# Transforming Commercial Textiles and Threads into Sewable and Weavable Electric Heaters

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Ⓢ Supporting Information

**ABSTRACT:** We describe a process to transform commercial textiles and threads into electric heaters that can be cut/sewn or woven to fashion lightweight fabric heaters for local climate control and personal thermal management. Off-the-shelf fabrics are coated with a 1.5 $\mu m$ thick film of a conducting polymer, poly(3,4-ethylenedioxythiophene), using an improved reactive vapor deposition method. Changes in the hand feel, weight, and breathability of the textiles after the coating process are imperceptible. The resulting fabric electrodes possess competitively low sheet resistances—44 $\Omega/\square$ measured for coated bast fiber textiles and 61 $\Omega/\square$ measured for coated cotton textiles—and act as low-power-consuming Joule heating elements. The electrothermal response of the textile electrodes remain unaffected after cutting and sewing due to the robustness of the conductive coating. Coated, conductive cotton yarns can also be plain-woven into a monolithic fabric heater. A demonstrative circuit design for a soft, lightweight, and breathable thermal glove is provided.

**KEYWORDS:** wearable electronics, Joule heating, conductive textiles, conjugated polymer, reactive vapor deposition
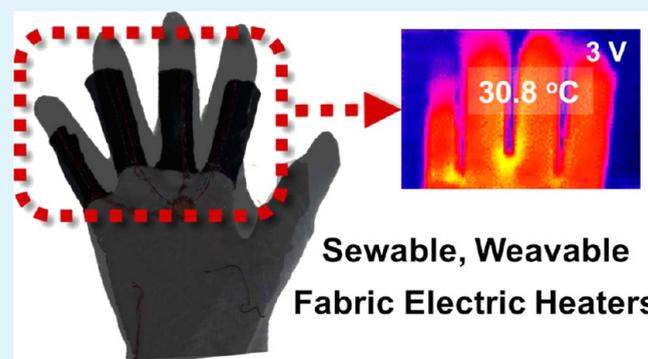
## 1. INTRODUCTION

Lightweight, breathable, and body-conformable electrical heaters have the potential to change traditional approaches to personal thermal management, medical heat therapy, joint pain relief, and athletic rehabilitation. Electrical heaters are also ubiquitous in indoor and automobile climate control systems and portable temporary shelters.

Joule heating elements are the functional component in electrical heaters.[1] Heat is generated under an applied voltage when inelastic collisions between accelerated electrons and phonons occur as current passes through a conductive material. Contemporary commercial products almost exclusively use copper wires as the Joule heating element.[1] Although cheap and widely available, electrical heaters containing copper wires are noticeably heavy and inflexible. Further, the copper wire heating elements cannot be cut, sewn, ironed, or woven, like standard threads, to fashion heated garments or joint braces.

An absence of seamless and imperceptible integration into everyday objects and garments has, thus far, relegated electrical heaters to a category of special-purpose electronics. For wearable devices to be broadly adopted, issues of comfort, aesthetics, haptic perception, and weight must be explicitly addressed. Therefore, it behooves us to innovate laboratory-scale prototypes that have the capacity to be easily and inconspicuously incorporated into everyday objects and garments.

To replace conventional-but-cumbersome copper wires, designer fibers composed of nanocarbon materials,[2,3] fabric mimics made of conductive nanowires or meshes,[4−10] and conducting polymer-impregnated cloths[11−16] have been explored as alternative Joule heating elements. However, despite their excellent electrical properties, these modern substitutes do not comprehensively address certain basic issues, such as breathability, haptic perception, bare skin compatibility, stable conductivity under frequent mechanical deformation, and straightforward integration into demanding textile and garment manufacturing routines.

We previously reported a vapor-coating method to transform familiar, off-the-shelf, plain-woven fabrics, such as cotton and bast fiber fabrics, into metal-free textile electrodes that were uniquely stable to bending, folding, rubbing, body heat/sweat, cold laundering, and dry ironing.[17,18] Further, these fabric electrodes possessed the feel, weight, breathability, and pliability of the original fabrics. Here, we use an improved coating method to transform cotton and bast fiber fabrics or threads into highly conductive and low-power-consuming Joule heating elements. We show that our rugged and lightweight fabric Joule heating elements are heat and moisture stable, can be cut and sewn without detriment to their electrothermal

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characteristics, and can be readily integrated into garment-based electrical circuits.

## 2. MATERIALS AND METHODS

**2.1. General Considerations.** All of the chemicals were purchased from Sigma-Aldrich and used without further purification. Scanning electron microscopy (SEM) was performed using a field emission SEM Magellan 400. Film thicknesses were measured on a Veeco Dektak 150 profilometer. Surface sheet conductivities, reported in $\Omega/\square$, of the conducting polymer-coated fabrics were calculated from the resistivity measurements made using a home-built four-point probe test station.[19] Lateral resistances, that is, the horizontal resistance across the short axis of a fabric swatch, reported simply in units of ohm, were measured using the standard stainless steel probe tips of an ohm meter.[19] Joule heating was powered by commercial alkaline batteries. Thermal images were taken using a forward looking infrared radiometer IR imaging camera.

