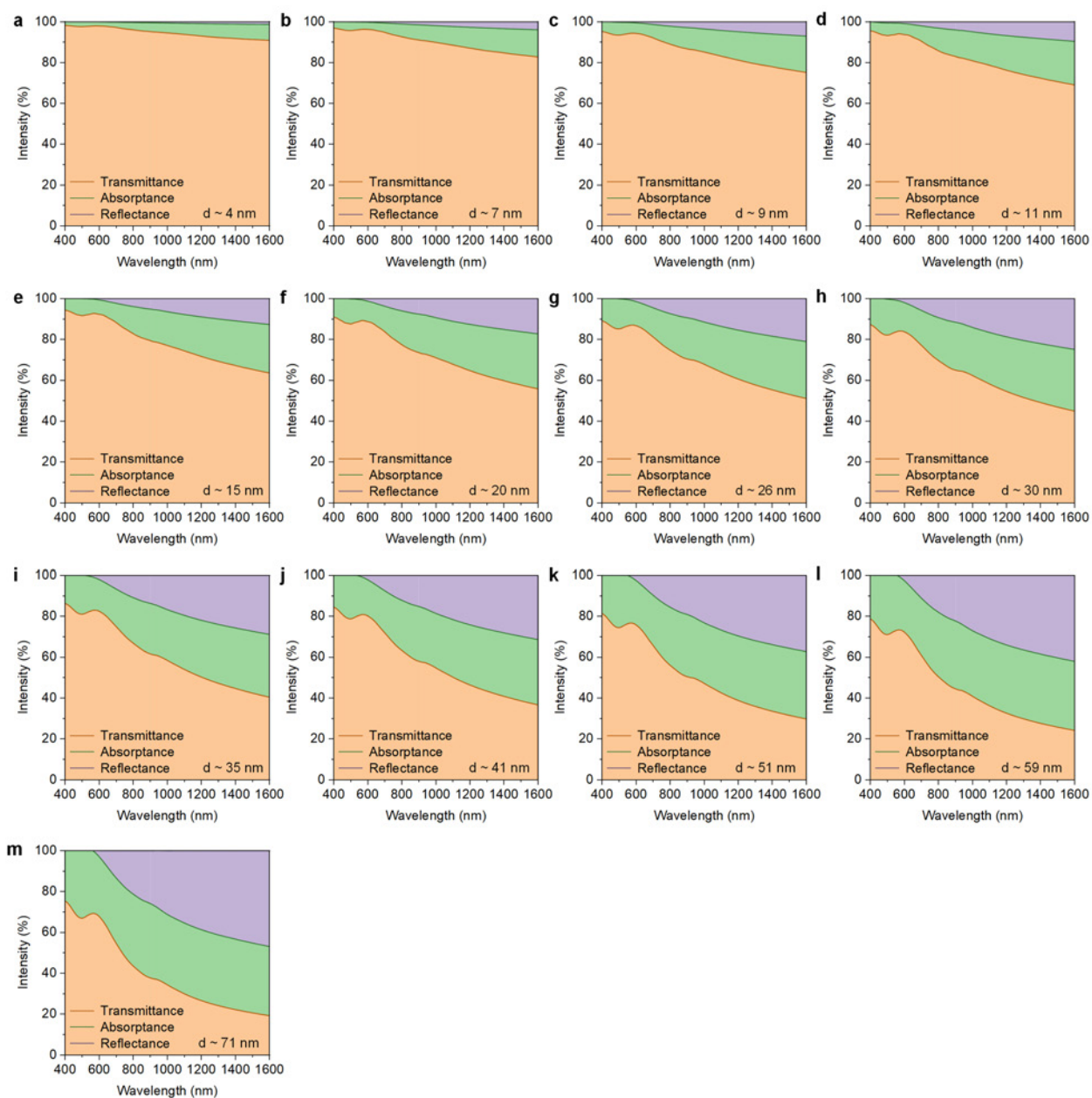


Figure S24. Wavelength-dependent optical properties of *n*-PBDF films presented as stacked area charts.

The subplots illustrate the allocation of incident light across three major modes: transmittance (orange), absorptance (green), and reflectance (purple), such that their sum is equal to 100 % at each wavelength. The data are presented for film thicknesses ranging from approximately (a) $d \approx 4$ nm to (m) $d \approx 71$ nm. The results demonstrate the expected trend: as the film thickness increased, the absorptance of the film increased across the visible and near-infrared spectra, leading to a corresponding decrease in transmittance.

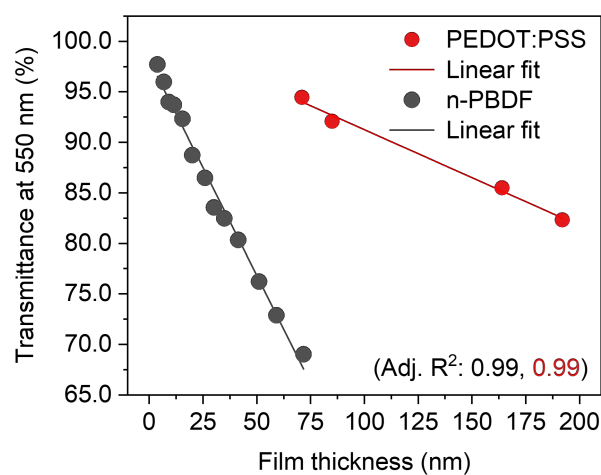


Figure S25. Optical transmittance of PEDOT:PSS (red circles) and *n*-PBDF (black circles) films measured at a wavelength of 550 nm for various film thicknesses.

The data demonstrate a clear linear dependence of transmittance on thickness for both polymers, which is confirmed by the excellent linear fits (solid lines) with adjusted R^2 values of 0.99.

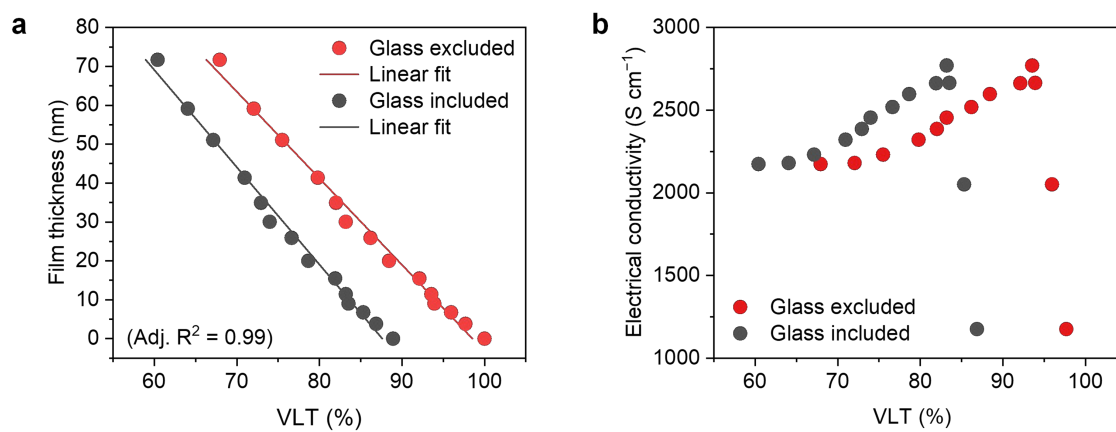


Figure S26. Relationship between Visible Light Transmittance (VLT), film thickness, and electrical conductivity.

(a) Film thickness as a function of VLT, demonstrating a highly linear inverse relationship (Adj. $R^2 = 0.99$). (b) Electrical conductivity as a function of VLT. The highest conductivities, exceeding 2500 S cm^{-1} , were achieved for films with lower VLT (thicker films). As the films became thinner and more transmissive, the conductivity exhibited stronger thickness-dependent behavior and decreased, showing a trade-off between transparency and conductivity. The measurements are shown with (black circles) and without (red circles) including the glass substrate in the VLT calculation.

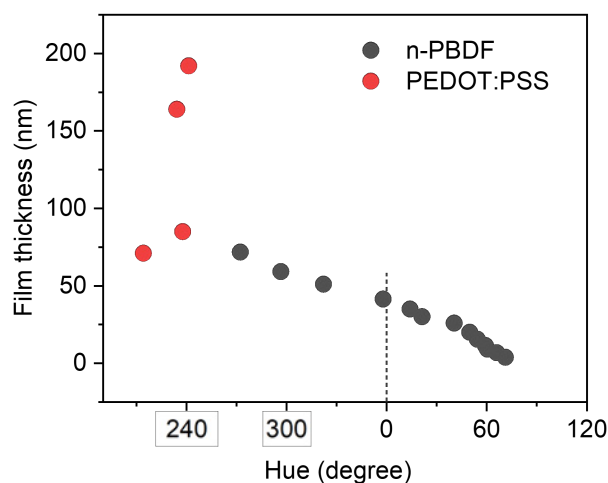


Figure S27. Relationship between film thickness and color hue for thin films of *n*-PBDF and PEDOT:PSS.

The data illustrates that the hue of the *n*-PBDF samples have a stronger dependence on thickness, spanning a wide range of the color spectrum. In contrast, PEDOT:PSS films exhibited a consistent hue near 240° for thicknesses ranging from approximately (70 to 200) nm. However, the low chroma observed in *n*-PBDF (compared to PEDOT:PSS; see **Main Text**) gives rise to its more neutral gray appearance.

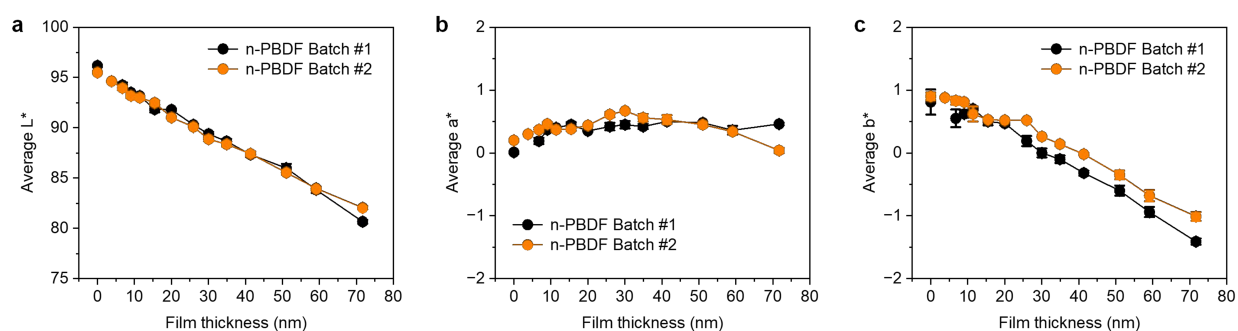


Figure S28. Quantitative analysis of the color and color reproducibility of *n*-PBDF thin films.

The average CIELAB color space values are shown for two different batches as a function of the film thickness. **(a)** The L^* value (lightness) decreased linearly with increasing thickness. **(b)** The a^* value (green-red axis) remained relatively constant near zero across all thicknesses. **(c)** The b^* value (blue-yellow axis) transitions from positive (yellow) to negative (blue) as the film thickness increases. The excellent agreement between Batch #1 (black) and Batch #2 (orange) demonstrates the high reproducibility of the colorimetric properties of the material. Furthermore, the linear and coupled nature of L^* and b^* with film thickness allows the color of the film to be precisely and reliably tuned to a desired appearance.

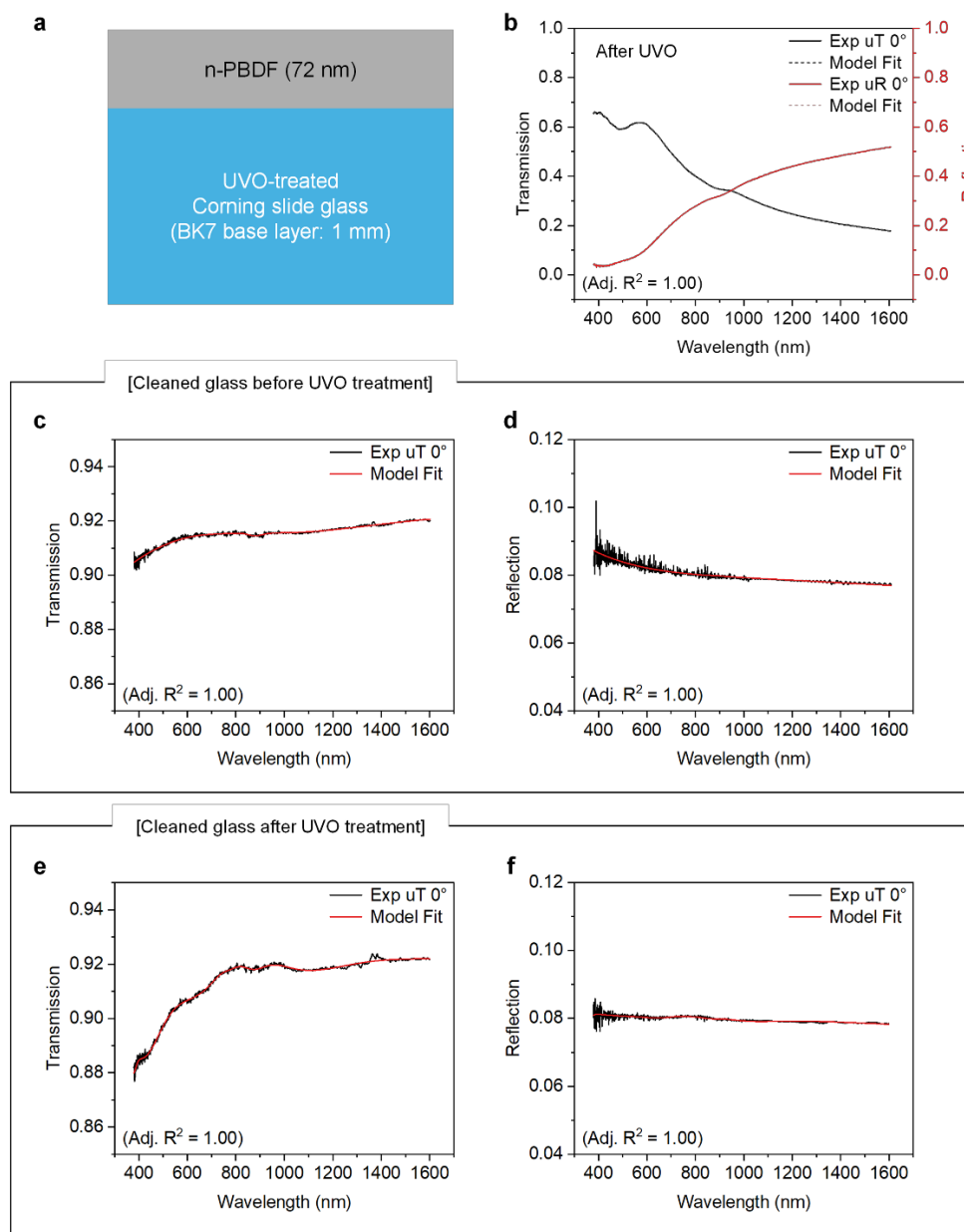


Figure S29. Development and validation of the refined two-layer substrate model used for optical analysis.

(a) A schematic of the final multi-layer structure used in the model, consisting of the *n*-PBDF film on the UVO-treated glass substrate. (b) The final model fit for the ≈ 72 nm *n*-PBDF film deposited on the accurately characterized UVO-treated substrate, demonstrating a near-perfect match. This step-by-step approach confirms that precisely modeling the substrate is critical for accurately extracting the intrinsic properties of the *n*-PBDF film. (c, d) Characterization of the clean, untreated Corning slide glass, showing an excellent fit between the experimental data (black) and a simple optical model (red). (e, f) Characterization of the same glass substrate after UV-ozone treatment. The equally high-quality fit ($\text{Adj. } R^2 = 1.00$) validates the refined "UVO-Glass" model, which accounts for the slight optical changes induced by the treatment.

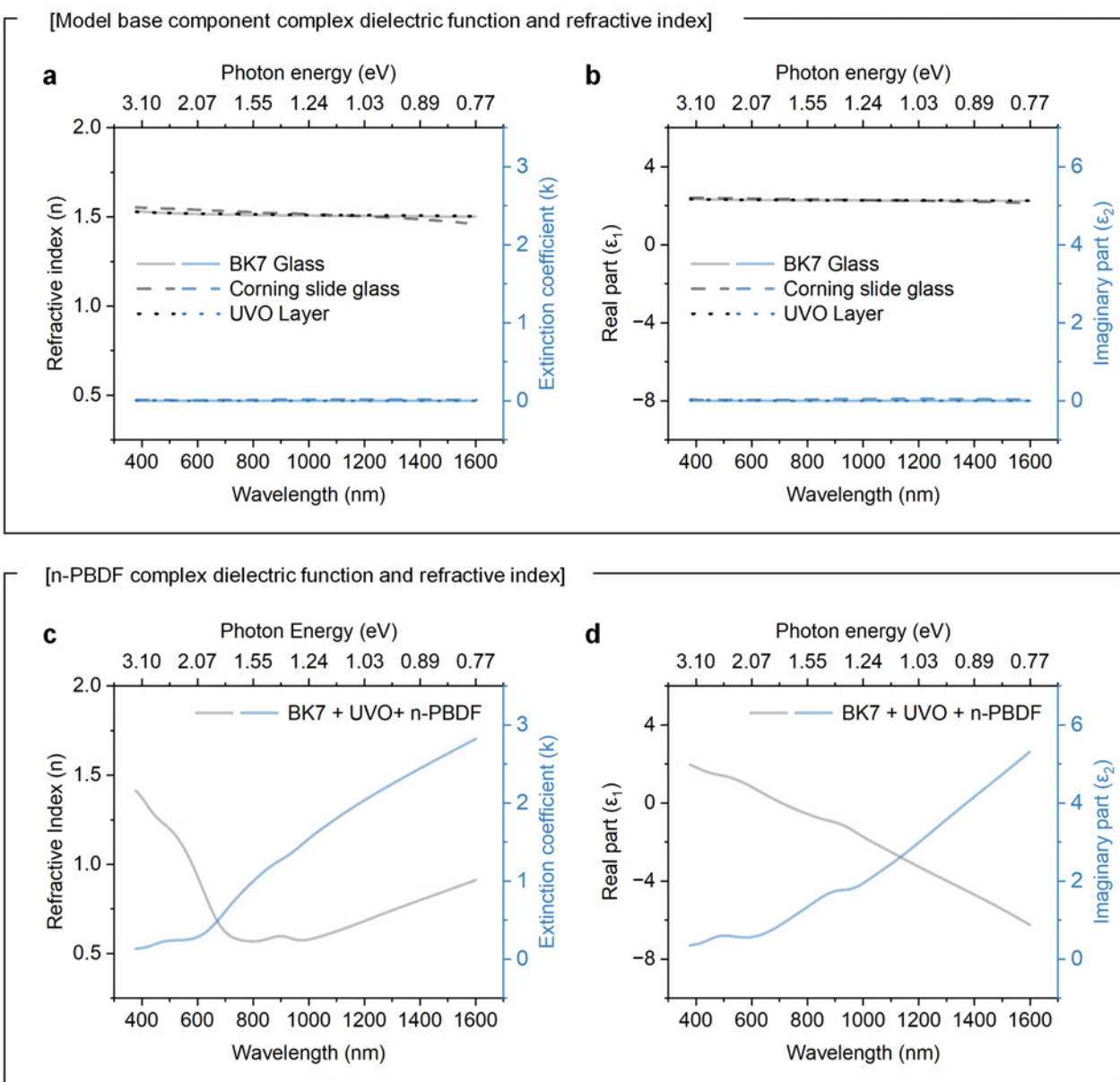


Figure S30. Extracted optical constants (n , k) and complex dielectric function (ϵ_1 , ϵ_2) from the spectroscopic ellipsometry model.

