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Scalable, washable and lightweight triboelectric-energy-generating fibers by the thermal drawing process for industrial loom weaving

Ziang Feng [a,b], Shuo Yang [a,b], Sixian Jia [c], Yujing Zhang [a,b], Shan Jiang [a,b], Li Yu [a,b], Rui Li [d], Guowen Song [d], Anbo Wang [a,b], Thomas Martin [b], Lei Zuo [c,*], Xiaoting Jia [a,b,**]

[a] Center for Photonics Technology, Bradley Department of Electrical and Computer Engineering, Virginia Polytechnic Institute and State University, Blacksburg, VA, 24061, USA

[b] Bradley Department of Electrical and Computer Engineering, Virginia Polytechnic Institute and State University, Blacksburg, VA, 24061, USA

[c] Center for Energy Harvesting Materials and Systems (CEHM), Virginia Polytechnic Institute and State University, Blacksburg, VA, 24061, USA

[d] Department of Apparel, Events and Hospitality Management, Iowa State University, Iowa, 50010, USA

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ABSTRACT

In the era of the internet of things (IoTs), it is desired to equip the decentralized electronics with distributed power sources. The fiber-based triboelectric nanogenerator (FTENG) provides one of the soundest solutions due to its high efficiency, easy deployment, excellent wearability, low cost, and eco-friendliness. Compared with other forms of TENGs, it can be woven into fabrics as wearable devices, offering good compactness and comfortability. However, the industrial-loom-compatible FTENGs have yet to be fabricated; the fiber diameter and length are typical challenges in the large scale weaving. In this paper, the thermal drawing process (TDP) is introduced to produce FTENGs that are compatible with industrial looms. The diameter of the polymer-cladding and metal-core fiber has been reduced to ~350 μm, and the length of a single fiber has been scaled up to sub-kilometer. Both hand-woven and loom-woven swatches are demonstrated, showing good flexibility, stretchability, power density, stability, washability, and breathability. Besides serving as power sources, such swatches have been used as self-powered sensors for body motion monitoring and communication. These applications show that the thermally drawn FTENGs can serve as powerful and reliable wearable devices in modern electronics.

1. Introduction

As the era of the internet of things (IoTs) is approaching, decentralized electronic systems are extending their territory since more and more people are equipped with portable sensors, actuators, and transmitters [1–6]. Such a network aims to increase the working efficiency and quality of life [7–15]. However, electricity, which is essential to all the electronics, is slowing down the IoTs' development because it is generally stored in batteries and capacitors, which are heavy and bulky and require regular replacement or recharging using the immobile power plants [16,17]. Researchers worldwide have been seeking power sources that are lightweight, miniature, and distributedly deployable and chargeable. Among the large amounts of attempts, wearable energy harvesters appear to be good candidates because they aim to collect the ambient energy and can be integrated into clothing or accessories [17–23]. Instead of being an independent power supply module, they can be perfectly embedded into the IoTs or even serve as self-powered sensors as part of the network.

A variety of wearable energy harvesting devices have been demonstrated in recent years, including solar energy, thermoelectric, triboelectric, and piezoelectric energy generators [24–29]. Among all of them, the fiber-based triboelectric nanogenerator (FTENG) that works in the single-electrode mode provides one of the soundest solutions due to its excellent wearability, easy deployment, high efficiency, low cost, and eco-friendliness [30–38]. As a typical form of the triboelectric generators (TENG), FTENG harvests energy by coupling two ubiquitous physical phenomena that have been thoroughly discussed in previous literature [39,40]. It generates energy based on the triboelectrification

* Corresponding author.

** Corresponding author. Center for Photonics Technology, Bradley Department of Electrical and Computer Engineering, Virginia Polytechnic Institute and State University, Blacksburg, VA, 24061, USA.

E-mail addresses: leizuo@vt.edu (L. Zuo), xjia@vt.edu (X. Jia).

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that occurs when any two different objects get into contact; the mechanical energy is then transduced to electricity with the electrical induction effect inside the electrodes. The FTENG can easily harvest different kinds of energy such as body motion, vibration, and wind that are usually wasted [41,42]. Compared with other forms of wearable TENG devices, FTENG is favorable mainly because it can be arbitrarily embedded into textiles or clothing due to its small sizes. Moreover, to work in the single-electrode mode, it does not need the rigid spacers, *e.g.*, metal springs, commonly used in other TENGs, making it flexible and comfortable. Also, its wide realization with many types of functional materials leads to its potential for future aesthetic needs.