**2.2. Vapor Coating of Fabrics.** Vapor phase polymerization of 3,4-ethylenedioxythiophene (EDOT) to form poly(3,4-ethylenedioxythiophene) (PEDOT) coatings on the textiles was carried out in a custom-built cube-shaped stainless steel chamber adapted from previous reports. The temperature of the downward-facing substrate holder located on top of the chamber was held at 120 °C. A solid oxidant, typically $FeCl_3$, was sublimed inside the chamber using a Luxel crucible heater. A glass ampule containing EDOT was heated with a resistive heating tape to 90 °C and the monomer vapor was introduced into the evacuated chamber via a side inlet, controlled by a needle valve. The needle valve was only opened slightly so that the monomer vapor introduced into the chamber did not immediately condense. Under this condition, the oxidant ($FeCl_3$) and not EDOT was the limiting reagent for polymerization. The temperature of the oxidant crucible heater was manually adjusted during deposition to maintain the film growth rate of 10 Å/s before tooling correction. The pressure inside the chamber was tuned between 100 and 500 mTorr by introducing and controlling the argon gas flow, in addition to the monomer and oxidant flux. Although the depositions carried out at 500 mTorr yielded textile electrodes with the highest conductivities, high pressure caused $FeCl_3$ to diffuse into and clog the monomer inlet tube. Therefore, to maintain the chamber longevity, 300 mTorr was used to create the Joule heating elements described herein.

Film thickness was monitored by a quartz crystal microbalance (QCM) located inside the cubic chamber. A corrective tooling factor for the readout obtained from the QCM sensor was obtained as follows. The silicon substrates were coated with films of varying thickness ("QCM reported") at three different monomer/oxidant flow rate ratios, rinsed with $H_2SO_4$/methanol, and the resulting film thickness ("actual thickness") measured using a profilometer. A tooling factor was obtained by taking the ratio of the actual film thickness after rinsing to the thickness reported by the QCM sensor when the tooling factor was set as 100%. The tooling factor was found to be 0.5 for all of the monomer/oxidant flow rate ratios.

Textiles used as substrates were used as received, without washing. After vapor deposition, the coated substrates were rinsed with 1 M aqueous HCl for 2 min to completely remove the trapped iron salts, as previously established,[17,18] followed by methanol to remove the residual monomer and HCl from the polymer coatings, and then dried overnight in air before electrothermal measurements. As previously described, the PEDOT coatings thus obtained remained stably doped even after rinsing and storage under ambient conditions.[17,18] For one example of a 1 cm × 1 cm cotton square, the measured mass before coating was 27.664 mg and that after coating with a 1.5 μm thick PEDOT film was 27.829 mg, a 0.6% increase in the mass.

**2.3. Biocompatibility of Vapor-Coated Cloths.** Following ISO 10993-5 regulatory guidelines for ensuring biocompatibility,[20] an agar overlay test with L929 cells (mouse connective tissue) was performed in triplicate by Nelson Laboratories (UT) for 3 in. × 3 in. samples of PEDOT-coated cotton cloths. The viability of the cells grown on a thin agar overlay placed over the PEDOT-coated samples was graded against a positive control (latex beads, reactivity grade "4") and a negative control (polypropylene pellets, reactivity grade "0"). The observed average reactivity grade of the PEDOT-coated cotton was 0, qualifying these samples to safely come into contact with human skin without causing adverse reactions due to chemical leaching.

## 3. RESULTS AND DISCUSSION

Low-power-consuming electric heaters require highly conductive Joule heating elements. We previously used reactive vapor deposition to coat off-the-shelf fabrics with a film of the conductive polymer poly(3,4-ethylenedioxythiophene) (PEDOT), thus transforming widely available fabrics into mechanically robust, wearable, metal-free textile electrodes.[17] However, the sheet resistances[19] of these previously reported textile electrodes were >200 $\Omega/\square$, which boded poorly for the minimum voltage input required to effect a noticeable Joule heating in these electrodes.[2−16] Therefore, we first sought to optimize the process parameters[21,22] used to vapor coat the fabrics with a conducting polymer film.

Prior studies on the reactive vapor deposition of PEDOT identified the substrate stage temperature as an important parameter affecting the conductivity of the resulting PEDOT films.[23] A stage temperature of 120 °C was concluded to afford the highest conductivity films on the glass substrates. However, in our hands, the sheet resistances of our fabric electrodes only decreased nominally when an elevated stage temperature of 120 °C was used (compared to 80 °C, per our previous report).

Instead, significant gains were obtained when the background chamber pressure during deposition was increased using the inert argon gas. Table S1 lists the lateral resistances[19] measured over a 1 in. distance for 100 nm thick PEDOT films deposited on plain-woven pineapple fiber textiles and cotton textiles at the chamber pressures of 100, 300, and 500 mTorr. A 7-fold decrease in the resistance was observed when the pineapple fiber fabrics were coated with PEDOT at a chamber pressure of 300 mTorr, instead of 100 mTorr. A further 5-fold decrease was observed when the chamber pressure was increased to 500 mTorr. Similar effects were also observed for cotton squares coated with PEDOT, with a chamber pressure of 500 mTorr also yielding the lowest measured lateral resistances across the plain-woven swatch.

Increasing the chamber pressures should result in shorter reactant mean free paths, which, in turn, should afford a greater surface coverage on the rough and textured surfaces due to a higher frequency of the surface-restricted reactions and suppression of line-of-sight deposition events. To confirm that higher chamber pressures lead to a more thorough surface coverage (perhaps even at shallowly buried interfaces), we examined the warp/weft intersects of the plain-woven pineapple fiber fabrics coated with PEDOT at 100 and 500 mTorr (Figure S1). At 100 mTorr, the warp and weft threads acted as each other's shadow masks and no PEDOT coating could be found in the buried interfaces where the warp thread crossed over the weft thread (or vice versa) because of the inefficient diffusion of the reactants. In contrast, at 500 mTorr, these buried interfaces were coated with PEDOT. Indeed, near 360° coverage of all of the warp and weft threads of the plain-woven fabric swatch were observed when the vapor coating was performed at 500 mTorr.