The top panels (a) and (b) show the extracted optical properties for the individual base components used to construct the refined "UVO-Glass" model, showing the refractive index (n), extinction coefficient (k), and the real (ϵ_1) and imaginary (ϵ_2) parts of the dielectric function. The bottom panels (c) and (d) show the final, effective optical constants for the complete n -PBDF film-on-substrate system, including the effective refractive index and extinction coefficient and the effective complex dielectric function.

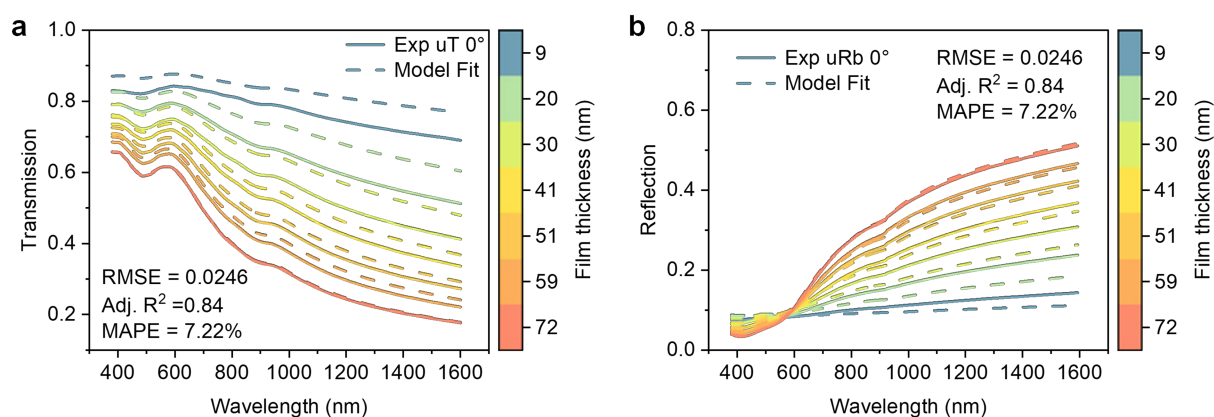


Figure S31. Validation of the optical model's predictive capability across a range of film thicknesses.

The optical model, which was derived from fitting the optical response of the thickest (≈ 72 nm) film, was used to predict the **(a)** transmittance and **(b)** reflectance spectra for thinner films. Experimental data are shown as solid lines, and the corresponding model predictions are shown as dashed lines, with color indicating film thickness. The model demonstrates strong predictive agreement across the entire experimental thickness range (≈ 9 to 72 nm), as indicated by the high adjusted R^2 (0.84) and low mean absolute percentage error (MAPE $\approx 7.22\%$). This result confirms the robustness of the model and its applicability for accurately predicting the optical properties of *n*-PBDF films without needing to model each thickness individually.

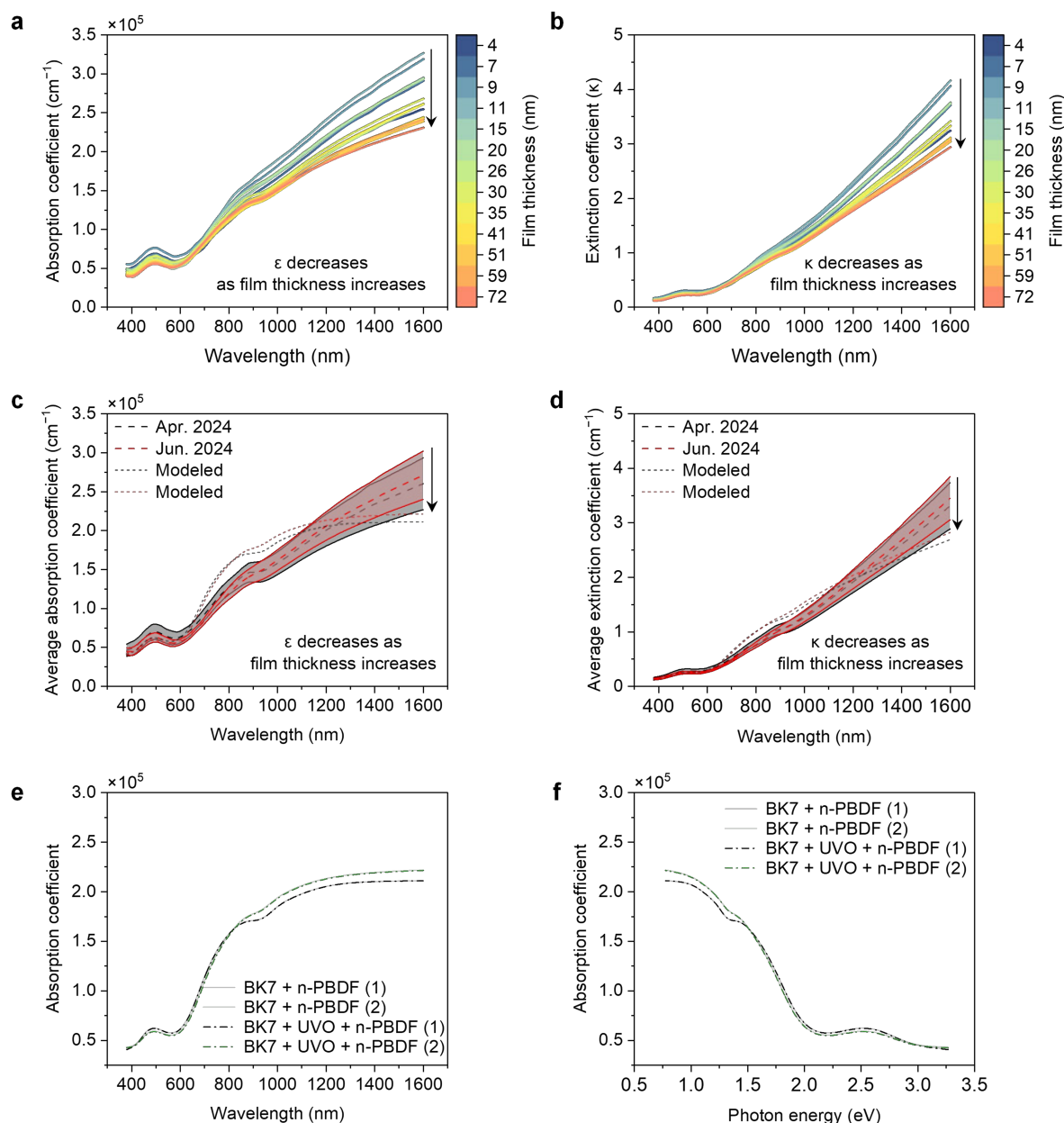


Figure S32. Analysis of the absorption (α) and extinction (k) coefficients.

(a, b) The coefficients extracted from the optical model for films of varying thickness, showing a clear trend of decreasing α and k with increasing film thickness. (c, d) Comparison between the average coefficients derived experimentally via Beer–Lambert law (solid lines with shaded error) and those extracted directly from the WVASE® optical model (dotted lines). The methods show good agreement in the visible spectrum (<700 nm) but diverge in the NIR, highlighting the model's superiority in correctly decoupling absorption from the high reflectance caused by the Drude response. (e, f) Demonstration of the high reproducibility of the extracted absorption coefficients, showing near-identical values for films from two independent *n*-PBDF batches and confirming that the refined UVO-Glass model yields a result consistent with the simpler model. Panel (f) presents the same data as (e) plotted against photon energy.

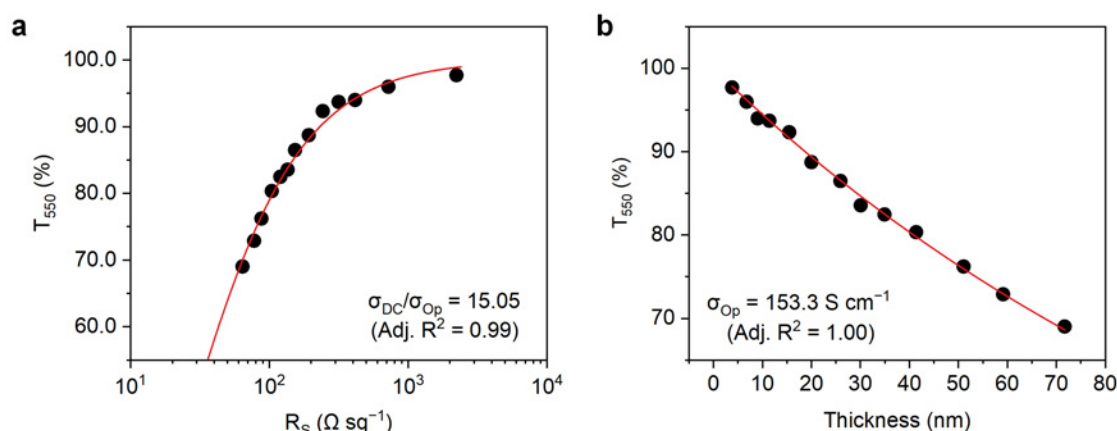


Figure S33. Determination of the transparent conductor Figure of Merit (FOM) for *n*-PBDF films.

The analysis was performed by fitting the experimental data to the standard thin-film optoelectronic models. **(a)** The relationship between transmittance and sheet resistance (R_s) was fitted to the corresponding bulk model, $T = [1 + (Z_0 / (2R_s \cdot \text{FOM}))]^{-2}$. This allowed for the direct extraction of the figure of merit ($\text{FOM} = \sigma_{\text{DC}}/\sigma_{\text{Op}}$), which was determined to be 15.05 ± 0.30 across the full dataset (consistent with the bulk-regime fit of 15.03 ± 0.31 discussed in the main text). The excellent quality of both fits (Adj. $R^2 > 0.98$) validated the model and extracted parameters. **(b)** The optical conductivity (σ_{Op}) was determined by fitting the transmittance-versus-thickness data to the equation $T = [1 + (Z_0/2) \cdot \sigma_{\text{Op}} \cdot d]^{-2}$, where Z_0 is the impedance of free space. This analysis yielded $\sigma_{\text{Op}} = (153.27 \pm 1.72) \text{ S cm}^{-1}$.

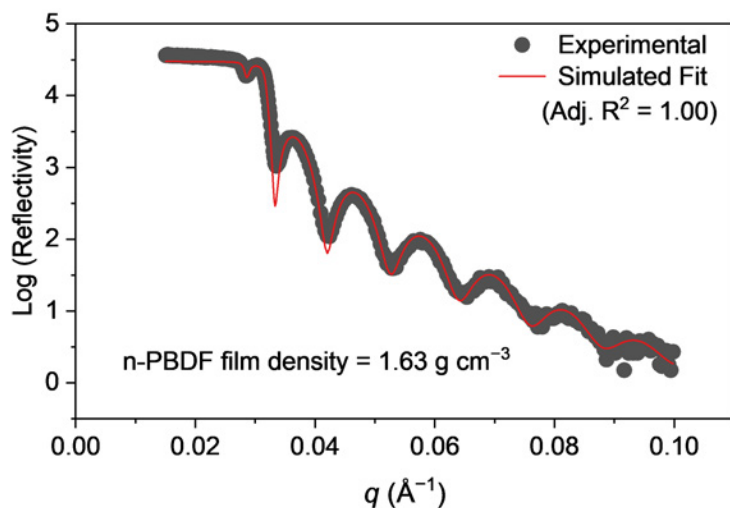


Figure S34. X-ray Reflectivity (XRR) characterization of a representative *n*-PBDF film on a silicon substrate.

The logarithm of the reflected X-ray intensity was plotted against the scattering vector q . The experimental data (gray circles) were modeled using a simulated fit (red line), which showed excellent agreement ($\text{Adj. } R^2 = 1.00$). Through the simulated fitting of the Kiessig fringes in the reflectivity profile, a film density value of 1.63 g cm^{-3} was extracted. This value was used in thermal modeling calculations.

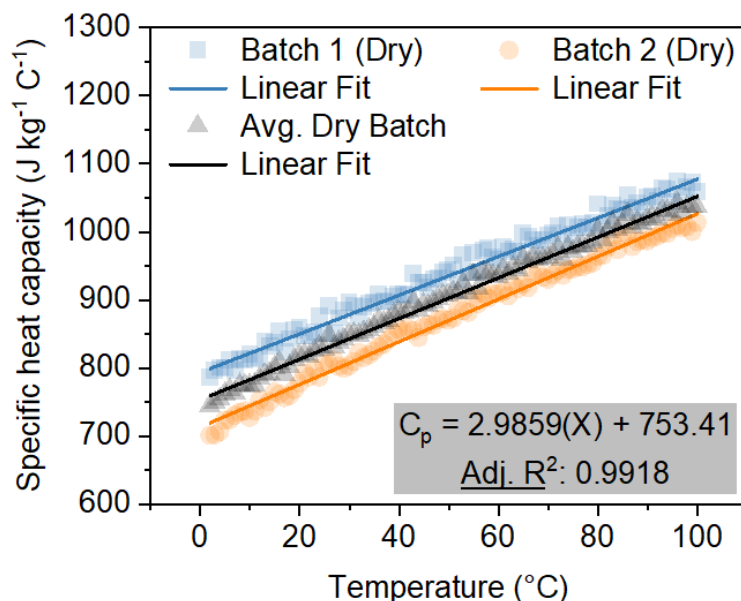


Figure S35. Determination of the temperature-dependent specific heat capacity (C_p or c_1) of *n*-PBDF for thermal modeling.

Data were collected via differential scanning calorimetry (DSC) on dried material from two independently synthesized batches and were found to be in excellent agreement. The average of the two data sets was fitted to a linear model (black line), yielding the equation $C_p(T) = (2.9859 \pm 0.0274) \text{ J kg}^{-1} \text{ °C}^{-2} \cdot T + (753.41 \pm 1.60) \text{ J kg}^{-1} \text{ °C}^{-1}$ [or in Kelvin, $C_p(T) = (2.9859 \pm 0.0274) \text{ J kg}^{-1} \text{ K}^{-2} \cdot T - (62.20 \pm 8.92) \text{ J kg}^{-1} \text{ K}^{-1}$]. The reported errors represent the standard error (S.E.) associated with the fitted value. The extracted function was used for all subsequent thermal models and calculations. At 25 °C, the specific heat capacity is approximately $830 \text{ J kg}^{-1} \text{ °C}^{-1}$, which is nearly identical to that of the glass substrate ($\approx 840 \text{ J kg}^{-1} \text{ °C}^{-1}$). This close match in the specific heat capacity is advantageous for the overall device reliability, as it promotes a synchronized thermal response and minimizes transient thermal gradients at the film-substrate interface during rapid heating and cooling cycles.

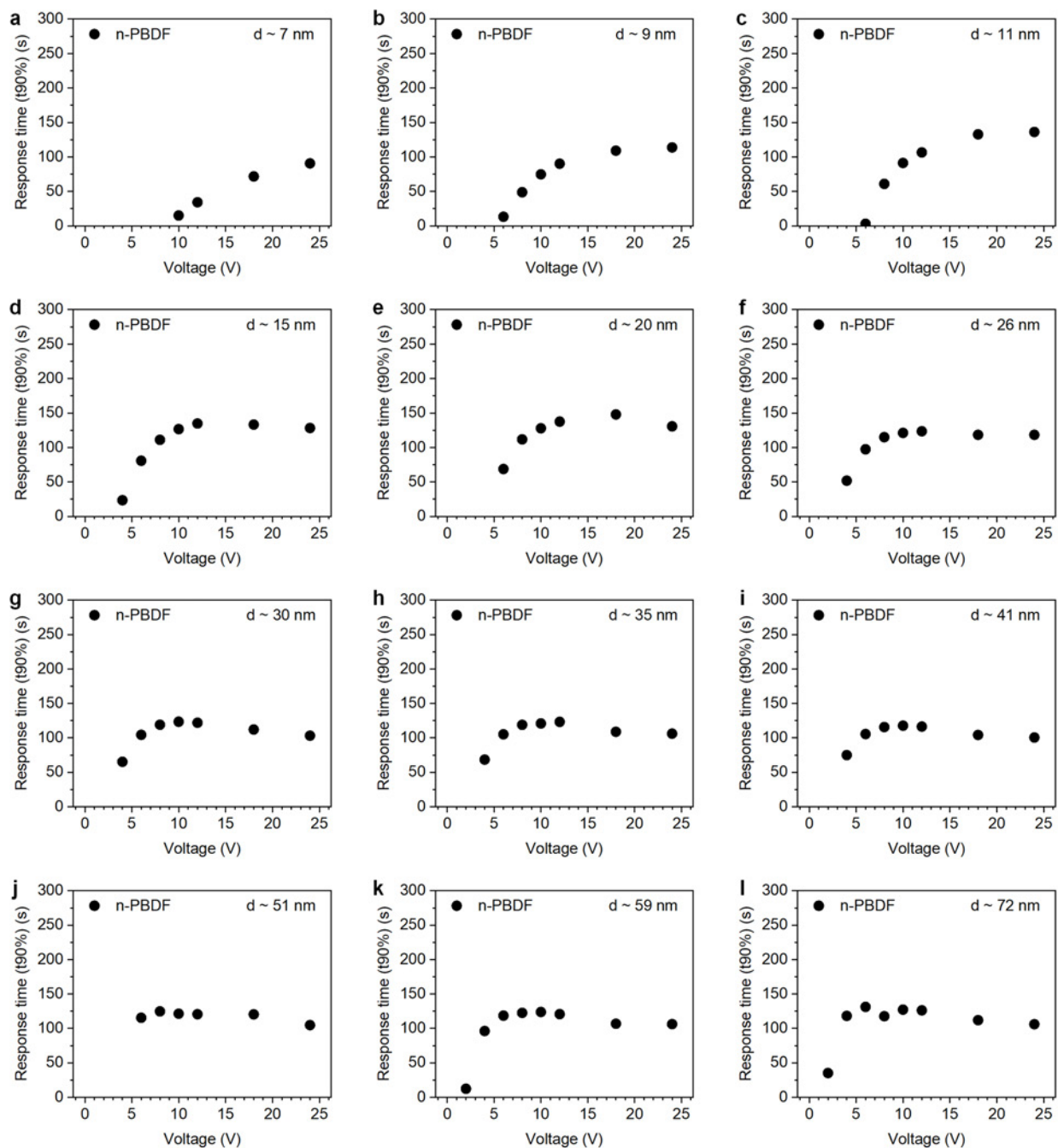


Figure S36. Characterization of the heating response time for $(3 \times 3) \text{ cm}^2$ n -PBDF Joule heating devices with various film thicknesses.