To be embedded into textiles, fibers need to be loom-friendly, meaning that they need to be thin and soft enough to form flexible fabrics, yet strong enough to survive the pulling stress and beating force applied on it. Besides, industrial looms generally need fibers of hundreds of meters long to weave large and seamless fabrics. What's more, for the wearable devices, washability, durability, and breathability are also important standards to evaluate the performance. Such requirements pose special challenges to the FTENG manufacturing process in terms of structure design, material selection, diameter control, scalability, and productivity. Currently, softness and lightweight are sacrificed in some FTENGs with the employment of rigid metal strands (large diameter or twined bundle) as electrodes [31,32,43]. Also, scalability and productivity are limiting some of the FTENG's weavability because the widely used coating method suffers from complicated process, low speed, short single fiber length, and small yield [44–48]. Furthermore, many TENG devices enlarge the contact area by involving nanomaterials, which will easily degrade after wearing and washing, resulting in unstable output after long-term use [17]. Such drawbacks adversely affect the weavability of the FTENGs and, therefore, many of them can only be hand-woven to small swatches for short-term use. FTENG that is compatible with industrial looms is yet to be developed.

Here we introduce the thermal drawing process (TDP) for weavable FTENG production. TDP has been used to fabricate sophisticated functional polymer fibers in the past few decades [49–60]. In TDP, a bulky preform with a customized structure is heated in a furnace above the materials' glass transition point, and high stress is applied to elongate the preform to thin fibers on a large scale. In this paper, we designed a FTENG with a simple core-cladding structure, in which a 50-μm-thin metal (tungsten) wire serves as the electrode in the core, and the polymer cladding generates triboelectrification on the outside. As both semicrystalline and amorphous materials can be drawn with TDP, we have demonstrated polypropylene (PP, semicrystalline) and polycarbonate (PC, amorphous) as the cladding materials, respectively. We have successfully drawn continuous FTENGs with a diameter down to 350 μm and a length of ~100 m with either cladding material. The drawing speed is up to 4 m min^{-1}. Both hand-woven and loom-woven swatches have been demonstrated, and they show good flexibility and stretchability. Their output power densities peak at 43.0 mW kg^{-1} and 67.4 mW kg^{-1} for PP and PC cladding, respectively. A series of 62 commercial light-emitting diodes (LEDs) can be readily lit up by rubbing a ~20 cm^2 swatch on a cotton shirt. The stable power output in the durability and washability tests and the good breathability also prove them to be good clothing components. In addition to serving as power sources, they can work as self-powered sensors. They can serve as wearable biosensors, such as pedometers and sitting timers. Also, they can operate as Morse code generators for communication use. Thereby, the thermally drawn FTENGs presented in this work can be woven into multifunctional textiles and clothing. This versatile platform will pave a way towards broad applications of the IoTs.

2. Results and discussions

2.1. The fabrication of FTENG

As illustrated in Fig. 1, we fabricated a FTENG with PP cladding and tungsten core by the thermal drawing process and subsequently wove it into fabrics. A bulk preform was prepared to be elongated to a thin fiber. It consisted of a PP tube surrounded by a sacrificial acrylic layer (Fig. 1a). A tungsten wire was fed into the tubing when the preform was heated in the furnace and pulled down with high stress (Fig. 1b). The PP layer will attach to the tungsten wire during the TDP when the draw-down-ratio is high enough. The acrylic layer was mechanically peeled off to expose the PP layer (Fig. 1c and d) after drawing. The reasons to select PP as the triboelectric layer are threefold. First, PP is located to the negative end of the triboelectric series, meaning that most clothes materials (cotton, polyester, etc.) and human body (skin and hair) are far easier than it to lose electrons, thus offering a large amount of electron transfer [61–64]. Second, PP is hydrophobic, resulting in its excellent washability [65–67]. Third, it is soft enough to be embedded in a fabric while strong enough to maintain integrity during the loom-weaving process. When heated to above its melting point, PP will experience a drastic drop in viscosity as it is semi-crystalline. Because materials in low-viscosity state can easily flow under the applied stress during the draw, neckings that lead to breakage will be formed. To address this challenge, we added a housing layer to apply boundary restrictions to the PP layer. Acrylic, a typical amorphous material, is a good candidate because such materials can maintain stable diameters during drawing [57]. Besides, thanks to the weak adhesive strength between the two polymers, the acrylic layer could be easily removed mechanically. To make softer fiber compared with existing FTENGs [30–32,68–70], we used metal wires with a small diameter. However, because the fiber needs to survive the stress applied during the thermal drawing, the pulling and beating force during loom weaving, the metal wire should also possess good tensile strength. Thus, the 50 μm-diameter tungsten wire was employed as the electrode. With such a fiber, we could weave it into multiple patterns manually or by industrial looms (Fig. 1e and f).