Higher-molecular-weight polymers could have also been obtained at higher chamber pressures due to the increased frequency of oligomer−oligomer couplings compared with the predominance of oligomer−monomer or monomer−monomer interactions at lower chamber pressures. However, this
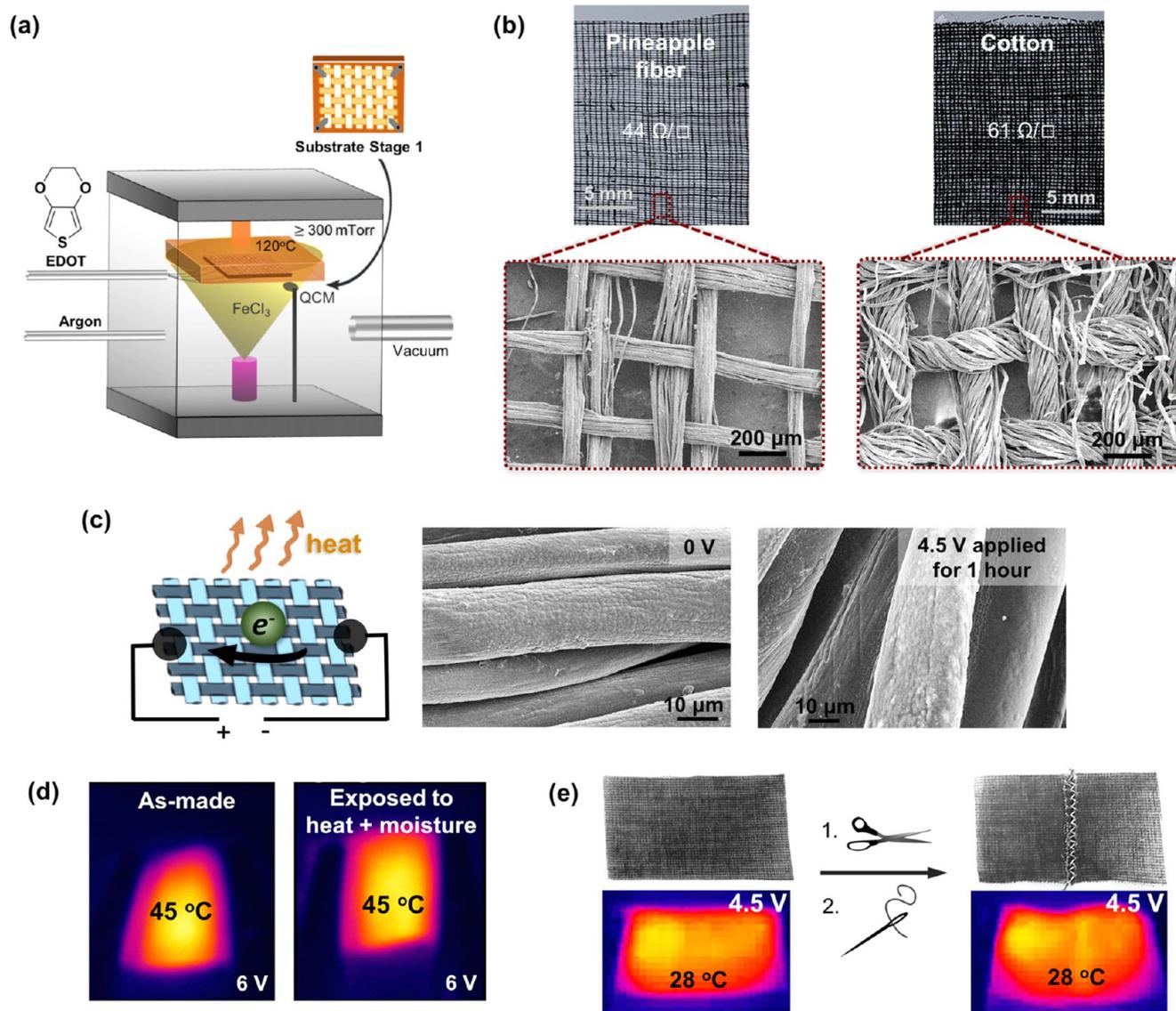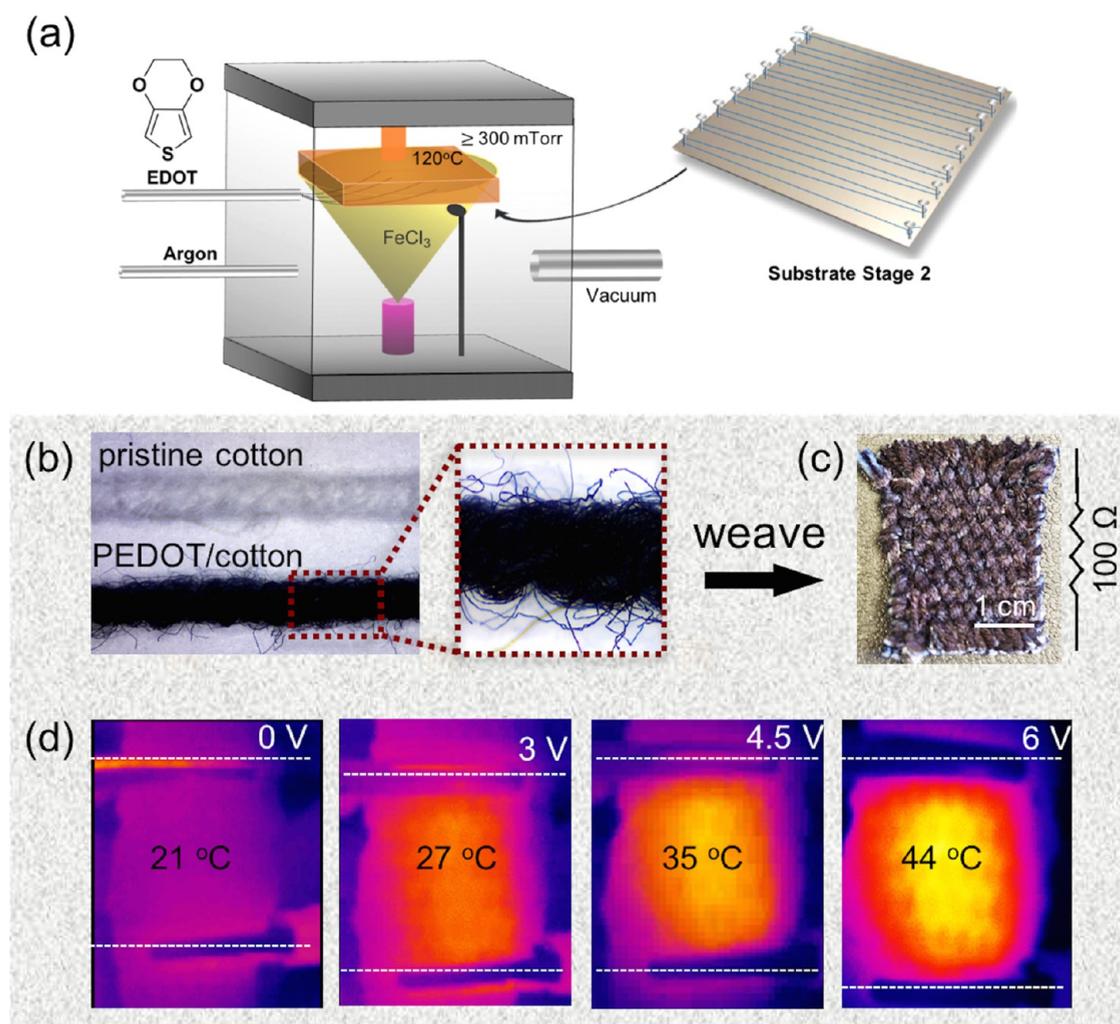
**Figure 1.** Vapor-coated textiles as Joule heating elements. (a) Schematic of the vapor deposition chamber used to coat plain-woven textiles. (b) Images of pineapple fiber and cotton textiles vapor coated with a 1.5 $\mu$m thick film of PEDOT. (c) SEM images of a cotton textile before and after continuous application of 4.5 V for 1 h. (d) Thermal camera images of Joule heating in a fluoroalkylsiloxane-packaged PEDOT-coated cotton textile before after exposure to heat and moisture. (e) Optical (top) and thermal camera (bottom) images of a naked PEDOT-coated textile before and after being cut and resewn back together with the cotton thread.