The time required to reach 90 % of the final steady-state temperature ($t_{90\%}$) is plotted against the applied DC voltage (V). The plots correspond to film thicknesses ranging from approximately (a) $d \approx 7 \text{ nm}$ to (l) $d \approx 72 \text{ nm}$. For most devices, a key trend was observed, in which the response time saturated across a wide range of higher voltages. This suggests that beyond a certain power input, the time constant for the device to reach thermal equilibrium with its surroundings becomes the dominant factor, making the response time largely independent of further increases in the voltage.

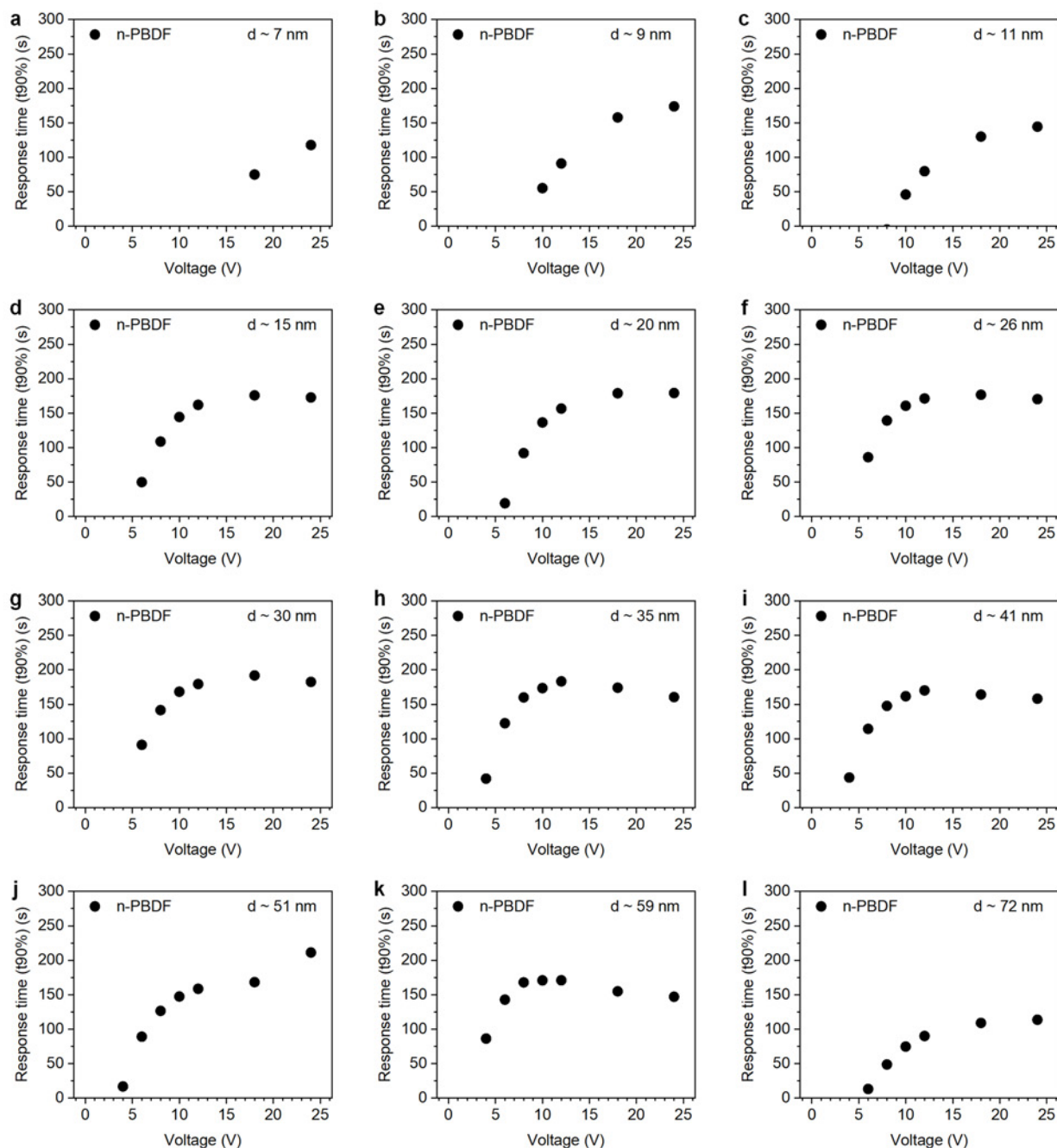


Figure S37. Characterization of the heating response time for $(5 \times 5) \text{ cm}^2$ n -PBDF Joule heating devices with various film thicknesses.

The time required to reach 90 % of the final steady-state temperature ($t_{90\%}$) is plotted against the applied DC voltage. The plots correspond to film thicknesses ranging from approximately (a) $d \approx 7 \text{ nm}$ to (l) $d \approx 72 \text{ nm}$. For most devices, a key trend is observed where the response time saturates across a wide range of higher voltages. This suggests that beyond a certain power input, the time constant for the device to reach thermal equilibrium with its surroundings becomes the dominant factor, making the response time largely independent of further increases in voltage.

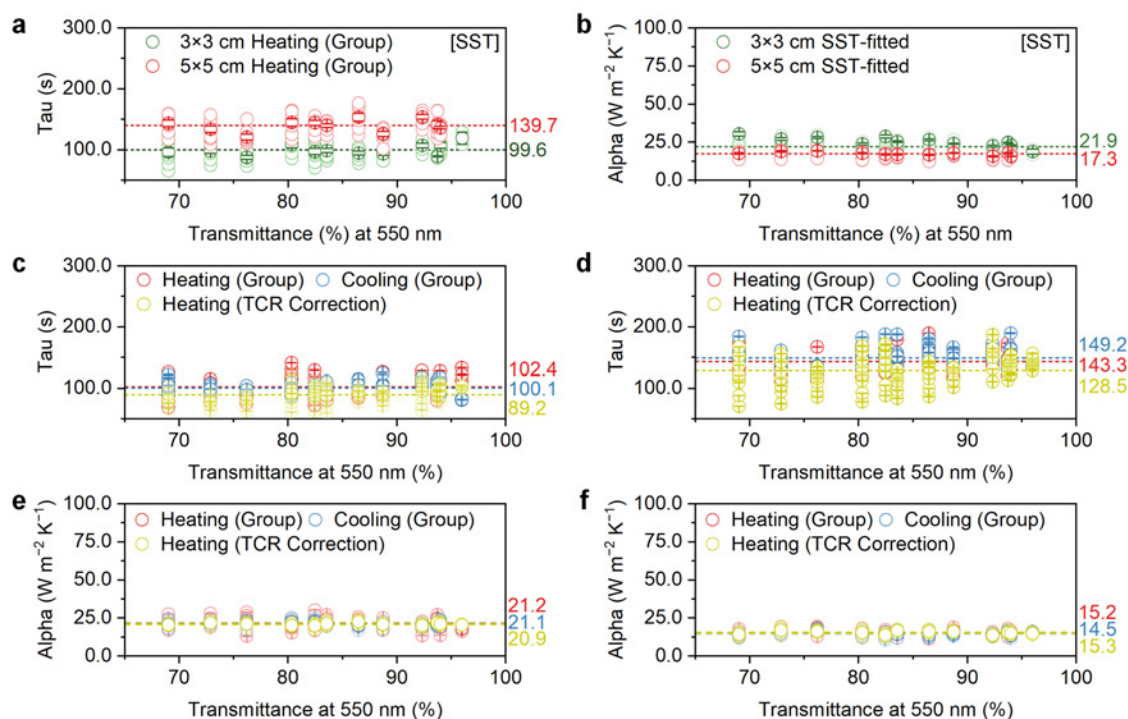


Figure S38. Summary and validation and of the key thermal performance parameters.

The thermal time constant (τ) and heat transfer coefficient (α), are plotted as a function of optical transmittance at 550 nm. **(a, b)** Comparison of τ and α extracted from steady-state temperature (SST) analysis for (3×3) cm² vs. (5×5) cm² heaters. The results show the expected size dependence, with the larger (5×5) cm² devices exhibiting a longer time constant and lower heat transfer coefficient. **(c-f)** Comparison of τ and α values for **(c, e)** (3×3) cm² and **(d, f)** (5×5) cm² devices, calculated using three different methods: dynamic heating curves ("Heating Group"), dynamic cooling curves ("Cooling Group"), and dynamic heating data corrected for the material's TCR ("Heating (TCR Correction)"). The strong agreement across the different analytical methods for a given device size validates the robustness of the thermal characterization. The dashed lines represent the average values for each data series.



Figure S39. Flexible *n*-PBDF transparent heaters and demonstration of practical applications.

Photographs of the large-area flexible transparent heaters fabricated on PET substrates, providing a visual reference for the thermal images shown in **Figure 6 (Main Text)**. PET substrates spray coated with *n*-PBDF to have $\approx 75\%$ VLT. Electrodes are painted along the long-edges of the samples using fast-drying silver paint and reinforced with copper tape at the connection points to the power supply for increased robustness. **(a)** the transparent heater element installed on the visor of a commercially available motorcycle helmet. **(b)** The same visor from (a), shown fully integrated and operating on the motorcycle helmet. **(c)** A second demonstration, showing a flexible *n*-PBDF heater of similar VLT integrated into the lens of a commercially available ski-goggle, further showcasing the practicality of this technology for real-world applications. The dimensions of the ski goggle are approximately $190.5\text{ mm} \times 76\text{ mm}$ ($7.5\text{ in} \times 3\text{ in}$), and those of the visor are approximately $330\text{ mm} \times 127\text{ mm}$ ($13\text{ in} \times 5\text{ in}$).

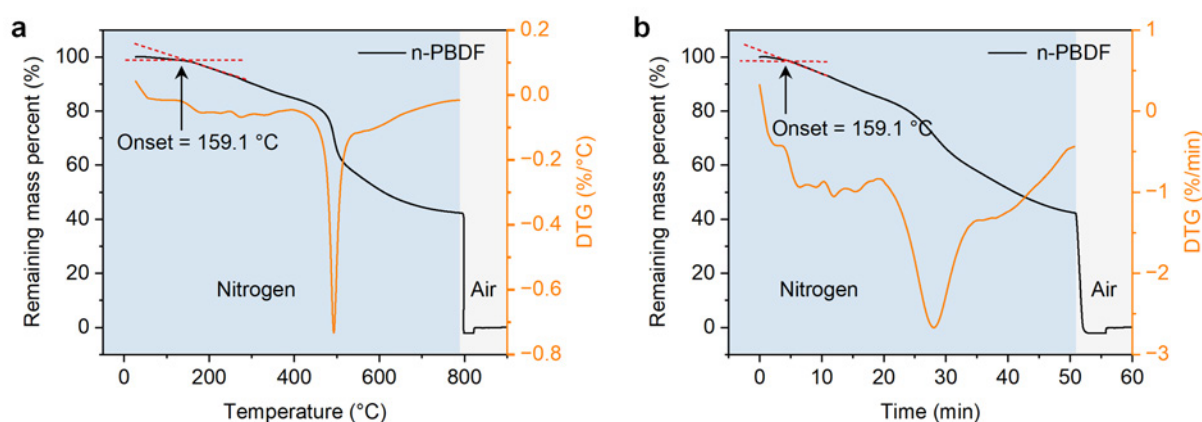


Figure S40. Thermogravimetric analysis (TGA) of *n*-PBDF to determine its thermal stability.

The TGA trace (black, left axis) and corresponding derivative thermogravimetry (DTG) curve (orange, right axis) are presented. The material was stable up to an onset temperature of 159.1 °C, where 98.2 % of the mass was still present. The initial decomposition proceeded at a slow rate, as indicated by the DTG values of approximately $-0.05\% \text{ } ^\circ\text{C}^{-1}$ (a) and $-0.9\% \text{ min}^{-1}$ (b). A major decomposition event occurred under nitrogen with a peak rate at approximately 500 °C, followed by the complete combustion of the char upon switching to an air atmosphere.

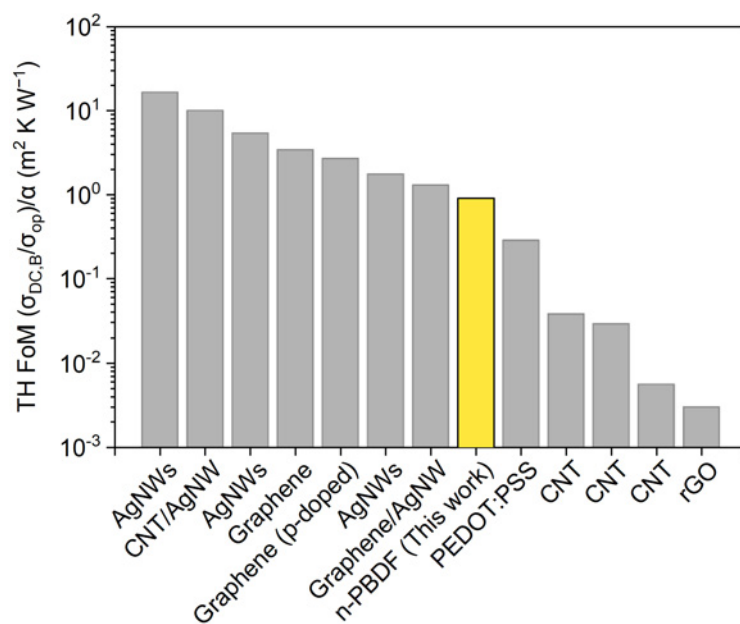


Figure S41. Transparent heater Figure of Merit (TH FOM) benchmark.

A bar chart comparing the TH FOM (FOM_{TH}) for *n*-PBDF (this work) against state-of-the-art transparent heating materials reported in the literature. The TH FOM is defined as the ratio of the optoelectronic figure of merit to the effective heat transfer coefficient, $(\sigma_{DC}/\sigma_{Op})/\alpha$. This metric evaluates a material's combined efficacy as both a transparent conductor and a thermal insulator. The values for all materials were calculated using experimentally determined parameters from this work or from the cited literature (see **Tables S9–S11**). The *n*-PBDF heater is shown to be highly competitive, surpassing other organic systems and approaching the performance of leading inorganic and nanostructured materials. The plotted TH FOM for *n*-PBDF, as shown above, represents the value extracted using our rigorous TCR-aware model ($FOM_{TH} = 0.91 \text{ m}^2 \text{ K W}^{-1}$). We note that the value extracted using the standard constant-resistance model ($FOM_{TH} = 0.87 \text{ m}^2 \text{ K W}^{-1}$) does not significantly change this assessment. The full dataset used to generate this plot, including the individual α , σ_{DC}/σ_{Op} , and calculated TH FOM values for each material, is provided in **Table S11**.

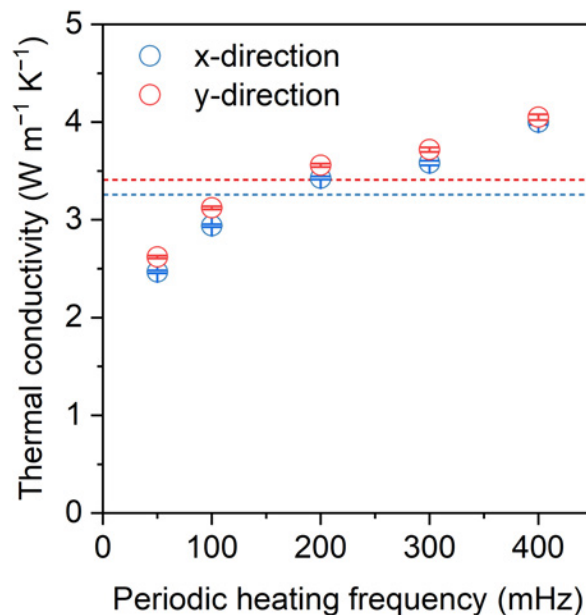


Figure S42. Frequency-dependent in-plane thermal conductivity.

The symbols represent the thermal conductivity values in the two in-plane orthotropic directions (κ_x and κ_y), extracted at each discrete periodic heating frequency by using an inverse fitting algorithm and least-squares fitting method based on a thermal diffusion model. The reported values, $\kappa_x = (3.283 \pm 0.009) \text{ W m}^{-1} \text{ K}^{-1}$ and $\kappa_y = (3.415 \pm 0.009) \text{ W m}^{-1} \text{ K}^{-1}$, correspond to the mean of the fitted conductivities obtained across five discrete heating frequencies in the tested frequency range (50 to 400) mHz. The reported uncertainties were obtained by propagating the 95 % confidence interval half-widths associated with the fitted conductivity from individual values measured at each tested frequency (see **Figure 5h** and **Note S9**).

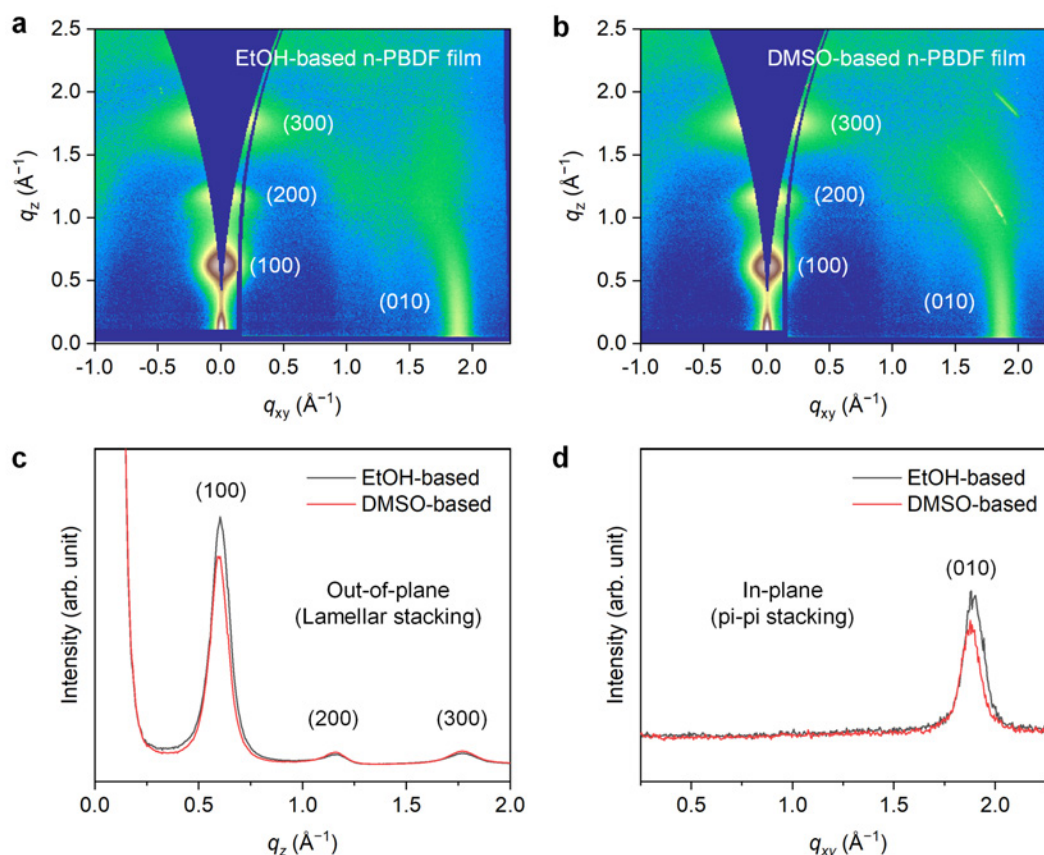


Figure S43. Comparison of the molecular packing structure of *n*-PBDF films processed from ethanol- and DMSO-based ink formulations.