The pictures of as-fabricated FTENGs are shown in Fig. 2. The cross-sectional optical image (Fig. 2a) shows that the fiber has a ~350 μm diameter, which is comparable to those of the commonly used yarns on industrial looms. A continuous fiber of 100 m (Fig. S1) was drawn at a speed of up to 4 m min^{-1}. The fiber is mechanically flexible, as shown in Fig. 2b. The weight per unit length of the fiber is only 0.11 g m^{-1}. The small diameter and weight, high scalability, productivity, and flexibility, along with the softness, contribute to the fiber's excellent weavability. It was woven into swatches by hand and by an industrial dobby loom (Fig. S2), respectively, which are shown in Fig. 2c and d. Fig. 2e–g shows the twill and plain weave patterns in the loom-woven swatch. The weaving process can be seen in Video S1. Like common cotton fabrics, the swatch could be easily folded, both horizontally and vertically, and stretched diagonally (Fig. 2h–j).

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2.2. Working mechanism and device performance

The FTENG works in the typical single-electrode mode, which has been discussed in previous works [41,42]. It is the coupling of the contact triboelectrification and the electrical induction effects. As can be seen in Fig. 3a, when external materials (*e.g.*, nylon or leather) get into contact with the PP cladding of the FTENG, the triboelectric effect takes place, and negative charges will transfer to and accumulate on the PP surface. When the two surfaces are separated, the electrostatic induction effect is triggered because of the time-varying potential created by the accumulated electrons. The current will flow from the ground to the PP/tungsten interface as the separation goes up. When the two surfaces get closer to each other, the current will flow back to the ground. Such current flow will occur as long as there is contact or separation motion between the PP cladding and external surfaces. Because any conductor can serve as the ground, we utilized a piece of aluminum foil due to its flexibility and lightweight. For better understanding of the triboelectrification-generated potential distribution, we did a numerical