hypothesis was not easy to prove experimentally because the final PEDOT films had negligible solubility in most solvents and, therefore, accurate molecular weight distributions could not be measured using the readily available instrumentation.

Having identified improved process parameters, we sought to create fabric Joule heating elements. We chose two commercially available textiles that were previously identified to yield robust and highly conductive textile electrodes: cotton and pineapple fiber fabrics. These textiles were also lightweight, porous (i.e., breathable and amenable to air flow through the fabric) and commonly used to create garments. A 1.5 $\mu$m thick PEDOT film was vapor deposited on both pineapple and cotton fiber textiles. This coating thickness was 2−3 times larger than the thickness reported in our previous work; here, we aimed to create a thick conductive coating so that sufficient current density could be supported to observe Joule heating.

Images of the textiles coated with a 1.5 $\mu$m thick PEDOT film are shown in Figure 1. Scanning electron micrograph (SEM) images revealed highly conformal coatings on both pineapple fiber and cotton fabrics, regardless of the morphology of microfibrils in the constituent textiles. Due to the conformality of the coating, the porosity and breathability of the starting textiles remained unaltered after PEDOT coating. Note that his feature is not readily demonstrated by previously reported conductive cloths obtained by in situ solution polymerization.[24] The measured total weight of the fabrics only increased by 1%, at most, after vapor coating with a 1.5 $\mu$m thick film of PEDOT. A difference in the hand feel between coated and uncoated fabrics was not evident to our bare fingers. In sum, the PEDOT-coated fabric electrodes reported herein remained lightweight and breathable after coating and retained their natural texture/hand feel, even with a 1.5 $\mu$m thick PEDOT coating.

**Figure 2.** Vapor-coated yarns as Joule heating elements. (a) Schematic of the vapor deposition chamber and substrate stage used to coat yarns. (b) Photograph of a pristine cotton yarn and a yarn coated with a 1.5 $\mu$m thick layer of PEDOT. (c) Optical micrograph of a plain-woven textile made using the PEDOT-coated cotton yarn. (d) Thermal camera images of the plain-woven textile under different applied voltages.

Low surface sheet resistances[19] of 44 and 61 $\Omega/\square$ were measured using a four-point probe on the PEDOT-coated pineapple fiber and cotton textiles, respectively. A battery was then connected to these naked fabric electrodes, using alligator clips, to effect Joule heating. A single sample of a PEDOT-coated cotton fabric could generate a temperature of 28 °C (ambient temperature 19 °C) when connected to a 4.5 V battery and 45 °C when connected to a 6 V battery. Figure 1c shows the SEM images of an as-made PEDOT-coated cotton fabric swatch and the same fabric after being continuously connected to a 4.5 V battery for 1 h under ambient conditions. After 1 h of continuous heating operation, the PEDOT film on the cotton textile became slightly smoother. However, no dramatic morphology changes, such as cracking, creasing, agglomeration, or delamination, were observed, indicating that the PEDOT-coated cotton textile is rugged and stable enough to maintain its performance when used as a Joule heating element.