Ex-situ 2D Grazing-incidence wide-angle X-ray scattering (GIWAXS) patterns of *n*-PBDF films prepared from (a) the optimized EtOH-based ink and (b) the standard DMSO-based ink. Corresponding 1D line-cut profiles along the (c) out-of-plane (q_z) and (d) in-plane (q_{xy}) directions. Both films exhibit nearly identical scattering features, indicating a preserved edge-on molecular orientation. This includes distinct ($h00$) lamellar stacking peaks ($h = 1-4$) in the out-of-plane direction ($q_z = 0.6044 \pm 0.0003$, 1.1512 ± 0.0012 , 1.7687 ± 0.0005 , and 2.3786 ± 0.0010) $\text{\AA}^{-1}$, respectively) and a strong (010) π - π stacking peak in the in-plane direction ($q_{xy} = 1.89 \pm 0.0005$) $\text{\AA}^{-1}$, corresponding to a π - π d -spacing of (3.32 ± 0.01) $\text{\AA}$ and a coherence length of $\approx (5.2 \pm 0.1)$ nm. Line cuts represent sector averages (10° width) at 90° for the out-of-plane direction and horizontal integrations (3-pixel width, +9 pixel offset) for the in-plane direction. The results confirm that ethanol-based formulation maintains the order, crystallinity, dominant edge-on molecular orientation of the original DMSO-based formulation. Moreover, we note that our results are consistent with those previously reported for DMSO-based films (≈ 4.8 nm).²⁹ Also see **Table S3** for additional details.

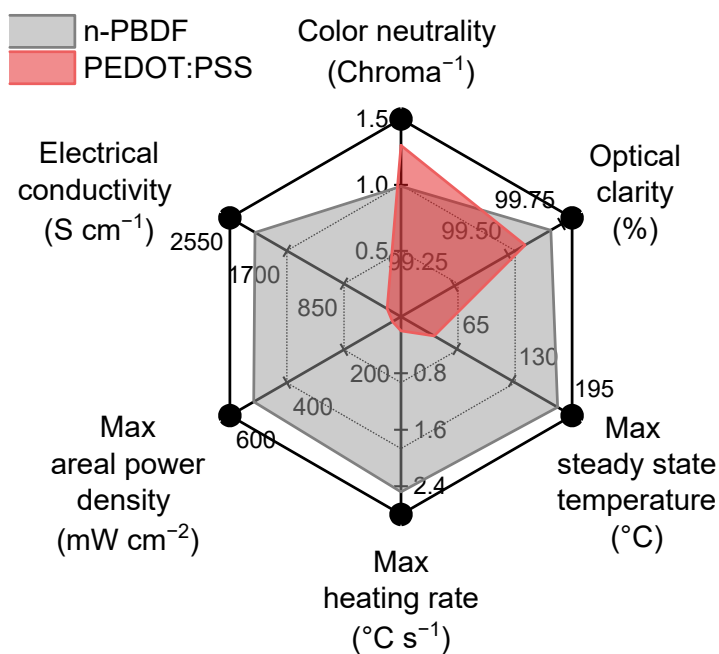


Figure S44. Direct performance comparison between *n*-PBDF and PEDOT:PSS heaters at a matched film thickness of ≈ 71 nm. The radar chart illustrates the peak electrothermal and optical performance for both systems within the tested range. Although PEDOT:PSS exhibits higher color neutrality at this thickness, it quickly changes at slightly increased thicknesses (see **Figure 3e**). *n*-PBDF demonstrates significantly stronger overall heating performance and higher electrical conductivity. Note that axis scales are adjusted relative to **Figure 1b** to accommodate the higher performance metrics achieved at the increased film thickness.

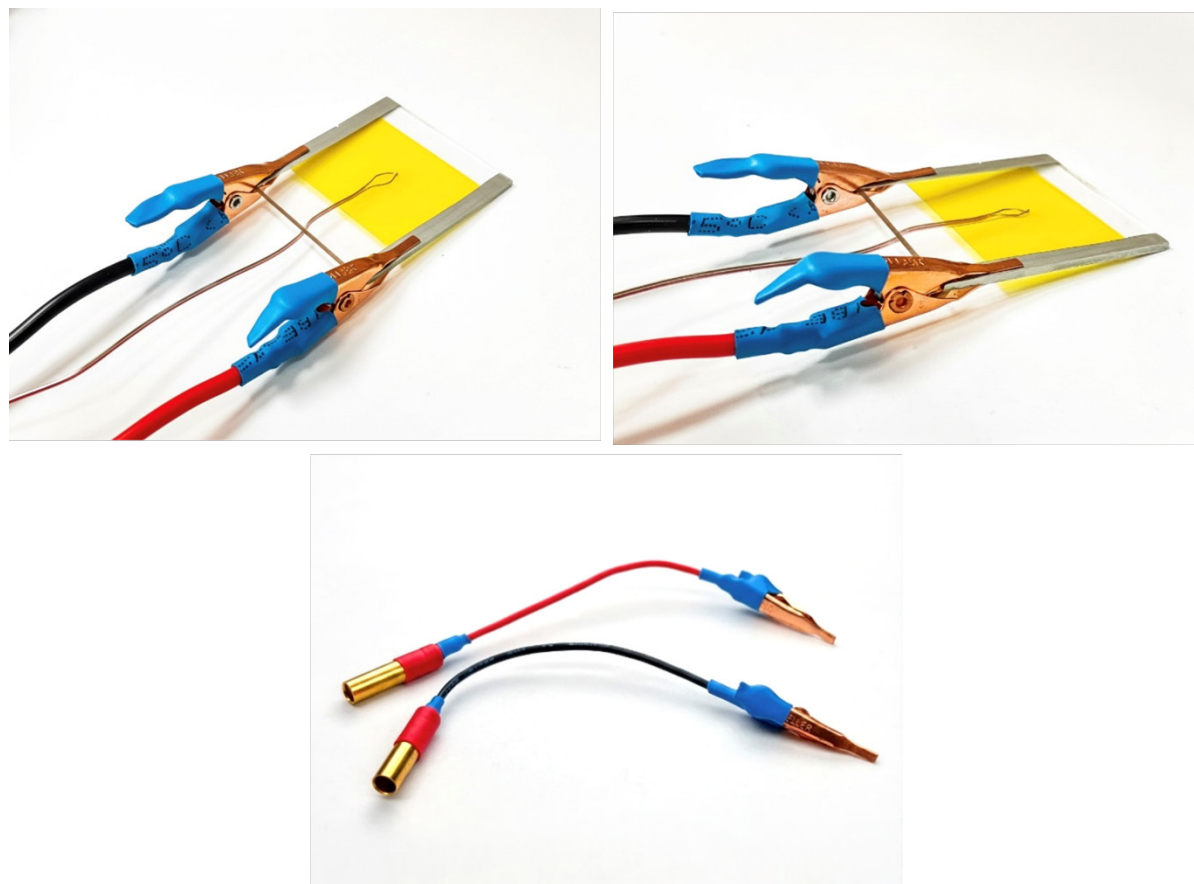


Figure S45. Photos showing a representative *n*-PBDF heater and the experimental testing setup.

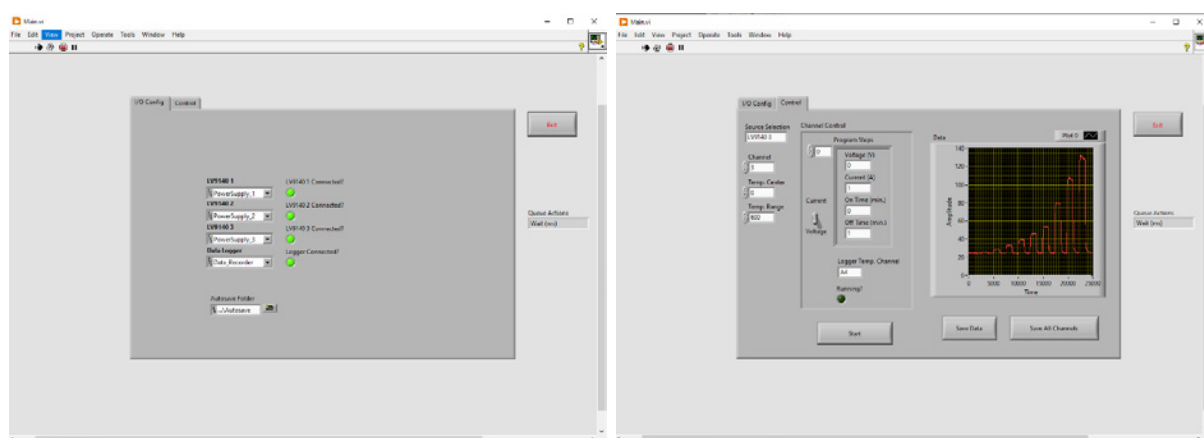


Figure S46. Photos showing graphical user interface (GUI) of the custom-made LabVIEW® program

Supporting Tables (S9 to S13)

Table S9. Various Figures of Merit (FOMs) of the reported transparent conducting film materials.

Materials	R_s ($\Omega \text{ sq.}^{-1}$)	σ_{DC} (S cm^{-1})	T (550 nm) (Decimal)	Contreras FOM ($\Omega^{-1/10}$)	Dressel–Grüner FOM (Ratio)	Fraser–Cook FOM (Ω^{-1})	Haacke FOM (Ω^{-1})	σ_{Op} (S cm^{-1})	Ref.
Benchmark									
Industry-preferred threshold	100	—	0.90	0.57	34.9	9.00E-03	3.49E-03	—	—
Polymers									
<i>n</i> -PBDF (EtOH-based) (*This work)	2235 ± 326	1176 ± 200	0.977 ± 0.0026	0.45	7.2	4.37E-04	3.55E-04	162 ± 24	—
	723 ± 56	2051 ± 238	0.960 ± 0.0060	0.50	12.6	1.33E-03	9.18E-04	163 ± 29	
	415 ± 17	2665 ± 163	0.940 ± 0.0058	0.51	14.4	2.26E-03	1.30E-03	185 ± 21	
	316 ± 18	2770 ± 228	0.937 ± 0.0049	0.53	18.1	2.96E-03	1.65E-03	153 ± 16	
	243 ± 11	2663 ± 136	0.923 ± 0.0051	0.53	19.1	3.80E-03	1.86E-03	140 ± 11	
	193 ± 8	2597 ± 133	0.887 ± 0.0032	0.52	15.9	4.61E-03	1.57E-03	163 ± 7	
	153 ± 4	2519 ± 90	0.865 ± 0.0022	0.52	16.3	5.65E-03	1.53E-03	154 ± 4	
	136 ± 4	2455 ± 73	0.836 ± 0.0048	0.51	14.8	6.17E-03	1.22E-03	166 ± 6	
	120 ± 4	2386 ± 82	0.825 ± 0.0056	0.51	15.5	6.87E-03	1.21E-03	154 ± 6	
	104 ± 4	2321 ± 89	0.803 ± 0.0056	0.50	15.6	7.71E-03	1.08E-03	148 ± 6	
	88 ± 2	2231 ± 52	0.762 ± 0.0047	0.49	14.8	8.68E-03	7.54E-04	151 ± 4	
	78 ± 2	2180 ± 67	0.729 ± 0.0039	0.47	14.2	9.39E-03	5.46E-04	154 ± 3	
	64 ± 2	2174 ± 62	0.690 ± 0.0035	0.46	14.4	1.08E-02	3.82E-04	151 ± 3	
PEDOT:PSS (*This work)	684 ± 86	206 ± 26	0.944 ± 0.0060	0.49	7.3	1.38E-03	8.27E-04	28 ± 2	—
	632 ± 78	186 ± 23	0.920 ± 0.0079	0.48	7.1	1.46E-03	6.93E-04	26 ± 1	
	190 ± 18	321 ± 31	0.855 ± 0.0044	0.51	12.2	4.50E-03	1.10E-03	26 ± 3	
	165 ± 15	315 ± 29	0.823 ± 0.01	0.49	14.6	4.99E-03	8.67E-04	22 ± 3	
PEDOT:PSS (Gueye et al.)	1.90E+04	—	0.98	0.36	1.0	5.14E-05	4.09E-05	—	2
	361	178	0.90	0.50	9.8	2.50E-03	9.77E-04	18	
	293	—	0.86	0.49	8.2	2.95E-03	7.89E-04	—	
	157	—	0.82	0.49	11.5	5.19E-03	8.45E-04	—	
	108	—	0.77	0.48	12.5	7.14E-03	6.92E-04	—	
	67	—	0.70	0.46	14.4	1.05E-02	4.31E-04	—	
PEDOT:PSS-EG (*This work)	83 ± 7	961 ± 77	0.829 ± 0.010	0.53	23.2	9.97E-03	1.86E-03	41 ± 3	—
	108 ± 8	843 ± 64	0.847 ± 0.0066	0.53	20.0	7.84E-03	1.74E-03	42 ± 3	
	179 ± 22	716 ± 89	0.927 ± 0.0082	0.55	27.4	5.18E-03	2.62E-03	26 ± 4	
	421 ± 67	439 ± 70	0.944 ± 0.0112	0.52	15.3	2.24E-03	1.34E-03	29 ± 7	
PEDOT:PSS-EG (Gueye et al.)	28	—	0.69	0.49	33.0	2.48E-02	8.60E-04	—	2
	46	—	0.75	0.51	26.5	1.61E-02	1.15E-03	—	
	58	—	0.80	0.54	27.5	1.38E-02	1.93E-03	—	
	94	—	0.87	0.55	27.8	9.26E-03	2.65E-03	—	
	68	1362	0.90	0.59	49.1	1.32E-02	4.90E-03	28	
	149	—	0.92	0.56	29.7	6.17E-03	2.85E-03	—	
	332	—	0.96	0.54	27.5	2.89E-03	1.95E-03	—	

Table S9 (continued). Various Figures of Merit (FOMs) of the reported transparent conducting film materials.

Materials	R_s (Ω sq. ⁻¹)	σ_{DC} (S cm ⁻¹)	T (550 nm) (Decimal)	Contreras FOM ($\Omega^{-1/10}$)	Dressel–Grüner FOM (Ratio)	Fraser–Cook FOM (Ω^{-1})	Haacke FOM (Ω^{-1})	σ_{Op} (S cm ⁻¹)	Ref.
PEDOT:OTf (Gueye et al.)	144	–	0.93	0.57	35.4	6.48E-03	3.37E-03	–	2
	96	–	0.88	0.56	29.7	9.21E-03	3.06E-03	–	
	81	3011	0.88	0.57	36.6	1.09E-02	3.60E-03	82	
	74	–	0.84	0.54	28.0	1.14E-02	2.27E-03	–	
	58	–	0.77	0.51	23.3	1.32E-02	1.24E-03	–	
	56	–	0.73	0.49	19.8	1.29E-02	7.34E-04	–	
PEDOT:Sulf (Gueye et al.)	266	–	0.97	0.56	46.2	3.65E-03	2.80E-03	–	2
	95	–	0.93	0.59	53.7	9.78E-03	5.08E-03	–	
	64	–	0.89	0.59	49.1	1.40E-02	5.01E-03	–	
PEDOT:Sulf (Gueye et al.)	57	3987	0.88	0.59	49.2	1.54E-02	4.78E-03	81	2
	49	–	0.85	0.58	45.4	1.75E-02	4.09E-03	–	
	38	–	0.79	0.55	39.7	2.09E-02	2.47E-03	–	
	37	–	0.75	0.52	33.0	2.03E-02	1.47E-03	–	
BBL (Pristine)	2.78E+10	3.60E-06	0.11	0.01	0.0	4.09E-12	1.28E-20	1044	30
BBL (PEI-doped)	1.29E+04	7.70	0.11	0.04	0.0	8.60E-06	2.20E-14	1055	
N2200 (Pristine)	1.00E+15	1.00E-10	0.80	0.03	0.0	7.99E-16	1.06E-16	63	31
N2200 (TDAE-doped)	1.43E+07	7.00E-03	0.72	0.14	0.0	5.04E-08	2.62E-09	95	
PDTzTI (Pristine)	1.11E+14	9.00E-10	0.52	0.02	0.0	4.69E-15	1.32E-17	205	
PDTzTI (TDAE-doped)	2.17E+04	4.60	0.67	0.25	0.0	3.08E-05	8.35E-07	118	
Carbon-based materials									
Graphene	200	–	0.85	0.50	11.1	4.25E-03	9.84E-04	–	32
	1350	1235	0.91	0.44	2.9	6.74E-04	2.88E-04	427	33
	210	1587	0.72	0.42	5.0	3.43E-03	1.78E-04	316	
	1000	3333	0.90	0.45	5.2	9.00E-04	3.49E-04	643	34
	770	4329	0.90	0.46	6.7	1.17E-03	4.53E-04	642	
	367	9080	0.80	0.44	6.3	2.18E-03	2.93E-04	1446	35
	272	6130	0.66	0.38	6.9	2.43E-03	5.77E-05	883	
	233	6130	0.62	0.36	7.0	2.66E-03	3.60E-05	881	
	510	6536	0.85	0.46	4.4	1.67E-03	3.86E-04	1497	36
	370	13514	0.82	0.45	4.9	2.22E-03	3.71E-04	2767	
	6100	540 to 810	0.98	0.41	3.0	1.60E-04	1.27E-04	177 to 266	37
	2000	1700 to 2500	0.80	0.37	0.8	4.00E-04	5.37E-05	2129 to 3131	
	750	4444	0.85	0.44	3.0	1.13E-03	2.62E-04	1123	38

Table S9 (continued). Various Figures of Merit (FOM) of the reported transparent conducting film materials.