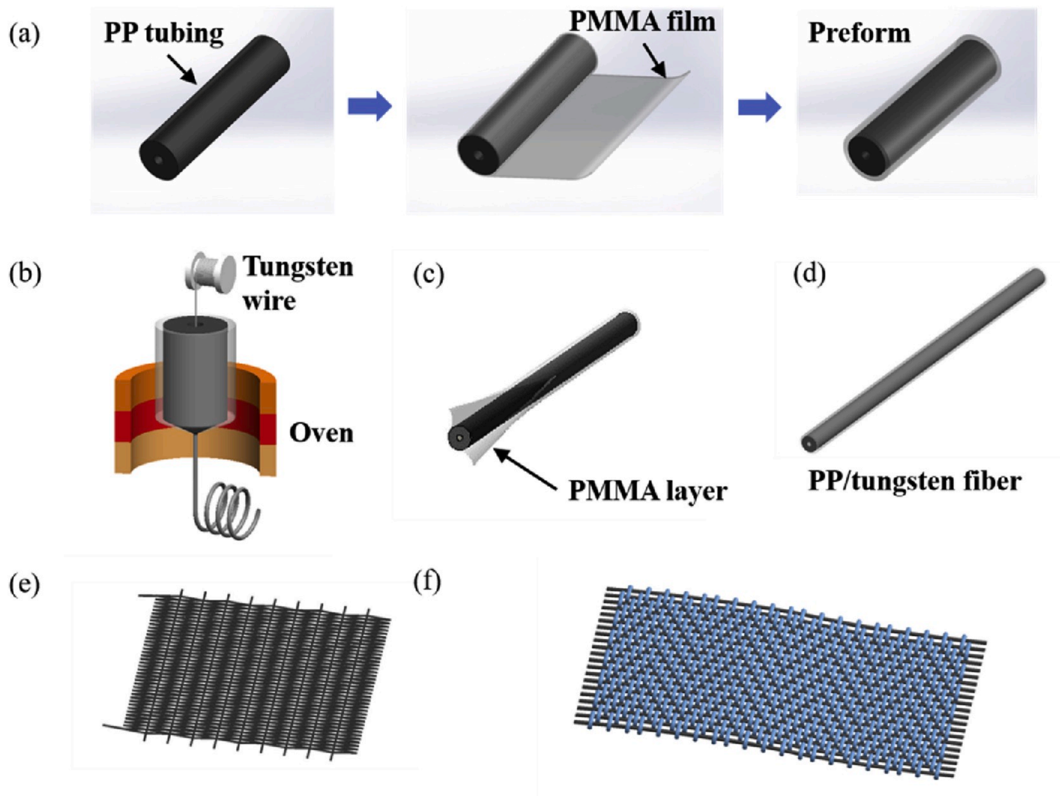

Fig. 1. Thermal drawing of PP/tungsten FTENG and schematics of woven structures. a) Illustration of the fiber preform fabrication. b) Illustration of the fiber thermal drawing process. c, d) The post-drawing process to remove the sacrificial acrylic layer. e, f) Illustration of e) hand-woven and f) loom-woven FTENG-based fabrics. The FTENGs were woven in the warp direction. The weft yarns are non-functional fibers, which are PP fiber in e) and cotton yarns in f) (color print). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

simulation, and the results are shown in Fig. 3b and Video S2, which show the static and dynamic electrical potential distribution, respectively. The charge density on the contacted surfaces was set to be 1 μC m^{-2}, and the maximum separation was 5 cm. We also investigated thermoplastic polymer-based fibers, and fabricated a PC-cladding FTENG. The fabrication process and fabrics are shown in Figs. S3 and S4.

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The electrical output of the swatch shown in Fig. 2c was quantitatively tested. A 1-inch x 1-inch (25.4 mm × 25.4 mm) nylon plate was driven by a linear motor to apply forces on the FTENG swatch cyclically (Fig. S5). As can be seen in Fig. 4, we investigated the effects of the applied force and the cycle frequency on the outputs. When the cycle frequency was fixed at 8 Hz (Fig. 4a), the short-circuit transferred charge (Q_{SC}) went up from 6.2 nC to 10.0 nC when the force was increased from 30 N to 90 N. This change was because a larger force will result in a larger contact area and, subsequently, stronger triboelectrification. As both the open-circuit voltage (V_{OC}) and the maximum short-circuit currents (I_{SC}) are dependent on the charge amount, they also increased when the force increased, going from 12.9 V to 0.42 μA to 21.4 V and 0.78 μA, respectively. When the applied force was fixed at 70 N (Fig. 4b), Q_{SC} and V_{OC} remain constant around 8.8 nC and 18.9 V, respectively. The peak short-circuit currents (I_{SC}) was increased from 0.11 μA to 0.68 μA when the moving frequency increased from 2 Hz to 8 Hz. This significant change was based on the formula: $I = Q/t$. Since Q_{SC} was nearly a constant in this test series, I_{SC} was inversely proportional to the frequency. When the force and frequency were fixed at 70 N and 8 Hz, the fabric's output current was measured with different external loads, and the power density (*PD*) was accordingly calculated with the following formula.