The next issue we sought to address was one of heat, moisture, and skin-contact stability. We previously reported that our naked PEDOT-coated fabrics displayed stable conductivities after being heated and exposed to warm moisture (akin to body sweat).[17] For electrical heaters meant to be worn

or otherwise body mounted, however, it is necessary to insulate the conductive element with a dielectric coating to prevent the wearer from experiencing electric shocks. Fluoroalkylsiloxanes have been previously reported to serve as biocompatible dielectric coatings for wearable electronic devices.[6] We vapor-treated our PEDOT-coated fabrics with trichloro-(1H,1H,2H,2H-perfluorooctyl)silane (PFOTS) in a closed container for 30 min, followed by thermal annealing in the presence of methanol vapor, to form an invisible packaging layer that prevented humidity invasion into the PEDOT film (Figure S2). Formation of a fluoroalkyl coating was obvious because the PEDOT-coated fabrics switched from being hydrophilic to noticeably hydrophobic after PFOTS packaging (Figure S3). The lateral resistances and the total weight of the PEDOT-coated fabrics did not observably change after PFOTS treatment. Importantly, PFOTS packaging imparted acceptable heat and moisture insensitivity to our fabric Joule heating elements (Figure 1d).

The naked PEDOT-coated fabrics (i.e., not packaged with PFOTS treatment) could be handled like any other commercial fabric, in that they could be cut and sewn together (with regular thread) without any detriment to their Joule heating performance. Figure 1e shows a PEDOT-coated cotton fabric swatch
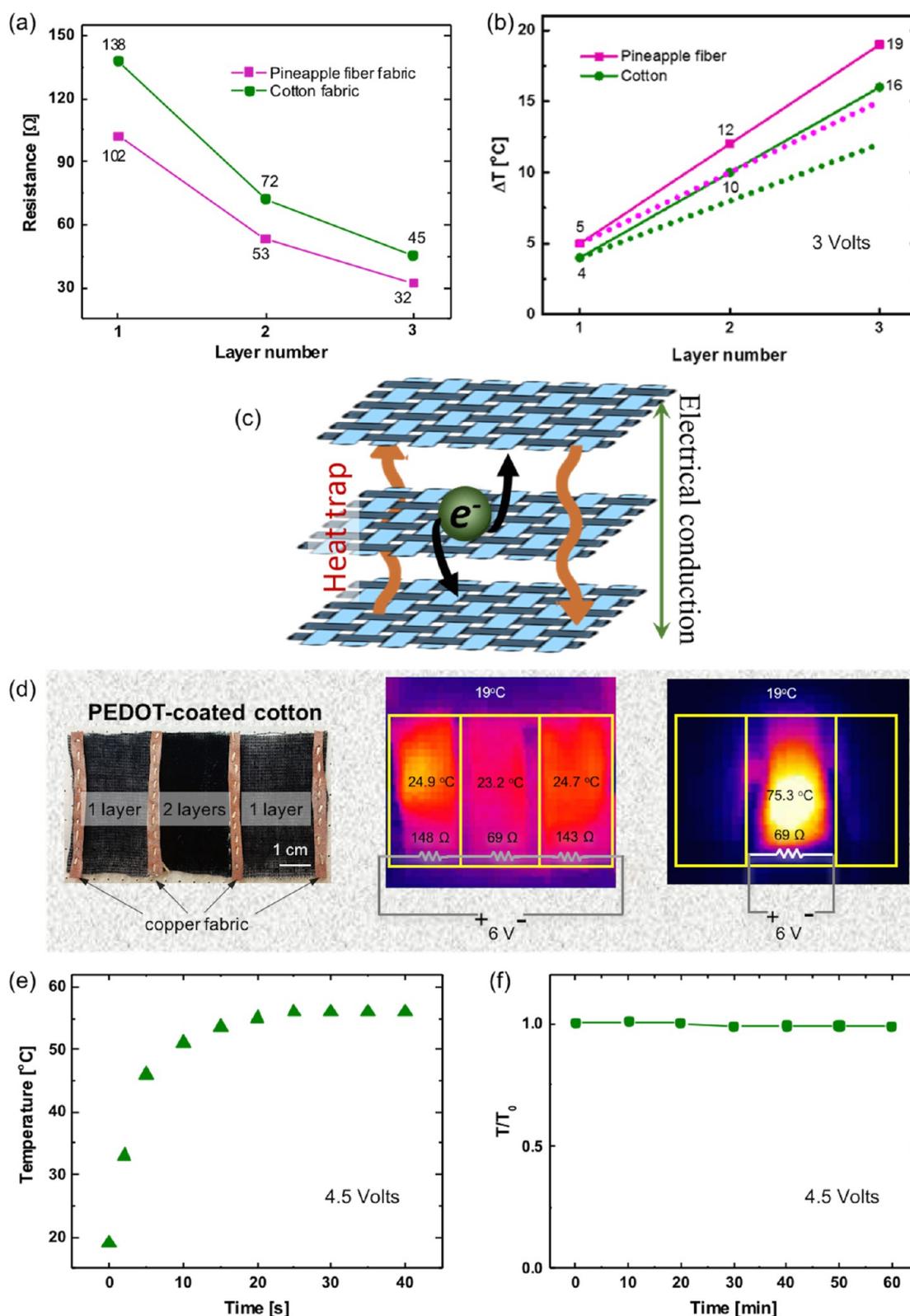
**Figure 3.** Tuning the performance of fabric Joule heating elements. (a) Decreasing lateral resistance upon layering PEDOT-coated fabrics. (b) Temperature change (increase over ambient) observed upon applying 3 V to layered PEDOT-coated fabrics. Dotted lines indicate that predicted temperature increases per eq 2 and solid lines/filled squares delineate actual values. (c) Cartoon illustration of electrical conduction and heat trapping between multilayered PEDOT-coated textiles. (d) Optical image of a fabric circuit comprised of varying layers of PEDOT-coated cotton fabrics sewn together in series (left). Thermal camera images when 6 V is applied across the entire fabric circuit (middle) and selectively across the double layer (right). (e) Response time of a three-layered cotton fabric Joule heater. (f) Electrothermal stability of a three-layered cotton fabric Joule heater.