Materials	R_s ($\Omega \text{ sq.}^{-1}$)	σ_{DC} ($S \text{ cm}^{-1}$)	T (550 nm) (Decimal)	Contreras FOM ($\Omega^{-1/10}$)	Dressel–Grüner FOM (Ratio)	Fraser–Cook FOM (Ω^{-1})	Haacke FOM (Ω^{-1})	σ_{Op} ($S \text{ cm}^{-1}$)	Ref.
r-GO	3.51E+04	81	0.86	0.30	0.1	2.45E-05	6.43E-06	1170	39
	4552	628	0.81	0.35	0.4	1.79E-04	2.78E-05	1650	
	2004	1426	0.73	0.34	0.6	3.66E-04	2.27E-05	2533	
	7.56E+04	38	0.88	0.29	0.0	1.16E-05	3.68E-06	1001	
	2.16E+04	132	0.87	0.32	0.1	4.02E-05	1.13E-05	1106	
	6657	429	0.84	0.35	0.3	1.26E-04	2.60E-05	1388	
	6079	45	0.81	0.34	0.3	1.33E-04	2.00E-05	159	40
	1568	188	0.53	0.25	0.3	3.38E-04	1.12E-06	583	
	641	446	0.34	0.18	0.4	5.30E-04	3.22E-08	1084	41
	1800	550	0.64	0.30	0.4	3.56E-04	6.41E-06	1313	
	2200	—	0.84	0.39	0.9	3.82E-04	7.95E-05	—	42
	8.70E+05	10	0.98	0.25	0.0	1.13E-06	9.39E-07	469	43
	3.50E+04	77	0.95	0.33	0.2	2.71E-05	1.71E-05	371	
	3000	160	0.78	0.35	0.5	2.60E-04	2.78E-05	337	
	7400	170	0.92	0.38	0.6	1.24E-04	5.87E-05	284	
	3500	180	0.82	0.36	0.5	2.34E-04	3.93E-05	349	
	4400	360	0.84	0.36	0.5	1.91E-04	3.98E-05	765	
	1100	410	0.76	0.38	1.2	6.91E-04	5.84E-05	352	
	730	450	0.67	0.35	1.2	9.18E-04	2.50E-05	386	
	250	520	0.18	0.10	0.6	7.20E-04	1.43E-10	936	
	270	550	0.29	0.17	0.8	1.07E-03	1.56E-08	675	
	2300	600	0.85	0.39	1.0	3.70E-04	8.56E-05	620	
	200	740	0.28	0.16	1.1	1.40E-03	1.48E-08	699	
	200	770	0.30	0.18	1.1	1.50E-03	2.95E-08	675	
	200	960	0.45	0.26	1.9	2.25E-03	1.70E-06	500	
	100	1000	—	—	—	—	—	—	
	210	1100	0.55	0.32	2.6	2.62E-03	1.21E-05	427	
	160	1500	0.20	0.12	1.0	1.25E-03	6.40E-10	1574	
	57	1900	0.02	0.01	0.5	3.51E-04	1.80E-19	3488	
	52	2000	—	—	—	—	—	—	
	42	2400	—	—	—	—	—	—	
	3.80E+05	8.2	0.93	0.26	0.0	2.45E-06	1.27E-06	611	
	2.60E+05	12	0.93	0.27	0.0	3.58E-06	1.86E-06	612	
	1.70E+05	21	0.92	0.28	0.0	5.41E-06	2.56E-06	806	
	3.50E+04	35	0.69	0.24	0.0	1.97E-05	6.99E-07	1325	
	3.10E+04	52	0.78	0.28	0.0	2.52E-05	2.69E-06	1131	
	1.20E+04	89	0.64	0.25	0.1	5.33E-05	9.61E-07	1416	
	9.90E+04	100	0.54	0.17	0.1	5.45E-06	2.13E-08	1895	
	1.20E+04	110	0.63	0.25	0.1	5.25E-05	8.21E-07	1820	
	2600	140	0.32	0.15	0.1	1.23E-04	4.33E-09	1483	

Table S9 (continued). Various Figures of Merit (FOMs) of the reported transparent conducting film materials.

Materials	R_s ($\Omega \text{ sq.}^{-1}$)	σ_{DC} ($S \text{ cm}^{-1}$)	T (550 nm) (Decimal)	Contreras FOM ($\Omega^{-1/10}$)	Dressel–Grüner FOM (Ratio)	Fraser–Cook FOM (Ω^{-1})	Haacke FOM (Ω^{-1})	σ_{Op} ($S \text{ cm}^{-1}$)	Ref.
r-GO (<i>continued</i>)	2000	160	0.29	0.14	0.1	1.45E-04	2.10E-09	1455	43
	2800	180	0.40	0.18	0.1	1.43E-04	3.74E-08	1554	
	1.40E+08	0.014	0.92	0.14	0.0	6.57E-09	3.10E-09	443	
	2.20E+08	0.015	0.94	0.14	0.0	4.27E-09	2.45E-09	550	
	7.40E+04	2.4	0.29	0.09	0.0	3.92E-06	5.69E-11	807	
	2001	200	0.25	0.12	0.1	1.24E-04	4.58E-10	2122	44
	4295	200	0.42	0.18	0.1	9.80E-05	4.07E-08	2257	
	5364	200	0.45	0.19	0.1	8.30E-05	5.68E-08	2257	
	7012	200	0.60	0.25	0.1	8.56E-05	8.62E-07	2257	
	8011	200	0.62	0.25	0.1	7.71E-05	1.01E-06	2257	
	1.00E+04	200	0.68	0.27	0.1	6.83E-05	2.24E-06	2257	
SWCNT	617	–	0.92	0.48	7.2	1.49E-03	6.81E-04	–	45
	418	–	0.85	0.46	5.3	2.03E-03	4.58E-04	–	
	286	–	0.76	0.43	4.5	2.66E-03	2.23E-04	–	
	258	–	0.70	0.40	3.7	2.72E-03	1.10E-04	–	
	248	–	0.65	0.37	3.2	2.63E-03	5.43E-05	–	
	2.26E+04	181	0.97	0.36	0.5	4.29E-05	3.26E-05	332	46
	30	6667	0.78	0.56	47.5	2.61E-02	2.86E-03	140	47
	700	714 to 1429	0.71	0.37	1.5	1.02E-03	4.86E-05	488 to 977	23
	783	638 to 1276	0.79	0.41	1.9	1.01E-03	1.24E-04	328 to 656	
	3304	151 to 303	0.80	0.36	0.5	2.42E-04	3.25E-05	313 to 626	
	1474	339 to 678	0.82	0.40	1.2	5.56E-04	9.31E-05	277 to 554	
	1599	313 to 625	0.84	0.40	1.3	5.25E-04	1.09E-04	242 to 483	
	1237	404 to 808	0.85	0.42	1.7	6.84E-04	1.52E-04	231 to 463	
	2028	247 to 493	0.90	0.42	1.7	4.44E-04	1.72E-04	143 to 287	
	8341	60 to 120	0.95	0.39	0.9	1.14E-04	7.18E-05	69 to 138	
	2.03E+04	25 to 49	0.94	0.35	0.3	4.65E-05	2.74E-05	79 to 158	
	6177	81 to 162	0.98	0.41	3.0	1.59E-04	1.32E-04	27 to 54	
	380	658	0.87	0.48	6.9	2.29E-03	6.54E-04	96	48
	160	1563	0.87	0.52	16.3	5.44E-03	1.55E-03	96	
	160	1500	0.80	0.48	7.5	5.00E-03	6.71E-04	199	49
	40	5500	0.75	0.52	30.0	1.88E-02	1.41E-03	183	
	200	1667	0.85	0.50	11.1	4.25E-03	9.84E-04	150	50
	47	–	0.60	0.41	13.0	1.26E-02	1.21E-04	–	28
	48	–	0.65	0.44	13.0	1.35E-02	2.71E-04	–	
	87	–	0.75	0.48	13.0	8.64E-03	6.72E-04	–	
	101	–	0.76	0.48	13.0	7.58E-03	6.57E-04	–	
	102	–	0.80	0.51	13.0	7.85E-03	1.10E-03	–	
	326	–	0.91	0.51	13.0	2.80E-03	1.23E-03	–	
	2441	–	0.96	0.44	13.0	3.92E-04	2.62E-04	–	

Table S9 (continued). Various Figures of Merit (FOMs) of the reported transparent conducting film materials.

Materials	R_s (Ω sq. ⁻¹)	σ_{DC} (S cm ⁻¹)	T (550 nm) (Decimal)	Contreras FOM ($\Omega^{-1/10}$)	Dressel–Grüner FOM (Ratio)	Fraser–Cook FOM (Ω^{-1})	Haacke FOM (Ω^{-1})	σ_{Op} (S cm ⁻¹)	Ref.
SWCNT (<i>continued</i>)	644	1011	0.96	0.50	12.8	1.48E-03	9.89E-04	79	51
	406	1272	0.91	0.50	9.3	2.24E-03	9.30E-04	137	
	264	1334	0.86	0.49	8.8	3.24E-03	7.97E-04	151	
	217	1458	0.83	0.48	8.7	3.81E-03	6.85E-04	168	
	169	1504	0.79	0.47	8.9	4.67E-03	5.59E-04	169	
	143	1577	0.77	0.47	9.2	5.36E-03	4.82E-04	171	
	118	1577	0.73	0.46	9.6	6.24E-03	3.84E-04	165	
	105	1589	0.71	0.45	9.6	6.75E-03	3.08E-04	166	
	84	1611	0.65	0.42	9.3	7.72E-03	1.57E-04	174	
	72	1623	0.60	0.39	8.9	8.31E-03	8.18E-05	181	
	54	1634	0.52	0.35	9.0	9.59E-03	2.75E-05	181	
MWCNT	699	143	0.81 to 0.85	0.42 to 0.44	2.4 to 3.2	1.16E-03 to 1.22E-03	1.74E-04 to 2.82E-04	45 to 59	52
	349	143	0.67 to 0.72	0.37 to 0.40	2.4 to 3.0	1.91E-03 to 2.06E-03	5.20E-05 to 1.07E-04	47 to 59	54
	758	264	0.89	0.46	4.3	1.18E-03	4.27E-04	62	
	756	–	0.88	0.45	3.8	1.16E-03	3.48E-04	–	
	342	–	0.68	0.38	2.6	1.97E-03	5.74E-05	–	
	172	–	0.48	0.29	2.5	2.79E-03	3.77E-06	–	
Metallic structures									
AgNWs	33	–	0.90	0.63	105.6	2.73E-02	1.06E-02	–	55
	10	–	0.90	0.71	348.5	9.00E-02	3.49E-02	–	56
	11	–	0.92	0.72	402.5	8.36E-02	3.95E-02	–	57
	0.49	38550	0.33	0.36	523.4	6.79E-01	3.21E-05	74	28
	0.88	26767	0.47	0.47	466.8	5.35E-01	5.83E-04	57	
	0.57	41406	0.39	0.42	559.2	6.93E-01	1.58E-04	74	
	0.87	36116	0.46	0.47	464.5	5.36E-01	5.27E-04	78	
	2.14	18316	0.64	0.59	345.7	2.97E-01	5.01E-03	53	
	3.07	15287	0.71	0.63	321.6	2.30E-01	9.89E-03	48	
	1.81	25875	0.64	0.60	410.7	3.51E-01	6.05E-03	63	
	3.07	17045	0.68	0.61	289.6	2.22E-01	6.95E-03	59	
	3.50	16762	0.75	0.66	354.0	2.15E-01	1.68E-02	47	
	2.68	21920	0.70	0.64	365.4	2.62E-01	1.10E-02	60	
	12.58	6244	0.82	0.64	146.6	6.54E-02	1.13E-02	43	
	22.86	4111	0.86	0.63	101.5	3.74E-02	9.17E-03	40	
	14.36	6578	0.82	0.63	124.2	5.70E-02	9.34E-03	53	
	5.85	16096	0.78	0.65	242.2	1.33E-01	1.41E-02	66	
	28.34	4150	0.86	0.61	82.7	3.02E-02	7.51E-03	50	
	20.15	5851	0.86	0.63	116.3	4.25E-02	1.06E-02	50	
	93.63	1679	0.92	0.59	50.4	9.87E-03	4.88E-03	33	
	93.63	1676	0.87	0.55	28.5	9.32E-03	2.73E-03	59	
	50	–	0.90	0.61	415.0	1.80E-02	6.97E-03	–	

Table S9 (continued). Various Figures of Merit (FOMs) of the reported transparent conducting film materials.

Materials	R_s (Ω sq. ⁻¹)	σ_{DC} (S cm ⁻¹)	T (550 nm) (Decimal)	Contreras FOM ($\Omega^{-1/10}$)	Dressel–Grüner FOM (Ratio)	Fraser–Cook FOM (Ω^{-1})	Haacke FOM (Ω^{-1})	σ_{Op} (S cm ⁻¹)	Ref.
Ag Metal	1.77	226372	0.37	0.35	167.4	2.11.E-01	2.96E-05	1352	28
	1.26	226398	0.26	0.25	155.3	2.06.E-01	1.11E-06	1458	
	0.65	308785	0.12	0.12	153.5	1.84.E-01	8.99E-10	2011	
Ag Mesh	1.43	17483	0.94	0.91	4195.2	6.57E-01	3.77E-01	4	59
	2.86	8741	0.97	0.87	4294.8	3.39E-01	2.58E-01	2	
	0.43	29070	0.94	1.02	13951.5	2.19E+00	1.25E+00	2	
	1.00	33333	0.77	0.77	1350.2	7.70E-01	7.33E-02	25	60
CuNWs	51.00	–	0.93	0.63	100.0	1.82E-02	9.49E-03	–	61
	7.70	–	0.68	0.56	117.0	8.88E-02	2.91E-03	–	
	1.40	–	0.14	0.14	80.0	1.00E-01	2.07E-09	–	
Metal oxides									
ITO	12.3	–	0.97	0.76	998.6	7.93E-02	6.24E-02	–	28
	28.0	–	0.98	0.70	663.1	3.50E-02	2.92E-02	–	
	15.0	5556	0.93	0.71	1.3	6.23E-02	3.40E-02	4130	41
	253.0	1318	0.88	0.51	0.1	3.49E-03	1.13E-03	17054	62
	157.0	1274	0.86	0.52	0.1	5.46E-03	1.36E-03	10399	
	151.0	946	0.82	0.49	0.1	5.41E-03	8.83E-04	7624	
	140.0	794	0.79	0.48	0.1	5.63E-03	6.64E-04	6049	
	131.0	694	0.80	0.49	0.1	6.09E-03	8.03E-04	4915	
	90.0	855	0.88	0.56	0.2	9.78E-03	3.09E-03	3943	
	79.0	844	0.93	0.60	0.3	1.18E-02	6.09E-03	3315	
	50.0	1176	0.91	0.62	0.4	1.82E-02	7.75E-03	2960	
	27.7	3610	0.85	0.61	80.4	3.07E-02	7.11E-03	45	63
	18.8	5319	0.85	0.63	118.4	4.52E-02	1.05E-02	45	
	12.9	7752	0.85	0.66	172.6	6.59E-02	1.53E-02	45	
	14.7	6803	0.85	0.65	151.5	5.78E-02	1.34E-02	45	
	16.5	6061	0.85	0.64	135.0	5.15E-02	1.19E-02	45	
	22.0	4545	0.85	0.62	101.2	3.86E-02	8.95E-03	45	
	32.1	3115	0.85	0.60	69.4	2.65E-02	6.13E-03	45	
	15.7	6369	0.85	0.65	141.8	5.41E-02	1.25E-02	45	
	12.2	8197	0.85	0.66	182.5	6.97E-02	1.61E-02	45	
	13.9	7194	0.85	0.65	160.2	6.12E-02	1.42E-02	45	
	14.4	6944	0.85	0.65	154.6	5.90E-02	1.37E-02	45	
	16.0	6250	0.85	0.64	139.2	5.31E-02	1.23E-02	45	
	17.0	5882	0.85	0.64	131.0	5.00E-02	1.16E-02	45	
	18.6	5376	0.85	0.63	119.7	4.57E-02	1.06E-02	45	
	20.4	4902	0.85	0.63	109.2	4.17E-02	9.65E-03	45	
	22.3	4484	0.85	0.62	99.9	3.81E-02	8.83E-03	45	

Table S9 (continued). Various Figures of Merit (FOMs) of the reported transparent conducting film materials.

Materials	R_s ($\Omega \text{ sq.}^{-1}$)	σ_{DC} (S cm^{-1})	T (550 nm) (Decimal)	Contreras FOM ($\Omega^{-1/10}$)	Dressel–Grüner FOM (Ratio)	Fraser–Cook FOM (Ω^{-1})	Haacke FOM (Ω^{-1})	σ_{Op} (S cm^{-1})	Ref.
ITO (continued)	4600.0	27	0.92	0.40	1.0	2.01E-04	9.70E-05	27	64
	65.6	1017	0.83	0.55	29.2	1.26E-02	2.33E-03	35	
	38.8	955	0.80	0.55	40.6	2.06E-02	2.69E-03	24	
	34.6	826	0.79	0.56	44.7	2.30E-02	2.89E-03	18	
	10.6	4739	0.89	0.70	297.8	8.44E-02	2.96E-02	16	65
	19.5	2564	0.85	0.63	114.2	4.36E-02	1.01E-02	22	
	27.6	1812	0.85	0.61	80.7	3.08E-02	7.13E-03	22	
	6.7	7463	0.84	0.69	308.9	1.25E-01	2.61E-02	24	66
	26.2	1491	0.76	0.55	48.9	2.90E-02	2.45E-03	30	67
	76.0	526	0.89	0.58	41.3	1.17E-02	4.10E-03	13	68
	152.0	331	0.89	0.54	20.9	5.86E-03	2.07E-03	16	69
	23.0	2185	0.91	0.66	160.1	3.93E-02	1.60E-02	14	
	11.0	4568	0.92	0.72	387.0	8.34E-02	3.82E-02	12	
	21.0	952	0.90	0.66	165.9	4.29E-02	1.66E-02	6	70
	10.8	5544	0.88	0.69	264.4	8.15E-02	2.58E-02	21	71
	12.6	4669	0.88	0.68	226.7	6.98E-02	2.21E-02	21	
	11.0	5411	0.88	0.69	259.6	8.00E-02	2.53E-02	21	
	28.0	1429	0.89	0.64	112.2	3.18E-02	1.11E-02	13	72
ITO NPs	2500.0	–	0.98	0.45	7.4	3.93E-04	3.33E-04	–	73
	633.0	–	0.97	0.51	19.4	1.54E-03	1.20E-03	–	74
FTO	10.0	–	0.81	0.64	169.6	8.09E-02	1.20E-02	–	41
	13.8	2131	0.82	0.63	132.14	5.95E-02	1.01E-02	16	75
	7.5	2469	0.81	0.66	223.30	1.08E-01	1.58E-02	11	
	253	132	0.88	0.51	11.29	3.48E-03	1.10E-03	12	76

Denote: **PEDOT:PSS** (poly(3,4-ethylenedioxythiophene):poly(styrene sulfonate)), **PEDOT:PSS-EG** (PEDOT:PSS with ethylene glycol post-treatment), **PEDOT:OTf** (poly(3,4-ethylenedioxythiophene):trifluoromethanesulfonate), **PEDOT:Sulf** (poly(3,4-ethylenedioxythiophene):sulfate), **BBL** (poly(benzimidazobenzophenanthroline)), **PEI-doped** (poly(iminoethylene) doped), **N2200** (poly[(*N,N'*-bis(2-octyldodecyl)-naphthalene-1,4,5,8-bis(dicarboximide)-2,6-diyl)-*alt*-5,5'-(2,2'-bithiophene)]), **TDAE-doped** (tetrakis(dimethylamino)ethylene-doped), **PDTzTI** (poly[4,4',9,9'-tetra(4-decylthienyl)naphtho[1,2-*c*:5,6-*c'*]bisthiadiazole-3,10-diyl-*alt*-2,5-thiophenediyl]), **r-GO** (reduced graphene oxide), **AgNWs** (silver nanowires), **SWCNT** (single-walled carbon tube), **MWCNT** (multi-walled carbon nanotube), **CuNWs** (copper nanowires), **ITO** (indium tin oxide), **ITO NPs** (indium tin oxide nanoparticles), **FTO** (fluorine-doped tin oxide).

Note: Data in this table are reproduced from the original authors' reported values (text and tables). In cases where values were not explicitly stated, they were obtained by calculation from the authors' published data and/or digital extraction from the published figures, using the reported thicknesses and any additional parameters required.