$$PD = \frac{I^2 R}{m} \tag{1}$$

where *I* is the maximum current, *R* is the external resistance, and *m* is the mass of the functioning FTENG. As mentioned in Ref. [17], there is currently no universal standard to evaluate the electrical output of FTENGs. While power per area is popularly used for evaluation, the diameter and the mass density, which are important parameters in wearable devices, cannot be reflected. Thus, we propose using power per weight that takes all the parameters mentioned above into consideration. The *PD* peaked at 43.0 mW kg^{-1} with an external load of 80 MΩ (Fig. 4c). To evaluate the durability of the FTENGs, we did a cyclic test for 100,000 cycles. The results (Fig. 4d) showed no obvious change of output in terms of I_{SC}. Besides, in the washability tests (Fig. 4e), the contaminant was first poured onto the fabrics (Fig. S6), and then washed with flowing water and naturally dried. The output was stable after each wash cycle. To evaluate the breathability of the FTENG swatches, we conducted air permeability tests following ASTM D737 with a commercial air permeability tester (Fig. S7). Under the pressure of 125 Pa, the air permeability of the swatch was 523.0 cm^3 cm^{-2} s^{-1}. This good breathability is because of the space between the fibers and the slick surfaces of the fiber claddings [17]. The output of the swatch loomed with PC cladding FTENG shown in Fig. S3a was also quantified and displayed in Fig. S8. The trends were the same. When the cycle frequency was fixed at 8 Hz, Q_{SC}, V_{OC}, and I_{SC} went up from 10.77 nC, 21.8 V, and 0.55 μA to 15.2 nC, 30.6 V, and 0.96 μA, respectively; when the applied force was fixed at 70 N, Q_{SC} and V_{OC} stabilized around 14.1 nC and 27.8 V, and I_{SC} went up from 0.14 μA to 0.86 μA. The highest *PD* was 67.4 mW kg^{-1}, and it as well showed good durability, washability, and breathability (394.8 cm^3 cm^{-2} s^{-1}).