heated to 28 °C (ambient temperature 19 °C) using a 4.5 V alkaline battery. Figure 1e also shows the same fabric swatch after it was cut in the middle with a pair of scissors and sewn back together with a needle and cotton thread. A zigzag pattern was used to sew the two pieces together so that the seam was obvious. No difference in the electrothermal response was observed for the cut/sewn sample, and no hot spots were generated at the sewing points. Such electrothermal ruggedness is essential for creating customized garment-based heating elements, which usually require cutting and sewing processes to tailor samples to different parts of body, such as palms and joints.

Next, we sought to investigate thread-based heating elements[22] that could be used to create embroidered heaters or woven textile heaters, among other possibilities. First, we needed to adapt our substrate stage to accommodate usable lengths of thread while also allowing for 360° coating of the surface of a thread/yarn in one deposition. A diagram of our stage design for threads/yarns is shown in Figure 2 and photographs are provided in Figure S4. Our design was meant to mimic an array of thread spools and could accommodate, on average, 7 ft lengths of thread when carefully wound in vertical layers.

A thick cotton yarn, typically used to make sweaters, was vapor coated with a 1.5 μm thick film of PEDOT to create thread-based Joule heating elements. Figure 2b shows the optical micrographs of the pristine and PEDOT-coated cotton yarn. The entire circumference of the yarn was uniformly coated in one deposition. The PEDOT-coated cotton yarn was then plain-woven into a textile (Figure 2c). The vapor-deposited PEDOT coating was not rubbed off during the weaving process, further demonstrating the mechanical robustness of our conductive coatings. Note that this PEDOT-coated cotton yarn can also be knitted, complex-woven, or embroidered into different structures and shapes, just like regular yarns, which provides high flexibility for fabricating customized heating elements. The resulting lateral resistance[19] across a 1 cm length of the plain-woven textile was 100 Ω. Figure 2d shows the electrothermal responses of this plain-woven textile upon application of various voltages. Body temperature was reached with 4.5 V, and 6 V gave rise to a temperature of 44 °C.

We posit that the cutting/sewing/weaving stability of our fabric or thread-based Joule heating elements arose due to the mechanical robustness[17,18] of our vapor-coated films and the near 360° coating achieved with chamber pressures greater than 300 mTorr. Elevated chamber pressures effected front-and-back coverage of the fabrics, even though only one face was directly exposed to the reactive vapor during deposition. To wit, the lateral resistances[19] measured on both faces of any coated fabric were the same, due to a near 360° coverage by the conductive PEDOT coating. This is opposite to our previous report, wherein we observed that only one face (front or back) of a fabric square could be selectively coated when vapor deposition was carried out at a low chamber pressure of 100 mTorr.

When multiple unpackaged textile electrodes were layered together, the overall lateral and transverse resistance of the stack linearly decreased with the stack number (Figure 3). Due to the presence of a near 360° conductive coating on each textile, stacking introduced electrical contact points between layers and increased the cross-sectional area of the conduction channel. Multilayered textiles were also expected to impede dissipation of the generated heat to ambient in cold weather,

just as layering normal textiles would do. Therefore, we expected that Joule heating elements constructed using multilayered PEDOT-coated fabrics would demonstrate both higher electrical efficiencies and heating temperatures due to increased thermal retention.

The electrical resistances of unpackaged, multilayered PEDOT-coated (1.5 μm) textiles are summarized in Table S2 and plotted in Figure 3a. The lateral resistance[19] was 102 Ω for a single layer of the pineapple fiber textile and 138 Ω for one of the cotton textiles, for swatch sizes of 1 cm × 1 cm. For both pineapple fiber textile and cotton textiles, the resistance of a double layer was 1/2 of the resistance of single layer and that of a triple layer was 1/3 of that of a single layer. This well-behaved linear trend suggests that near-ideal contact between the fabrics layers can be achieved with simple, physical layering.

The theoretical equilibrium temperature that can be achieved due to Joule heating is determined by

$$T = \frac{VI}{hA} + T_a \tag{1}$$

where $V$ is the voltage supply, $I$ is the current, $h$ is the convective heat transfer coefficient, $A$ is the device surface area, and $T_a$ is the ambient air temperature. Equation 1 can be rewritten as

$$T = \frac{V^2}{RhA} + T_a \tag{2}$$

where $R$ is the lateral resistance of the entire heating element. Thus, temperature increases due to Joule heating are inversely proportional to resistance.