Table S10. Literature survey of thermal conductivity for varied materials.

Materials		Thermal conductivity (W m ^{−1} K ^{−1})			σ_{DC} (S cm ^{−1})	S ($\mu\text{V K}^{-1}$)	PF ($\mu\text{W m}^{-1} \text{K}^{-2}$)	ZT	Method	SHC (J g ^{−1} K ^{−1})	ρ (g cm ^{−3})	Ref.
		In-plane ($\kappa_{x,y}$ or $\kappa_{\parallel}$)	Cross-plane (κ_z or $\kappa_{\perp}$)	Anisotropy ratio ($\kappa_{\parallel}/\kappa_{\perp}$)								
Polymers												
PDTzTI	Pristine	0.216 ± 0.016	—	—	9.00E-10	−638.00	3.66E-08	5.10E-11	3 ω	—	—	31
	TDAE-doped (8 h soak)	0.225 ± 0.013	—	—	4.6	−130.90	7.6	0.01	3 ω	—	—	
N2200 [P(NDI2OD-T2)]	Pristine (100 nm)	—	—	—	1.00E-10	−662.00	4.38E-09	—	3 ω	—	—	
	TDAE-doped (100 nm; 30 min soak)	—	—	—	7.00E-03	−133.55	0.06	—	3 ω	—	—	
	Pristine (300 nm)	0.43	—	—	—	—	—	—	Völklein 3 ω	—	—	78
	Pristine (345 ± 18) nm	0.27 ± 0.02	0.16 ± 0.01	1.69	—	—	—	—	3 ω	—	—	
P3HT	Pristine (300 ± 15) nm	0.35 ± 0.03	0.27 ± 0.02	1.30	—	—	—	—	3 ω	—	—	79
		—	0.17 ± 0.004	—	—	—	—	—	FA-FDTR	—	—	
PEDOT:PSS (PH 1000)	Pristine	0.52 ± 0.08	—	—	—	—	—	—	3 ω	—	—	80
	5 % vol. DMSO-mixed Pristine (180 nm)	0.42 ± 0.07	0.30 ± 0.07	1.40 ± 0.22	621.0	33.44	69.37	0.05	3 ω	—	—	
	5 % vol. EG-mixed Pristine (180 nm)	0.52 ± 0.07	0.32 ± 0.08	1.62 ± 0.35	638.2	27.31	47.72	0.03	3 ω	—	—	
	5 % vol. DMSO-mixed 150 – 200 min soak (180 nm)	0.31	0.2236	1.42	982.4	65.34	416.45	0.39	3 ω	—	—	
	5 % vol. EG-mixed 150 – 200 min soak (180 nm)	0.39	0.2405	1.60	797.34	62.61	311.69	0.24	3 ω	—	—	
	5 % vol. DMSO-mixed (1.4 μm)	0.42 ± 0.07	0.242 ± 0.002	1.73 ± 0.27	—	—	—	—	3 ω	—	—	
	5 % vol. EG-mixed (1.4 μm)	0.52 ± 0.11	0.227 ± 0.002	2.30 ± 0.47	—	—	—	—	3 ω	—	—	
BBL	Pristine	—	—	—	1.00E-05	—	—	—	—	—	—	30
	PEI doped	—	—	—	8	−482 to −65	11 to 12	—	—	—	—	
	Pristine	—	—	—	1.00E-07	—	—	—	—	—	—	81
	TDAE doped	—	—	—	1.7± 0.6	—	0.43	—	—	—	—	
<i>n</i> -PBDF	κ_x (in-plane) (*This work)	3.283 ± 0.009	—	35.05 to 36.66	—	—	—	—	—	—	—	This study
	κ_y (in-plane) (*This work)	3.415 ± 0.009	—		—	—	—	—	—	—	—	
	κ_z (cross-plane) (*This work)	—	0.093 ± 0.004		—	—	—	—	—	—	—	
		Dedoped w/ FeCl ₃	0.35	—	—	970 ± 26	−56.2 ± 1.6	306.1 ± 8.7	0.27	3 ω	—	—
PBFDO	TMQ-based (before dialysis)	4.04	—	—	—	−20.8 ± 2.6	16.4 ± 4.9	0.004	—	—	—	83
	TMQ-based (after dialysis)	6.04	—	—	—	−26.8 ± 0.6	80.4 ± 6.2	0.01	—	—	—	
	α -TQ (before dialysis)	0.48	—	—	1321 ± 67	−30.9 ± 0.8	100.4 ± 8.8	0.068	—	—	—	
	α -TQ (after dialysis)	6.84	—	—	1333 ± 60	−30.9 ± 0.7	111.2 ± 6.9	0.01	—	—	—	
PVDF	Bulk	0.21 ± 0.02	—	—	—	—	—	—	3 ω	—	—	78

Table S10 (continued). Literature survey of thermal conductivity for varied materials.

Materials		Thermal conductivity (W m ⁻¹ K ⁻¹)			σ_{DC} (S cm ⁻¹)	S (μ V K ⁻¹)	PF (μ W m ⁻¹ K ⁻²)	ZT	Method	SHC (J g ⁻¹ K ⁻¹)	ρ (g cm ⁻³)	Ref.
		In-plane ($\kappa_{x,y}$ or $\kappa_{ }$)	Cross-plane (κ_z or $\kappa_{\perp}$)	Anisotropy ratio ($\kappa_{ }/\kappa_{\perp}$)								
Poly(aniline) (PANI)	Bulk	0.47 $\pm$ 10 %	0.39 $\pm$ 18 %	–	–	–	–	–	–	1.576	1.113	84
	Bulk	0.59	–	–	–	–	–	–	–	–	–	85
	Thin films (110 nm)	0.1286	–	–	–	–	–	–	–	–	–	
	Thin films (20 to 110) nm	0.144	–	–	–	–	–	–	–	–	–	86
Poly(acetylene) (PA)	As cast / Oriented film	0.44 to 0.77; 14.01 (Oriented)	–	–	–	–	–	–	–	–	–	87
Poly(carbonate) (PC)	Bulk	0.19 to 0.24	–	–	–	–	–	–	–	1.10	1.19 to 1.22	88
PTFE (Teflon®)	Bulk	0.25 to 0.27	–	–	–	–	–	–	–	0.97	2.13 to 2.20	89,90
Poly(ethylene) (PE)	LDPE, bulk	0.29 to 0.34	–	–	–	–	–	–	–	2.03 to 2.09	0.91 to 0.93	89,91
	HDPE, bulk	0.44 to 0.53	–	–	–	–	–	–	–	1.69 to 1.76	0.95 to 0.98	89,92
Poly(imide) (PI)	–	0.10 to 0.20	–	–	–	–	–	–	–	1.09	1.42	89
Poly(styrene) (PS)	–	0.04 to 0.14	–	–	–	–	–	–	–	1.11	1.03 to 1.06	89,93
Poly(methyl methacrylate) (PMMA)	(285 nm $\pm$ 12) nm	0.16 to 0.25	0.19 $\pm$ 0.01	–	–	–	–	–	3 ω	–	–	78,89
Structured carbon materials												
Graphene	–	4481	–	–	–	–	–	–	–	–	–	94
	–	$\approx$ 1000 to 5000	–	–	–	–	–	–	–	–	–	95
	–	3541	–	–	–	–	–	–	–	0.7505	–	96
	–	4840 $\pm$ 440 to 5300 $\pm$ 480	–	–	–	–	–	–	–	–	–	97
r-GO	–	3.30 to 61.85	0.092 to 0.105	31.43 to 672.28	–	–	–	–	–	–	–	98
GO	–	2.9	0.186	–	–	–	–	–	–	–	–	
Graphite (HOPG)	–	1910	–	–	–	–	–	–	–	–	–	99
	–	1660	7.9	210	–	–	–	–	–	0.7178	2.2	100
	–	1850	–	–	–	–	–	–	–	–	–	101
Graphite	–	2195	2	1097.5	–	–	–	–	–	–	–	96
	–	1948.17	5.50	354.5	–	–	–	–	–	0.737	–	102
SWCNT	–	3360	–	–	–	–	–	–	–	–	–	103
	–	3290.679	–	–	–	–	–	–	–	–	–	102
	–	3500	–	–	–	–	–	–	–	–	–	104
MWCNT	–	3000	–	–	–	–	–	–	–	–	–	
	–	2963.178	–	–	–	–	–	–	–	–	–	102
Diamond	–	2.30E+03	–	0.53	–	–	–	–	–	–	–	

Table S10 (continued). Literature survey of thermal conductivity for varied materials.

Materials		Thermal conductivity (W m ⁻¹ K ⁻¹)			σ_{DC} (S cm ⁻¹)	S ($\mu\text{V K}^{-1}$)	PF ($\mu\text{W m}^{-1} \text{K}^{-2}$)	ZT	Method	SHC (J g ⁻¹ K ⁻¹)	ρ (g cm ⁻³)	Ref.
		In-plane ($\kappa_{x,y}$ or $\kappa_{\parallel}$)	Cross-plane (κ_z or $\kappa_{\perp}$)	Anisotropy ratio ($\kappa_{\parallel}/\kappa_{\perp}$)								
Inorganic materials												
Silicon	Single crystal	142.2	—	—	—	—	—	—	—	0.1813	2.32	105
		156	—	—	—	—	—	—	—	—	—	106
ITO	Thin films	5.1 to 10.6	—	—	—	—	—	—	—	—	—	107
Copper	Bulk	400	—	—	—	—	—	—	—	—	—	104
		401 to 403	—	—	—	—	—	—	—	0.385	—	108
Iron	Bulk	80.2	—	—	—	—	—	—	—	0.449	—	
Aluminum	Bulk	237	—	—	—	—	—	—	—	0.900	2.7	
Silver	Bulk	429	—	—	—	—	—	—	—	0.235	—	
Gold	Bulk	315	—	—	—	—	—	—	—	0.0129	—	109
Muscovite mica	Bulk	4.26 ± 0.41	—	—	—	—	—	—	3 ω	—	—	78
Soda-lime glass	Bulk	0.9 to 1.1	1.0 to 1.1	—	—	—	—	—	—	0.72	—	110,111
Air												
Air	—	0.025	—	—	—	—	—	—	—	—	—	97

Denote: **SHC** (specific heat capacity), **PF** (power factor), **p** (density), **3 ω** (3-omega method), **Völklein 3 ω** (Völklein 3-omega method), **FA-FDTR** (fiber-aligned frequency domain thermoreflectance), **PDTzTI** (poly[4,4',9,9'-tetra(4-decylthienyl)naphtho[1,2-c:5,6-c']bisthiadiazole-3,10-diyl-*alt*-2,5-thiophenediyl]), **N2200** (poly[(*N,N'*-bis(2-octyldodecyl)-naphthalene-1,4,5,8-bis(dicarboximide)-2,6-diyl)-*alt*-5,5'-(2,2'-bithiophene)]), **P3HT** (poly(3-hexylthiophene)), **PEDOT:PSS** (poly(3,4-ethylenedioxythiophene):poly(styrene sulfonate)), **BBL** (poly(benzimidazobenzophenanthroline)), **PVDF** (poly(vinylidene fluoride)), **r-GO** (reduced graphene oxide), **HOPG** (highly oriented pyrolytic graphite), **AgNWs** (silver nanowires), **SWCNT** (single-walled carbon nanotube), **MWCNT** (multi-walled carbon nanotube), **CuNWs** (copper nanowires), **ITO** (indium tin oxide), **PTFE** (poly(tetrafluoroethylene)).

Note: Data in this table are reproduced from the original authors' reported values (text and tables). In cases where values were not explicitly stated, they were obtained by calculation or digital extraction from the authors' published data using the reported thicknesses and any additional parameters required.

Table S11. Literature survey of Figure of Merit (FOM) for transparent Joule heating (TH) materials.

Materials	Max temp. (°C)	Range of T%	Estimated value of α (W m ⁻² K ⁻¹)	TH FOM ($\sigma_{\text{DC,B}}/\sigma_{\text{Op}})/\alpha$ (m ² K W ⁻¹)	$\sigma_{\text{DC,B}}/\sigma_{\text{Op}}$	Ref.	Note
AgNW	100	60 to 98	18	16.5	300	56	20 Ω sq. ⁻¹ , 90 %, $\sigma_{\text{DC,B}}/\sigma_{\text{Op}}$ =300
	150	35 to 92	59	5.4	316	57	11 Ω sq. ⁻¹ , 90 %, $\sigma_{\text{DC,B}}/\sigma_{\text{Op}}$ =316
	≈60	57 to 98.5	40	1.75	70	14	
Graphene	120	90 to 92	15	3.42	51	12	68 Ω sq. ⁻¹ , 90 %, $\sigma_{\text{DC,B}}/\sigma_{\text{Op}}$ =51
Graphene (p-doped)	100	89	27	2.69	73	15	43 Ω sq. ⁻¹ , 89 %, $\sigma_{\text{DC,B}}/\sigma_{\text{Op}}$ =73
Graphene/AgNW	225	78 to 82	44	1.3	57	113	30 Ω sq. ⁻¹ , 81 %, $\sigma_{\text{DC,B}}/\sigma_{\text{Op}}$ =57
CNT/AgNW	110	≈93	11	10	100	112	$\sigma_{\text{DC,B}}/\sigma_{\text{Op}}$ ≈100
<i>n</i> -PBDF (Standard SST, *This work*)	≈183	69 to 98	21.9	0.87	19.1	–	$\sigma_{\text{DC,B}}/\sigma_{\text{Op}}$ =19.08; Evaluated using standard constant-resistance SST model for direct literature comparison.
<i>n</i> -PBDF (TCR-aware, *This work*)	≈183	69 to 98	20.9	0.91	19.1	–	Evaluated using our TCR-aware transient model.
PEDOT:PSS	45	90	35	0.28571	10	2	$\sigma_{\text{DC,B}}/\sigma_{\text{Op}}$ =10
CNT	80	60 to 80	39	0.038	1.48	52	1225 Ω sq. ⁻¹ , 82 %, $\sigma_{\text{DC,B}}/\sigma_{\text{Op}}$ =1.48
	200	65 to 95	123	0.029	3.6	45	356 Ω sq. ⁻¹ , 76 %, $\sigma_{\text{DC,B}}/\sigma_{\text{Op}}$ =3.6
	47	94 to 98	95	0.0056	0.53	46	23k Ω sq. ⁻¹ , 97 %, $\sigma_{\text{DC,B}}/\sigma_{\text{Op}}$ =0.53
r-GO	200	34 to 81	97	0.003	0.28	40	6080 Ω sq. ⁻¹ , 81 %, $\sigma_{\text{DC,B}}/\sigma_{\text{Op}}$ =0.28

Denote: **AgNWs** (silver nanowires), **CNT** (carbon nanotube), **PEDOT:PSS** (poly(3,4-ethylenedioxythiophene):poly(styrene sulfonate)), **r-GO** (reduced graphene oxide).

Note: Data in this table are reproduced from the original authors’ reported values (text and tables). In cases where values were not explicitly stated, they were obtained by calculation or digital extraction from the authors’ published data using the reported thicknesses and any additional parameters required. Additionally, the $\sigma_{\text{DC,B}}/\sigma_{\text{Op}}$ ratio of 19.1 for *n*-PBDF represents the peak single-film value achieved (at $d \approx 15.48$ nm, see **Table S9**) to evaluate the maximum TH FOM, whereas the 15.03 ± 0.31 value discussed in the **Main Text** represents the bulk-fitted average. The TH FOM calculated using the standard constant-resistance model is 0.87 m² K W⁻¹; the value of 0.91 m² K W⁻¹ reported here represents the more rigorous TCR-aware extraction.

Table S12. Side-by-side performance metrics for *n*-PBDF and PEDOT:PSS heaters. Performance is compared under two relevant baselines: matched film thickness (≈ 71 nm) and matched optical transmittance ($\approx 90\%$ VLT). The transmittance-matched data corresponds to the radar chart benchmark comparison shown in **Figure 1b**, while the thickness-matched data is provided for benchmarking added performance potential (see **Figure S.44**).

Property	Matched thickness (≈ 71 nm)		Matched transmittance ($\approx 90\%$ VLT)	
	<i>n</i> -PBDF	PEDOT:PSS	<i>n</i> -PBDF	PEDOT:PSS
Color neutrality (chroma ⁻¹)	0.99	1.30	1.47	0.60
Optical clarity (100% – haze)	99.70	99.58	99.74	99.01
Max. steady state temp. (°C)	182.96	38.79	91.8	80.64
Max. heating rate (°C s ⁻¹)	2.48	0.20	0.89	1.04
Max. areal power density (mW cm ⁻²)	516.35	29.77	233.32	145.74
Electrical conductivity (S cm ⁻¹)	2174	206	2770	321

Note: "Color neutrality" was calculated as the reciprocal of the measured chroma value (1/chroma). Smaller values of chroma correspond to enhanced color neutrality, as do larger values of 1/chroma. Moreover, "optical clarity" was calculated as Optical clarity = 100 – haze (%), for comparative visualization purposes only and does not represent a formal standardized clarity measurement (such as **ASTM D1003/D1746**).

Table S13. Comparison of steady-state temperature (SST) for the two most comparable (3 × 3) cm² PEDOT:PSS-based heaters fabricated and measured in this work to be used as benchmarks, and the values reported by Gueye et al.² for a comparably-sized (2.5 × 2.5) cm² heater. Absolute and percent differences are reported relative to the values from their work.