For PEDOT-coated pineapple fiber fabrics, a single layer demonstrated a 5 °C temperature increase when attached to a 3 V battery. Based on this, the predicted temperature increase was calculated to be 10 °C if a double layer was to be used and 15 °C if a triple layer was to be used (plotted as a magenta dashed line in Figure 3b). The actual temperature increase was measured to be 12 and 19 °C for the double layer and triple layer, respectively. For cotton textiles, temperature increases of 8 and 12 °C were predicted for double and triple layers (green dashed line in Figure 3b), respectively, but increases in 10 and 16 °C were measured. As expected, the measured temperature increases for both of our layered fabric Joule heaters were higher than predicted because of added heat retention (infrared reflection) between the fabric layers. The average equilibrium temperatures achieved with a 4.5 V battery are summarized in Table S2. Layered pineapple fiber heaters reached 57 °C and layered cotton heaters reached 56 °C. Both are adequate for wearable electric heaters.

Varying thermal gradients could be easily and predictably generated by creating circuits of layered PEDOT-coated fabric strips. Figure 3d shows an optical image of a Joule heating element composed of three distinct pieces longitudinally sewn together (with regular cotton thread): a single rectangle of PEDOT-coated cotton (148 Ω), a double layer of the same (69 Ω), and a second single layer (143 Ω). For the purposes of this experiment, narrow strips of copper fabric were sewn onto the overlapping edges of the three PEDOT-coated pieces to provide a uniform electric field across the sample. However, as previously noted, a metal fabric electrode is not necessary for operating the PEDOT-coated fabrics as the Joule heating elements. When a voltage of 6 V was applied across the entire sample, the three fabric resistors shared the same current, and the resulting temperature increase was primarily determined by
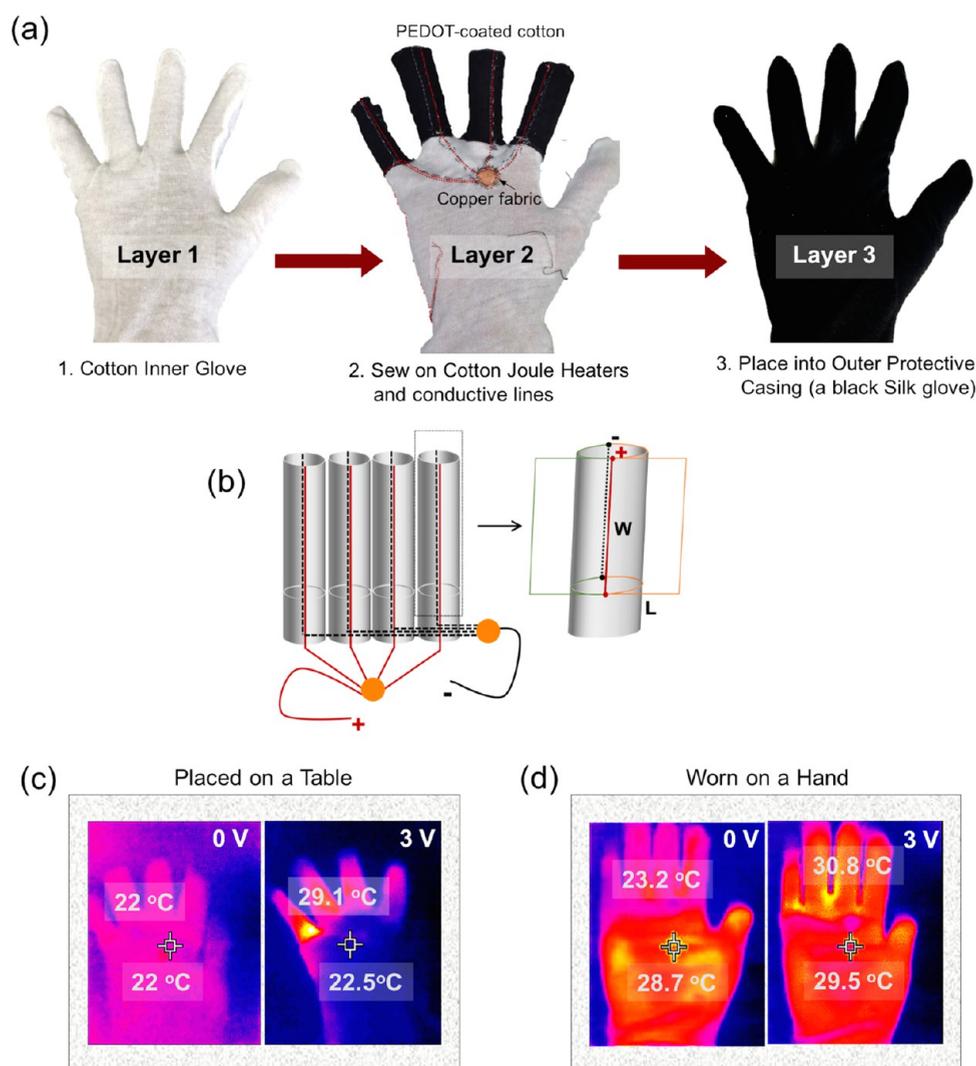
**Figure 4.** (a) Optical images of the three layers of a prototype lightweight thermal glove containing cotton Joule heating elements. (b) Illustration of the equivalent circuit for the Joule heating elements on the four digits of the prototype. (c) Thermal images of the finished glove placed on a table before and after voltage is applied. (d) Thermal images of the finished glove worn on a laboratory member's hand before and after voltage is applied.

the most resistive piece (148 Ω, in this case). When the same voltage was applied only across the least-resistive middle piece, an equilibrium temperature of 75.3 °C was attained after 20 s (with an ambient temperature of 19 °C). Thus, various thermal gradient patterns can be easily realized using a combination of sewing patterns, fabric layering, and simple circuit design.