Applied voltage (V)	This work: no EG SST (°C)	Gueye et al.: no EG SST (°C)	Δ SST (°C)	Abs. % diff.	This work: EG-treated SST (°C)	Gueye et al.: EG-treated SST (°C)	Δ SST (°C)	Abs. % diff.
4	26.67	29.85	−3.19	10.67	31.18	43.79	−12.61	28.80
6	29.04	33.75	−4.71	13.95	39.37	58.28	−18.91	32.45
8	33.38	38.63	−5.25	13.58	50.23	74.89	−24.66	32.93
10	39.75	44.48	−4.73	10.63	63.12	93.88	−30.76	32.77
12	47.74	51.31	−3.57	6.96	77.42	112.64	−35.22	31.27
Comparison pair	This work film thickness (nm)	Gueye et al. film thickness (nm)	Δ Film thickness (nm)	Abs. % diff.	Note: Absolute percent difference was calculated as: ΔSST /SST _{Gueye} · 100.			
No EG Treatment	164	156	8	5.13				
EG Treated	110	108	2	1.85				

Supporting Information References

- (1) Ke, Z.; Abtahi, A.; Hwang, J.; Chen, K.; Chaudhary, J.; Song, I.; Perera, K.; You, L.; Baustert, K. N.; Graham, K. R.; Mei, J. Highly Conductive and Solution-Processable n-Doped Transparent Organic Conductor. *J. Am. Chem. Soc.* **2023**, *145* (6), 3706–3715. <https://doi.org/10.1021/jacs.2c13051>.
- (2) Gueye, M. N.; Carella, A.; Demadrille, R.; Simonato, J.-P. All-Polymeric Flexible Transparent Heaters. *ACS Appl. Mater. Interfaces* **2017**, *9* (32), 27250–27256. <https://doi.org/10.1021/acsami.7b08578>.
- (3) Lee, W.-J.; Mehra, P.; Thurston, J. R.; Tian, Y.; Liu, X.; Samal, S.; You, L.; Song, I.; Ruan, X.; Toney, M. F.; Mei, J. Robust Fast-Switching Black Electrochromic Windows Based on Solution-Processed n-Doped Transparent Organic Conductor. *Nat. Commun.* **2026**, *17* (1), 575. <https://doi.org/10.1038/s41467-025-67271-w>.
- (4) Ilavsky, J. Nika: Software for Two-Dimensional Data Reduction. *J Appl Cryst* **2012**, *45* (2), 324–328. <https://doi.org/10.1107/S0021889812004037>.
- (5) Smilgies, D.-M. Scherrer Grain-Size Analysis Adapted to Grazing-Incidence Scattering with Area Detectors. *J. Appl. Cryst.* **2009**, *42* (6), 1030–1034. <https://doi.org/10.1107/S0021889809040126>.
- (6) Merzlyakov, M.; Schick, C. Step Response Analysis in DSC — a Fast Way to Generate Heat Capacity Spectra. *Thermochimica Acta* **2001**, *380* (1), 5–12. [https://doi.org/10.1016/S0040-6031\(01\)00631-1](https://doi.org/10.1016/S0040-6031(01)00631-1).
- (7) Höhne, G. W. H.; Merzlyakov, M.; Schick, C. Calibration of Magnitude and Phase Angle of TMDSC: Part1: Basic Considerations. *Thermochimica Acta* **2002**, *391* (1), 51–67. [https://doi.org/10.1016/S0040-6031\(02\)00163-6](https://doi.org/10.1016/S0040-6031(02)00163-6).
- (8) Gaitonde, A.; Nimmagadda, A.; Marconnet, A. Measurement of Interfacial Thermal Conductance in Lithium Ion Batteries. *Journal of Power Sources* **2017**, *343*, 431–436. <https://doi.org/10.1016/j.jpowsour.2017.01.019>.
- (9) Gaitonde, A. U.; Candadai, A. A.; Weibel, J. A.; Marconnet, A. M. A Laser-Based Ångstrom Method for in-Plane Thermal Characterization of Isotropic and Anisotropic Materials Using Infrared Imaging. *Review of Scientific Instruments* **2023**, *94* (7), 074904. <https://doi.org/10.1063/5.0149659>.
- (10) Gaitonde, A. U.; Candadai, A. A.; Weibel, J. A.; Marconnet, A. M. Systems and Methods for In-Plane Characterization of Isotropic and Anisotropic Materials. US20250130187A1, April 24, 2025. <https://patents.google.com/patent/US20250130187A1/en> (accessed 2025-10-26).
- (11) Gaitonde, A. U.; Weibel, J. A.; Marconnet, A. M. Range and Accuracy of In-Plane Anisotropic Thermal Conductivity Measurement Using the Laser-Based Ångstrom Method. *Rev. Sci. Instrum.* **2025**, *96* (1), 014903. <https://doi.org/10.1063/5.0238285>.
- (12) Bae, J. J.; Lim, S. C.; Han, G. H.; Jo, Y. W.; Doung, D. L.; Kim, E. S.; Chae, S. J.; Huy, T. Q.; Van Luan, N.; Lee, Y. H. Heat Dissipation of Transparent Graphene Defoggers. *Adv. Funct. Mater.* **2012**, *22* (22), 4819–4826. <https://doi.org/10.1002/adfm.201201155>.
- (13) Sorel, S.; Bellet, D.; Coleman, J. N. Relationship between Material Properties and Transparent Heater Performance for Both Bulk-like and Percolative Nanostructured Networks. *ACS Nano* **2014**, *8* (5), 4805–4814. <https://doi.org/10.1021/nn500692d>.
- (14) Ji, S.; He, W.; Wang, K.; Ran, Y.; Ye, C. Thermal Response of Transparent Silver Nanowire/PEDOT:PSS Film Heaters. *Small* **2014**, *10* (23), 4951–4960. <https://doi.org/10.1002/sml.201401690>.

- (15) Kang, J.; Kim, H.; Kim, K. S.; Lee, S.-K.; Bae, S.; Ahn, J.-H.; Kim, Y.-J.; Choi, J.-B.; Hong, B. H. High-Performance Graphene-Based Transparent Flexible Heaters. *Nano Lett.* **2011**, *11* (12), 5154–5158. <https://doi.org/10.1021/nl202311v>.
- (16) Anand, A.; Islam, M. M.; Meitzner, R.; Schubert, U. S.; Hoppe, H. Introduction of a Novel Figure of Merit for the Assessment of Transparent Conductive Electrodes in Photovoltaics: Exact and Approximate Form. *Advanced Energy Materials* **2021**, *11* (26), 2100875. <https://doi.org/10.1002/aenm.202100875>.
- (17) Jacobs, D. A.; Catchpole, K. R.; Beck, F. J.; White, T. P. A Re-Evaluation of Transparent Conductor Requirements for Thin-Film Solar Cells. *J. Mater. Chem. A* **2016**, *4* (12), 4490–4496. <https://doi.org/10.1039/C6TA01670G>.
- (18) Fraser, D. B.; Cook, H. D. Highly Conductive, Transparent Films of Sputtered $\text{In}_{2-x}\text{Sn}_x\text{O}_{3-y}$. *J. Electrochem. Soc.* **1972**, *119* (10), 1368. <https://doi.org/10.1149/1.2403999>.
- (19) De, S.; King, P. J.; Lyons, P. E.; Khan, U.; Coleman, J. N. Size Effects and the Problem with Percolation in Nanostructured Transparent Conductors. *ACS Nano* **2010**, *4* (12), 7064–7072. <https://doi.org/10.1021/nn1025803>.
- (20) Haacke, G. New Figure of Merit for Transparent Conductors. *J. Appl. Phys.* **1976**, *47* (9), 4086–4089. <https://doi.org/10.1063/1.323240>.
- (21) Cisneros-Contreras, I. R.; Muñoz-Rosas, A. L.; Rodríguez-Gómez, A. Resolution Improvement in Haacke's Figure of Merit for Transparent Conductive Films. *Results Phys.* **2019**, *15*, 102695. <https://doi.org/10.1016/j.rinp.2019.102695>.
- (22) De, S.; Coleman, J. N. The Effects of Percolation in Nanostructured Transparent Conductors. *MRS Bull.* **2011**, *36* (10), 774–781. <https://doi.org/10.1557/mrs.2011.236>.
- (23) Hu, L.; Hecht, D. S.; Grüner, G. Percolation in Transparent and Conducting Carbon Nanotube Networks. *Nano Lett.* **2004**, *4* (12), 2513–2517. <https://doi.org/10.1021/nl048435y>.
- (24) Stauffer, D.; Aharony, A. *Introduction To Percolation Theory: Second Edition*, 2nd ed.; Taylor & Francis: London, 2017. <https://doi.org/10.1201/9781315274386>.
- (25) Dressel, M.; Grüner, G. *Electrodynamics of Solids: Optical Properties of Electrons in Matter*; Cambridge University Press: Cambridge, U.K., **2002**.
- (26) Gordon, R. G. Criteria for Choosing Transparent Conductors. *MRS Bull.* **2000**, *25* (8), 52–57. <https://doi.org/10.1557/mrs2000.151>.
- (27) De, S.; Coleman, J. N. Are There Fundamental Limitations on the Sheet Resistance and Transmittance of Thin Graphene Films? *ACS Nano* **2010**, *4* (5), 2713–2720. <https://doi.org/10.1021/nn100343f>.
- (28) De, S.; Higgins, T. M.; Lyons, P. E.; Doherty, E. M.; Nirmalraj, P. N.; Blau, W. J.; Boland, J. J.; Coleman, J. N. Silver Nanowire Networks as Flexible, Transparent, Conducting Films: Extremely High DC to Optical Conductivity Ratios. *ACS Nano* **2009**, *3* (7), 1767–1774. <https://doi.org/10.1021/nn900348c>.
- (29) Ke, Z.; Chaudhary, J.; Flagg, L. Q.; Baustert, K. N.; Yusuf, A. O.; Liu, G.; You, L.; Graham, K. R.; DeLongchamp, D. M.; Mei, J. Controlled Dedoping and Redoping of N-Doped Poly(Benzodifurandione) (n-PBDF). *Advanced Functional Materials* **2024**, *34* (33), 2400255. <https://doi.org/10.1002/adfm.202400255>.
- (30) Yang, C.-Y.; Stoeckel, M.-A.; Ruoko, T.-P.; Wu, H.-Y.; Liu, X.; Kolhe, N. B.; Wu, Z.; Puttisong, Y.; Musumeci, C.; Massetti, M.; Sun, H.; Xu, K.; Tu, D.; Chen, W. M.; Woo, H. Y.; Fahlman, M.; Jenekhe, S. A.; Berggren, M.; Fabiano, S. A High-Conductivity n-Type Polymeric Ink for Printed Electronics. *Nat. Commun.* **2021**, *12* (1), 2354. <https://doi.org/10.1038/s41467-021-22528-y>.

- (31) Liu, J.; Shi, Y.; Dong, J.; Nugraha, M. I.; Qiu, X.; Su, M.; Chiechi, R. C.; Baran, D.; Portale, G.; Guo, X.; Koster, L. J. A. Overcoming Coulomb Interaction Improves Free-Charge Generation and Thermoelectric Properties for n-Doped Conjugated Polymers. *ACS Energy Lett.* **2019**, *4* (7), 1556–1564. <https://doi.org/10.1021/acsenenergylett.9b00977>.
- (32) Cai, W.; Zhu, Y.; Li, X.; Piner, R. D.; Ruoff, R. S. Large Area Few-Layer Graphene/Graphite Films as Transparent Thin Conducting Electrodes. *Appl. Phys. Lett.* **2009**, *95* (12), 123115. <https://doi.org/10.1063/1.3220807>.
- (33) Wang, Y.; Chen, X.; Zhong, Y.; Zhu, F.; Loh, K. P. Large Area, Continuous, Few-Layered Graphene as Anodes in Organic Photovoltaic Devices. *Appl. Phys. Lett.* **2009**, *95* (6), 063302. <https://doi.org/10.1063/1.3204698>.
- (34) Reina, A.; Jia, X.; Ho, J.; Nezich, D.; Son, H.; Bulovic, V.; Dresselhaus, M. S.; Kong, J. Large Area, Few-Layer Graphene Films on Arbitrary Substrates by Chemical Vapor Deposition. *Nano Lett.* **2009**, *9* (1), 30–35. <https://doi.org/10.1021/nl801827v>.
- (35) Güneş, F.; Han, G. H.; Kim, K. K.; Kim, E. S.; Chae, S. J.; Park, M. H.; Jeong, H.-K.; Lim, S. C.; Lee, Y. H. Large-Area Graphene-Based Flexible Transparent Conducting Films. *Nano* **2009**, *04* (02), 83–90. <https://doi.org/10.1142/S1793292009001538>.
- (36) Sun, J.; Chen, Z.; Yuan, L.; Chen, Y.; Ning, J.; Liu, S.; Ma, D.; Song, X.; Priyadarshi, M. K.; Bachmatiuk, A.; Rummeli, M. H.; Ma, T.; Zhi, L.; Huang, L.; Zhang, Y.; Liu, Z. Direct Chemical-Vapor-Deposition-Fabricated, Large-Scale Graphene Glass with High Carrier Mobility and Uniformity for Touch Panel Applications. *ACS Nano* **2016**, *10* (12), 11136–11144. <https://doi.org/10.1021/acsnano.6b06066>.
- (37) Sun, J.; Chen, Y.; Priyadarshi, M. K.; Chen, Z.; Bachmatiuk, A.; Zou, Z.; Chen, Z.; Song, X.; Gao, Y.; Rummeli, M. H.; Zhang, Y.; Liu, Z. Direct Chemical Vapor Deposition-Derived Graphene Glasses Targeting Wide Ranged Applications. *Nano Lett.* **2015**, *15* (9), 5846–5854. <https://doi.org/10.1021/acs.nanolett.5b01936>.
- (38) Lee, B.-J.; Jeong, G.-H. Fabrication of Defrost Films Using Graphenes Grown by Chemical Vapor Deposition. *Curr. Appl. Phys.* **2012**, *12*, S113–S117. <https://doi.org/10.1016/j.cap.2012.05.012>.
- (39) Liang, Y.; Frisch, J.; Zhi, L.; Norouzi-Arasi, H.; Feng, X.; Rabe, J. P.; Koch, N.; Müllen, K. Transparent, Highly Conductive Graphene Electrodes from Acetylene-Assisted Thermolysis of Graphite Oxide Sheets and Nanographene Molecules. *Nanotechnology* **2009**, *20* (43), 434007. <https://doi.org/10.1088/0957-4484/20/43/434007>.
- (40) Sui, D.; Huang, Y.; Huang, L.; Liang, J.; Ma, Y.; Chen, Y. Flexible and Transparent Electrothermal Film Heaters Based on Graphene Materials. *Small* **2011**, *7* (22), 3186–3192. <https://doi.org/10.1002/sml.201101305>.
- (41) Wang, X.; Zhi, L.; Müllen, K. Transparent, Conductive Graphene Electrodes for Dye-Sensitized Solar Cells. *Nano Lett.* **2008**, *8* (1), 323–327. <https://doi.org/10.1021/nl072838r>.
- (42) Pham, V. H.; Cuong, T. V.; Hur, S. H.; Shin, E. W.; Kim, J. S.; Chung, J. S.; Kim, E. J. Fast and Simple Fabrication of a Large Transparent Chemically-Converted Graphene Film by Spray-Coating. *Carbon* **2010**, *48* (7), 1945–1951. <https://doi.org/10.1016/j.carbon.2010.01.062>.
- (43) Becerril, H. A.; Mao, J.; Liu, Z.; Stoltenberg, R. M.; Bao, Z.; Chen, Y. Evaluation of Solution-Processed Reduced Graphene Oxide Films as Transparent Conductors. *ACS Nano* **2008**, *2* (3), 463–470. <https://doi.org/10.1021/nn700375n>.

- (44) Wang, J.; Fang, Z.; Zhu, H.; Gao, B.; Garner, S.; Cimo, P.; Barcikowski, Z.; Mignerey, A.; Hu, L. Flexible, Transparent, and Conductive Defrosting Glass. *Thin Solid Films* **2014**, *556*, 13–17. <https://doi.org/10.1016/j.tsf.2013.12.060>.
- (45) Yoon, Y.-H.; Song, J.-W.; Kim, D.; Kim, J.; Park, J.-K.; Oh, S.-K.; Han, C.-S. Transparent Film Heater Using Single-Walled Carbon Nanotubes. *Adv. Mater.* **2007**, *19* (23), 4284–4287. <https://doi.org/10.1002/adma.200701173>.
- (46) Kang, T. J.; Kim, T.; Seo, S. M.; Park, Y. J.; Kim, Y. H. Thickness-Dependent Thermal Resistance of a Transparent Glass Heater with a Single-Walled Carbon Nanotube Coating. *Carbon* **2011**, *49* (4), 1087–1093. <https://doi.org/10.1016/j.carbon.2010.11.012>.
- (47) Wu, Z.; Chen, Z.; Du, X.; Logan, J. M.; Sippel, J.; Nikolou, M.; Kamaras, K.; Reynolds, J. R.; Tanner, D. B.; Hebard, A. F.; Rinzler, A. G. Transparent, Conductive Carbon Nanotube Films. *Science* **2004**, *305* (5688), 1273–1276. <https://doi.org/10.1126/science.1101243>.
- (48) Zhang, D.; Ryu, K.; Liu, X.; Polikarpov, E.; Ly, J.; Tompson, M. E.; Zhou, C. Transparent, Conductive, and Flexible Carbon Nanotube Films and Their Application in Organic Light-Emitting Diodes. *Nano Lett.* **2006**, *6* (9), 1880–1886. <https://doi.org/10.1021/nl0608543>.
- (49) Geng, H.-Z.; Lee, D. S.; Kim, K. K.; Kim, S. J.; Bae, J. J.; Lee, Y. H. Effect of Carbon Nanotube Types in Fabricating Flexible Transparent Conducting Films. *J. Korean Phys. Soc.* **2008**, *53* (9), 979–985. <https://doi.org/10.3938/jkps.53.979>.
- (50) Rowell, M. W.; Topinka, M. A.; McGehee, M. D.; Prall, H.-J.; Dennler, G.; Sariciftci, N. S.; Hu, L.; Gruner, G. Organic Solar Cells with Carbon Nanotube Network Electrodes. *Appl. Phys. Lett.* **2006**, *88* (23), 233506. <https://doi.org/10.1063/1.2209887>.
- (51) Geng, H.-Z.; Kim, K. K.; So, K. P.; Lee, Y. S.; Chang, Y.; Lee, Y. H. Effect of Acid Treatment on Carbon Nanotube-Based Flexible Transparent Conducting Films. *J. Am. Chem. Soc.* **2007**, *129* (25), 7758–7759. <https://doi.org/10.1021/ja0722224>.
- (52) Jang, H.-S.; Jeon, S. K.; Nahm, S. H. The Manufacture of a Transparent Film Heater by Spinning Multi-Walled Carbon Nanotubes. *Carbon* **2011**, *49* (1), 111–116. <https://doi.org/10.1016/j.carbon.2010.08.049>.
- (53) Zhang, M.; Fang, S.; Zakhidov, A. A.; Lee, S. B.; Aliev, A. E.; Williams, C. D.; Atkinson, K. R.; Baughman, R. H. Strong, Transparent, Multifunctional, Carbon Nanotube Sheets. *Science* **2005**, *309* (5738), 1215–1219. <https://doi.org/10.1126/science.1115311>.
- (54) Jung, D.; Kim, D.; Lee, K. H.; Overzet, L. J.; Lee, G. S. Transparent Film Heaters Using Multi-Walled Carbon Nanotube Sheets. *Sens. Actuators, A* **2013**, *199*, 176–180. <https://doi.org/10.1016/j.sna.2013.05.024>.
- (55) Celle, C.; Mayousse, C.; Moreau, E.; Basti, H.; Carella, A.; Simonato, J.-P. Highly Flexible Transparent Film Heaters Based on Random Networks of Silver Nanowires. *Nano Res.* **2012**, *5* (6), 427–433. <https://doi.org/10.1007/s12274-012-0225-2>.
- (56) Kim, T.; Kim, Y. W.; Lee, H. S.; Kim, H.; Yang, W. S.; Suh, K. S. Uniformly Interconnected Silver-Nanowire Networks for Transparent Film Heaters. *Adv. Funct. Mater.* **2013**, *23* (10), 1250–1255. <https://doi.org/10.1002/adfm.201202013>.
- (57) Wang, S.; Zhang, X.; Zhao, W. Flexible, Transparent, and Conductive Film Based on Random Networks of Ag Nanowires. *J. Nanomater.* **2013**, *2013* (1), 456098. <https://doi.org/10.1155/2013/456098>.
- (58) Scardaci, V.; Coull, R.; Lyons, P. E.; Rickard, D.; Coleman, J. N. Spray Deposition of Highly Transparent, Low-Resistance Networks of Silver Nanowires over Large Areas. *Small* **2011**, *7* (18), 2621–2628. <https://doi.org/10.1002/smll.201100647>.

- (59) Yu, S.; Han, H. J.; Kim, J. M.; Yim, S.; Sim, D. M.; Lim, H.; Lee, J. H.; Park, W. I.; Park, J. H.; Kim, K. H.; Jung, Y. S. Area-Selective Lift-Off Mechanism Based on Dual-Triggered Interfacial Adhesion Switching: Highly Facile Fabrication of Flexible Nanomesh Electrode. *ACS Nano* **2017**, *11* (4), 3506–3516. <https://doi.org/10.1021/acsnano.7b00229>.
- (60) Kiruthika, S.; Gupta, R.; Kulkarni, G. U. Large Area Defrosting Windows Based on Electrothermal Heating of Highly Conducting and Transmitting Ag Wire Mesh. *RSC Adv.* **2014**, *4* (91), 49745–49751. <https://doi.org/10.1039/C4RA06811D>.
- (61) Guo, H.; Lin, N.; Chen, Y.; Wang, Z.; Xie, Q.; Zheng, T.; Gao, N.; Li, S.; Kang, J.; Cai, D.; Peng, D.-L. Copper Nanowires as Fully Transparent Conductive Electrodes. *Sci. Rep.* **2013**, *3* (1), 2323. <https://doi.org/10.1038/srep02323>.
- (62) Kim, M.-J. A Study on Optimal Indium Tin Oxide Thickness as Transparent Conductive Electrodes for Near-Ultraviolet Light-Emitting Diodes. *Materials* **2023**, *16* (13), 4718. <https://doi.org/10.3390/ma16134718>.
- (63) Maniyara, R. A.; Graham, C.; Paulillo, B.; Bi, Y.; Chen, Y.; Herranz, G.; Baker, D. E.; Mazumder, P.; Konstantatos, G.; Pruneri, V. Highly Transparent and Conductive ITO Substrates for near Infrared Applications. *APL Mater.* **2021**, *9* (2), 021121. <https://doi.org/10.1063/5.0040864>.
- (64) Benoy, M. D.; Mohammed, E. M.; Suresh Babu, M.; Binu, P. J.; Pradeep, B. Thickness Dependence of the Properties of Indium Tin Oxide (ITO) FILMS Prepared by Activated Reactive Evaporation. *Braz. J. Phys.* **2009**, *39*, 629–632. <https://doi.org/10.1590/S0103-97332009000600003>.
- (65) Inritsapong, Y.; Chindaudom, P.; Nuntawong, N.; Patthanasetthakul, V.; Horphathum, M.; Eiamchai, P.; Pokaipisit, A.; Limsuwan, P. Post-Annealing Effects on the Structural, Optical and Electrical Properties of ITO Films Studied by Spectroscopic Ellipsometry. *Mod. Phys. Lett. B* **2010**, *24* (06), 595–605. <https://doi.org/10.1142/S0217984910022652>.
- (66) Pokaipisit, A.; Horprathum, M.; Limsuwan, P. Influence of Annealing Temperature on the Properties of Nanostructure ITO Thin Films Prepared by Ion-Assisted Electron Beam Evaporation. *Adv. Mater. Res.* **2008**, *55–57*, 373–376. <https://doi.org/10.4028/www.scientific.net/AMR.55-57.373>.
- (67) Koseoglu, H.; Turkoglu, F.; Kurt, M.; Yaman, M. D.; Akca, F. G.; Aygun, G.; Ozyuzer, L. Improvement of Optical and Electrical Properties of ITO Thin Films by Electro-Annealing. *Vacuum* **2015**, *120*, 8–13. <https://doi.org/10.1016/j.vacuum.2015.06.027>.
- (68) Sathiaraj, T. S. Effect of Annealing on the Structural, Optical and Electrical Properties of ITO Films by RF Sputtering under Low Vacuum Level. *Microelectron. J.* **2008**, *39* (12), 1444–1451. <https://doi.org/10.1016/j.mejo.2008.06.081>.
- (69) Khusayfan, N. M.; El-Nahass, M. M. Study of Structure and Electro-Optical Characteristics of Indium Tin Oxide Thin Films. *Adv. Condens. Matter Phys.* **2013**, *2013* (1), 408182. <https://doi.org/10.1155/2013/408182>.
- (70) Zhang, J.; Chia, A. C. E.; LaPierre, R. R. Low Resistance Indium Tin Oxide Contact to N-GaAs Nanowires. *Semicond. Sci. Technol.* **2014**, *29* (5), 054002. <https://doi.org/10.1088/0268-1242/29/5/054002>.
- (71) Askari, H.; Fallah, H.; Askari, M.; Mohammadiyeh, M. C. Electrical and Optical Properties of ITO Thin Films Prepared by DC Magnetron Sputtering for Low-Emitting Coatings. *arXiv preprint arXiv:1409.5293* **2014**.
- (72) Wang, L.; Yang, Y.; Marks, T. J.; Liu, Z.; Ho, S.-T. Near-Infrared Transparent Electrodes for Precision Teng–Man Electro-Optic Measurements: In₂O₃ Thin-Film Electrodes with

- Tunable near-Infrared Transparency. *Appl. Phys. Lett.* **2005**, *87* (16), 161107. <https://doi.org/10.1063/1.2089184>.
- (73) Im, K.; Cho, K.; Kwak, K.; Kim, J.; Kim, S. Flexible Transparent Heaters with Heating Films Made of Indium Tin Oxide Nanoparticles. *J. Nanosci. Nanotechnol.* **2013**, *13* (5), 3519–3521. <https://doi.org/10.1166/jnn.2013.7322>.
- (74) Im, K.; Cho, K.; Kim, J.; Kim, S. Transparent Heaters Based on Solution-Processed Indium Tin Oxide Nanoparticles. *Thin Solid Films* **2010**, *518* (14), 3960–3963. <https://doi.org/10.1016/j.tsf.2009.10.164>.
- (75) Kwaśnicki, P.; Gronba-Chyła, A.; Generowicz, A.; Ciula, J.; Makara, A.; Kowalski, Z. Characterization of the TCO Layer on a Glass Surface for PV IIrd and IIIrd Generation Applications. *Energies* **2024**, *17* (13), 3122. <https://doi.org/10.3390/en17133122>.
- (76) Hudaya, C.; Park, J. H.; Choi, W.; Lee, J. K. Characteristics of Fluorine-Doped Tin Oxide as a Transparent Heater on PET Prepared by ECR-MOCVD. *ECS Trans.* **2013**, *53* (4), 161–166. <https://doi.org/10.1149/05304.0161ecst>.
- (77) Selezneva, E.; Di Pietro, R.; Jiao, X.; McNeill, C. R.; Sirringhaus, H. Investigation of the Effect of Microstructural Changes on Thermal Transport in Semicrystalline Polymer Semiconductors. *APL Mater.* **2019**, *7* (8), 081118. <https://doi.org/10.1063/1.5111023>.
- (78) Kommandur, S.; Yee, S. A Suspended 3-Omega Technique to Measure the Anisotropic Thermal Conductivity of Semiconducting Polymers. *Rev. Sci. Instrum.* **2018**, *89* (11), 114905. <https://doi.org/10.1063/1.5045077>.
- (79) Malen, J. A.; Baheti, K.; Tong, T.; Zhao, Y.; Hudgings, J. A.; Majumdar, A. Optical Measurement of Thermal Conductivity Using Fiber Aligned Frequency Domain Thermoreflectance. *J. Heat Transfer* **2011**, *133* (081601). <https://doi.org/10.1115/1.4003545>.
- (80) Kim, G.-H.; Shao, L.; Zhang, K.; Pipe, K. P. Engineered Doping of Organic Semiconductors for Enhanced Thermoelectric Efficiency. *Nat. Mater.* **2013**, *12* (8), 719–723. <https://doi.org/10.1038/nmat3635>.
- (81) Wang, S.; Ruoko, T.-P.; Wang, G.; Riera-Galindo, S.; Hultmark, S.; Puttisong, Y.; Moro, F.; Yan, H.; Chen, W. M.; Berggren, M.; Müller, C.; Fabiano, S. Sequential Doping of Ladder-Type Conjugated Polymers for Thermally Stable n-Type Organic Conductors. *ACS Appl. Mater. Interfaces* **2020**, *12* (47), 53003–53011. <https://doi.org/10.1021/acsami.0c16254>.
- (82) Chen, Z.; Wen, Y.; Hu, Y.; Wu, C.; Xu, C.; Zhang, T.; Ni, Q.; Shin, S.; Sun, K.; Ouyang, J. An N-Type Polymer with High-Performance Thermoelectric Properties by Solvent-Mediated Oxidation. *Adv. Energy Mater.* **2025**, e02996. <https://doi.org/10.1002/aenm.202502996>.
- (83) Huang, J.-D.; Li, Q.; Wang, Q.; Liu, T.; Jeong, S. Y.; Paleti, S. H. K.; van der Pol, T. P. A.; Xu, K.; Wu, H.-Y.; Pinchin, N.; Stoeckel, M.-A.; Jin, W.; Perevedentsev, A.; Liu, X.; Reparaz, J. S.; Campoy-Quiles, M.; Woo, H. Y.; Müller, C.; Fahlman, M.; Yang, C.-Y.; Fabiano, S. Preventing Benzoquinone-Based Catalyst Aggregation Enables the One-Step Synthesis of Highly Conductive Poly(Benzodifurandione) without Post-Reaction Purification. *Adv. Mater.* **2025**, *37* (17), 2502426. <https://doi.org/10.1002/adma.202502426>.
- (84) Famengo, A.; Rossi, S.; Bison, P.; Boldrini, S. Thermal Conductivity Characterization of Polyaniline Doped Material for Thermoelectric Applications; Bison, P., Burleigh, D., Eds.; Anaheim, California, United States, 2017; p 102141C. <https://doi.org/10.1117/12.2262080>.
- (85) Kaul, P. B.; Day, K. A.; Abramson, A. R. Application of the Three Omega Method for the Thermal Conductivity Measurement of Polyaniline. *J. Appl. Phys.* **2007**, *101* (8), 083507. <https://doi.org/10.1063/1.2714650>.

- (86) Jin, J.; Manoharan, M. P.; Wang, Q.; Haque, M. A. In-Plane Thermal Conductivity of Nanoscale Polyaniline Thin Films. *Appl. Phys. Lett.* **2009**, *95* (3), 033113. <https://doi.org/10.1063/1.3184786>.
- (87) Piraux, L.; Kinany-Alaoui, M.; Issi, J.-P.; Begin, D.; Billaud, D. Thermal Conductivity of an Oriented Polyacetylene Film. *Solid State Communications* **1989**, *70* (4), 427–429. [https://doi.org/10.1016/0038-1098\(89\)91073-9](https://doi.org/10.1016/0038-1098(89)91073-9).
- (88) Zhou, C.; Bai, Y.; Zou, H.; Zhou, S.; Zhou, C.; Bai, Y.; Zou, H.; Zhou, S. Improving Thermal Conductivity of Injection Molded Polycarbonate/Boron Nitride Composites by Incorporating Spherical Alumina Particles: The Influence of Alumina Particle Size. *Polymers* **2022**, *14* (17). <https://doi.org/10.3390/polym14173477>.
- (89) Li, Z.; Sun, Y.; Hu, F.; Liu, D.; Zhang, X.; Ren, J.; Guo, H.; Shalash, M.; He, M.; Hou, H.; El-Bahy, S. M.; Pan, D.; El-Bahy, Z. M.; Guo, Z. An Overview of Polymer-Based Thermally Conductive Functional Materials. *Journal of Materials Science & Technology* **2025**, *218*, 191–210. <https://doi.org/10.1016/j.jmst.2024.07.053>.
- (90) Li, Q.; Chen, X.; Zhou, J.; Shen, J.; Chen, W. Enhanced Thermal Conductivity of Polytetrafluoroethylene Dielectric Composite with Fluorinated Graphite Inducing Molecular Chain Orientation. *Materials* **2025**, *18* (13), 3010. <https://doi.org/10.3390/ma18133010>.
- (91) Abbasgholi-NA, B.; Nokhbeh, S. R.; Aldaghri, O. A.; Ibnaouf, K. H.; Madkhali, N.; Cabrera, H.; Abbasgholi-NA, B.; Nokhbeh, S. R.; Aldaghri, O. A.; Ibnaouf, K. H.; Madkhali, N.; Cabrera, H. Thermal Diffusivity and Conductivity of Polyolefins by Thermal Lens Technique. *Polymers* **2022**, *14* (13). <https://doi.org/10.3390/polym14132707>.
- (92) Sacchet, S.; Valentini, F.; Rizzo, C.; Po, R.; Fambri, L. High Density Polyethylene with Phase Change Materials for Thermal Energy Management. *Energy Mater.* **2025**, *5* (4), 50033–50042. <https://doi.org/10.20517/energymater.2024.112>.
- (93) Gong, P.; Tran, M.-P.; Buahom, P.; Detrembleur, C.; Thomassin, J.-M.; Kenig, S.; Wang, Q.; Park, C. B.; Gong, P.; Tran, M.-P.; Buahom, P.; Detrembleur, C.; Thomassin, J.-M.; Kenig, S.; Wang, Q.; Park, C. B. Thermal Insulation Foam of Polystyrene/Expanded Graphite Composite with Reduced Radiation and Conduction. *Polymers* **2025**, *17* (8). <https://doi.org/10.3390/polym17081040>.
- (94) Chen, S.; Wu, Q.; Mishra, C.; Kang, J.; Zhang, H.; Cho, K.; Cai, W.; Balandin, A. A.; Ruoff, R. S. Thermal Conductivity of Isotopically Modified Graphene. *Nat. Mater.* **2012**, *11* (3), 203–207. <https://doi.org/10.1038/nmat3207>.
- (95) Yucel, K. T.; Basyigit, C.; Ozel, C. Thermal Insulation Properties of Expanded Polystyrene as Construction and Insulating Materials. In *15th Symposium on Thermophysical Properties*; Boulder, CO, **2003**; pp 54–66.
- (96) Alofi, A. Thermal Conductivity of Graphene and Graphite. *Phys. Rev. B* **2013**, *87* (11). <https://doi.org/10.1103/PhysRevB.87.115421>.
- (97) Balandin, A. A.; Ghosh, S.; Bao, W.; Calizo, I.; Teweldebrhan, D.; Miao, F.; Lau, C. N. Superior Thermal Conductivity of Single-Layer Graphene. *Nano Lett.* **2008**, *8* (3), 902–907. <https://doi.org/10.1021/nl0731872>.
- (98) Renteria, J. D.; Ramirez, S.; Malekpour, H.; Alonso, B.; Centeno, A.; Zurutuza, A.; Cocemasov, A. I.; Nika, D. L.; Balandin, A. A. Strongly Anisotropic Thermal Conductivity of Free-Standing Reduced Graphene Oxide Films Annealed at High Temperature. *Adv. Funct. Mater.* **2015**, *25* (29), 4664–4672. <https://doi.org/10.1002/adfm.201501429>.
- (99) Klemens, P. G.; Pedraza, D. F. Thermal Conductivity of Graphite in the Basal Plane. *Carbon* **1994**, *32* (4), 735–741. [https://doi.org/10.1016/0008-6223\(94\)90096-5](https://doi.org/10.1016/0008-6223(94)90096-5).

- (100) Taylor, R. The Thermal Conductivity of Pyrolytic Graphite. *J. Theor. Exp. Appl. Phys.* **1966**, *13* (121), 157–166. <https://doi.org/10.1080/14786436608211993>.
- (101) Holland, M. G.; Klein, C. A.; Straub, W. D. The Lorenz Number of Graphite at Very Low Temperatures. *J. Phys. Chem. Solids* **1966**, *27* (5), 903–906. [https://doi.org/10.1016/0022-3697\(66\)90265-4](https://doi.org/10.1016/0022-3697(66)90265-4).
- (102) Pop, E.; Varshney, V.; Roy, A. K. Thermal Properties of Graphene: Fundamentals and Applications. *MRS Bulletin* **2012**, *37* (12), 1273–1281. <https://doi.org/10.1557/mrs.2012.203>.
- (103) Pop, E.; Mann, D.; Wang, Q.; Goodson, K.; Dai, H. Thermal Conductance of an Individual Single-Wall Carbon Nanotube above Room Temperature. *Nano Lett.* **2006**, *6* (1), 96–100. <https://doi.org/10.1021/nl052145f>.
- (104) Balandin, A. A. Thermal Properties of Graphene and Nanostructured Carbon Materials. *Nat. Mater.* **2011**, *10* (8), 569–581. <https://doi.org/10.1038/nmat3064>.
- (105) Shanks, H. R. Thermal Conductivity of Silicon from 300 to 1400°K. *Phys. Rev.* **1963**, *130* (5), 1743–1748. <https://doi.org/10.1103/PhysRev.130.1743>.
- (106) Glassbrenner, C. J. Thermal Conductivity of Silicon and Germanium from 3°K to the Melting Point. *Phys. Rev.* **1964**, *134* (4A), A1058–A1069. <https://doi.org/10.1103/PhysRev.134.A1058>.
- (107) Kaźmierczak-Bałata, A.; Bodzenta, J.; Dehbashi, M.; Mayandi, J.; Venkatachalapathy, V. Influence of Post Processing on Thermal Conductivity of ITO Thin Films. *Materials* **2023**, *16* (1), 362. <https://doi.org/10.3390/ma16010362>.
- (108) Touloukian, Y. S.; Powell, R. W.; Ho, C. Y.; Klemens, P. G. *Thermophysical Properties of Matter—The TPRC Data Series. Volume I. Thermal Conductivity-Metallic Elements and Alloys.(Reannouncement). Data Book*; Purdue Univ., Lafayette, IN (United States). Thermophysical and Electronic Properties Information Analysis Center, **1970**.
- (109) Touloukian, Y. S.; Buyco, E. H. Thermophysical Properties of Matter—The TPRC Data Series. Volume 4. Specific Heat-Metallic Elements and Alloys. **1971**.
- (110) Symoens, E.; Van Coile, R.; Belis, J. Experimental Study on the Thermal Performance of Soda-Lime-Silica Glass by Radiant Panel Testing. *Challenging Glass Conference Proceedings*; **2024**; Vol. 9.
- (111) Liu, L.; Shinozaki, K. Thermal Conductivity and Mechanical Properties of Soda-Lime Glass with Interfacially Connected Au Layer Fabricated via Sputtering and Spark Plasma Sintering. *J. Asian Ceram. Soc.* **2022**, *10* (2), 424–429. <https://doi.org/10.1080/21870764.2022.2068286>.
- (112) Kim, D.; Zhu, L.; Jeong, D.-J.; Chun, K.; Bang, Y.-Y.; Kim, S.-R.; Kim, J.-H.; Oh, S.-K. Transparent Flexible Heater Based on Hybrid of Carbon Nanotubes and Silver Nanowires. *Carbon* **2013**, *63*, 530–536. <https://doi.org/10.1016/j.carbon.2013.07.030>.
- (113) Zhang, X.; Yan, X.; Chen, J.; Zhao, J. Large-Size Graphene Microsheets as a Protective Layer for Transparent Conductive Silver Nanowire Film Heaters. *Carbon* **2014**, *69*, 437–443. <https://doi.org/10.1016/j.carbon.2013.12.046>.