The response times and heater stabilities under constant operation were measured for unpackaged, triple-layered cotton electrodes connected to a 4.5 V alkaline battery. Figure 3e shows the heating response, and Figure 3f shows the stability. Within 20 s, an equilibrium temperature of 56 °C was attained and remained stable over 1 h of continuous operation.

Layered PEDOT-coated cotton textiles were then used as Joule heating elements in a prototype lightweight thermal glove (Figure 4). Cotton Joule heating elements were chosen because they are thin, breathable, lightweight, and readily available. Our prototype glove consisted of three thin layers: one inner layer that would directly come in contact with the users' skin; a middle layer comprising the fabric Joule heating elements and contact pads for a coin cell battery (Energizer 1632, weight 1.8 g); and an outer cover that would serve as a heat-retaining and aesthetically tunable overall packaging layer. We chose a

commercially available cotton lining glove for the inner layer and a black silk glove for the outer layer.

Four pieces of double-layered PEDOT-coated cotton were curled into cylinders and stitched onto four digits of the lining glove to serve as the Joule heating elements. Figure 4a shows the optical images of the cotton lining glove before and after the fabric Joule heating elements were sewn on. Regular cotton thread was used to sew the heating elements onto the lining glove. However, the two layers of PEDOT-coated cotton used for each cylinder were, separately, sewn together using conductive copper thread to ensure stable contact with flexing. Additionally, two lines of conductive copper thread per finger were placed onto the lining glove and cross-stitched into place using regular cotton thread. These conductive copper thread lines—four on the inner palm side and four on the outer face of the glove—connected to two small circles of conductive copper fabric on each face of the glove, which served as connection points to the positive and negative leads from the coin cell battery. The red dashed lines in the optical image in Figure 4a highlight the conducting pathways to the positive lead of the battery. Note that the conductive copper fabrics and threads did not display Joule heating characteristics—that is, applying a

voltage across a swatch of conductive copper fabric did not produce an observable temperature increase. Therefore, these copper fabrics and threads simply served as connective and field-equalization components in our prototype glove.

Finally, the silk outer glove was fitted over the inner glove modified with Joule heating elements to create a packaged, yet lightweight and breathable, glove. This outer casing can be easily changed to tailor the glove to the aesthetic and haptic preferences of a potential wearer. Further, if desired, bulky outer gloves can also be invoked to improve heat retention and manifest warmer temperatures from the Joule heating elements.

The equivalent circuit for the four cylindrical fabric Joule heaters is illustrated in Figure 4b. One half of each cylinder was considered as a resistor, and each complete cylinder was considered as two resistors connected in parallel when two lines of conductive thread were stitched on the inside and outside faces of the glove. The complete circuit was equivalent to eight hemicylinders connected in parallel, with each hemicylinder possessing a resistance of 80 $\Omega$.

Figure 4 shows the thermal camera images of the glove placed on a table and physically worn on one of our laboratory member's hands. When placed on a table, the entire glove showed a uniform temperature of 22.0 °C before the voltage was applied. The four digits of the glove were warmed up to 29.1 °C when 3 V was applied, whereas the palm area without fabric heaters remained at 22.5 °C. When worn on a hand, the four digits with PEDOT-coated cotton overlayers registered a lower temperature than the areas lacking these overlayers because less body heat radiated to the surface of the glove through areas of multilayered cotton. When 3 V was applied, the four digits of the glove were warmed up to the same temperature as that of the palm area. The wearer could feel the heat transferred from the fabric heaters to her fingers a few seconds after the voltage was applied.

## 4. CONCLUSIONS

To encourage widespread and long-lasting adoption of wearable electronics, proposed devices need to be seamlessly and imperceptibly integrated into everyday objects and garments. Thus far, such inconspicuous integration has not been fully realized for electric heaters. Although numerous potential heating elements have been proposed, issues of comfort, aesthetics, haptic perception, and weight still need to be explicitly addressed.

In this report, we demonstrate that, under improved vapor deposition conditions, highly conductive PEDOT films can be obtained on commercial, porous textiles. Low-power inputs are therefore needed to effect Joule heating in these textiles. PEDOT coating does not noticeably change the weight, feel or breathability of the starting textiles. The PEDOT-coated textiles can be treated as regular fabrics, without extreme care, thanks to the robustness of the vapor coating, which endures frequent friction and mechanical deformation. Cutting, sewing, and weaving processes do not alter the electrical conductivity and electrothermal responses of the PEDOT-coated textiles. In addition to thin and porous textiles, a thick cotton yarn typically used to knit sweaters is also vapor coated with PEDOT and plain-woven into a textile heater.

Our work is one preliminary example of a proposed strategy to use vapor deposition methods to grow robust electronic devices directly from the rough and textured surface of readily available and familiar textiles. The remarkable mechanical

robustness of our vapor-coated fabric electrodes suggests that this strategy is worth further development.

A wearable prototype garment heater, a thermal glove, is demonstrated. This thermal glove is comprised of three lightweight and breathable fabric layers and only needs, on average, a 3 V battery to effect a noticeable and satisfactory hand warming after 10−20 s. At present, our prototype model is powered using a commercial coin cell battery (Energizer 1632), which is a conspicuous component. In the future, we aim to incorporate flexible power sources to create a fully conformable, garment-integrated electric heater.

## ■ ASSOCIATED CONTENT

### Ⓢ Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acsami.7b10514.

Optical images of chambers parts and packaging process; tables of fabric conductivities (PDF)

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