The energy generated by the FTENG could be consumed instantly or

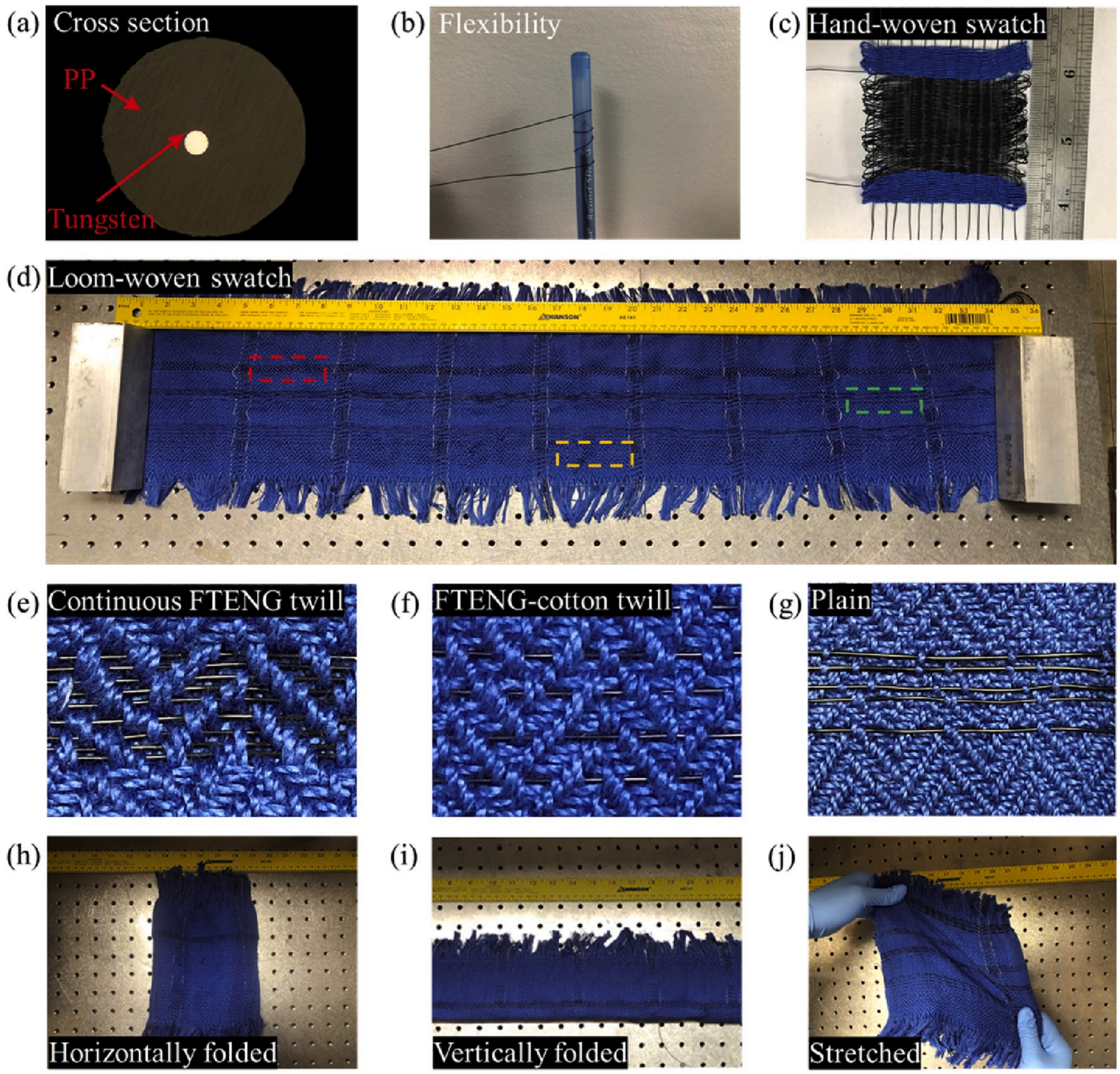

Fig. 2. Images of FTENG a) Optical microscope image of the cross section of FTENG. The diameter of the tungsten wire is 50 μm. b) Flexible FTENG wrapped on a pen. c) A hand-woven FTENG swatch (4 cm × 6 cm) d) A loom-woven swatch (~90 cm width). The FTENG is embedded in cotton (blue) yarns. e-g) Three areas in d). e) Red box: continuous-FTENG twill weaving; f) Yellow box: FTENG-cotton twill weaving; g) Green box: plain weaving. h, i) FTENG swatch being folded h) horizontally and i) vertically. j) FTENG swatch being stretched. (color print). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

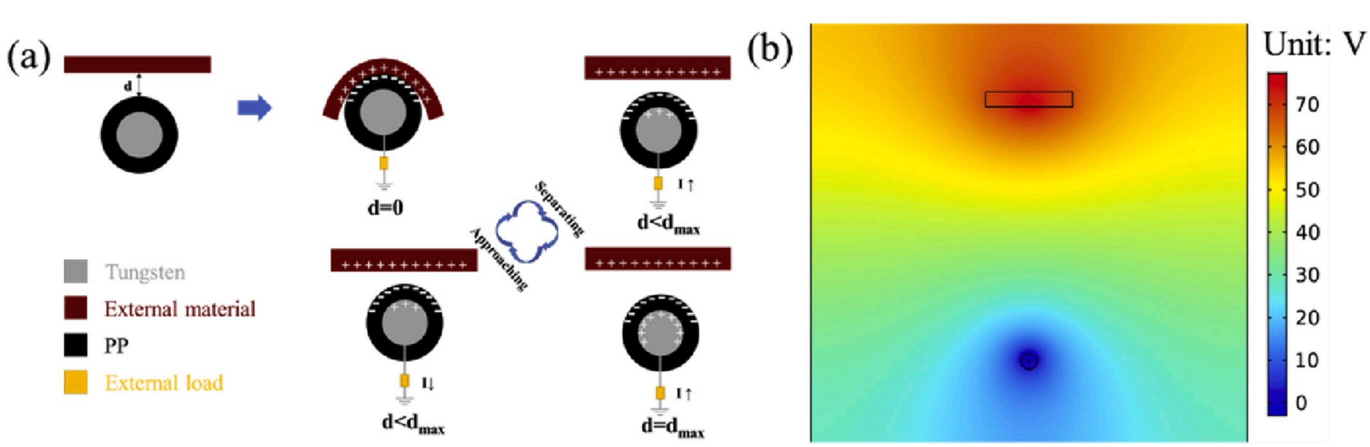

Fig. 3. The working mechanism of FTENG. a) Schematic of the working mechanism of the FTENG in single-electrode mode. The core/cladding ratio is much larger than the actual fiber for better illustration b) Numerical simulation of the potential distribution when external material and FTENG are contacted and separated by COMSOL software. (color print). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

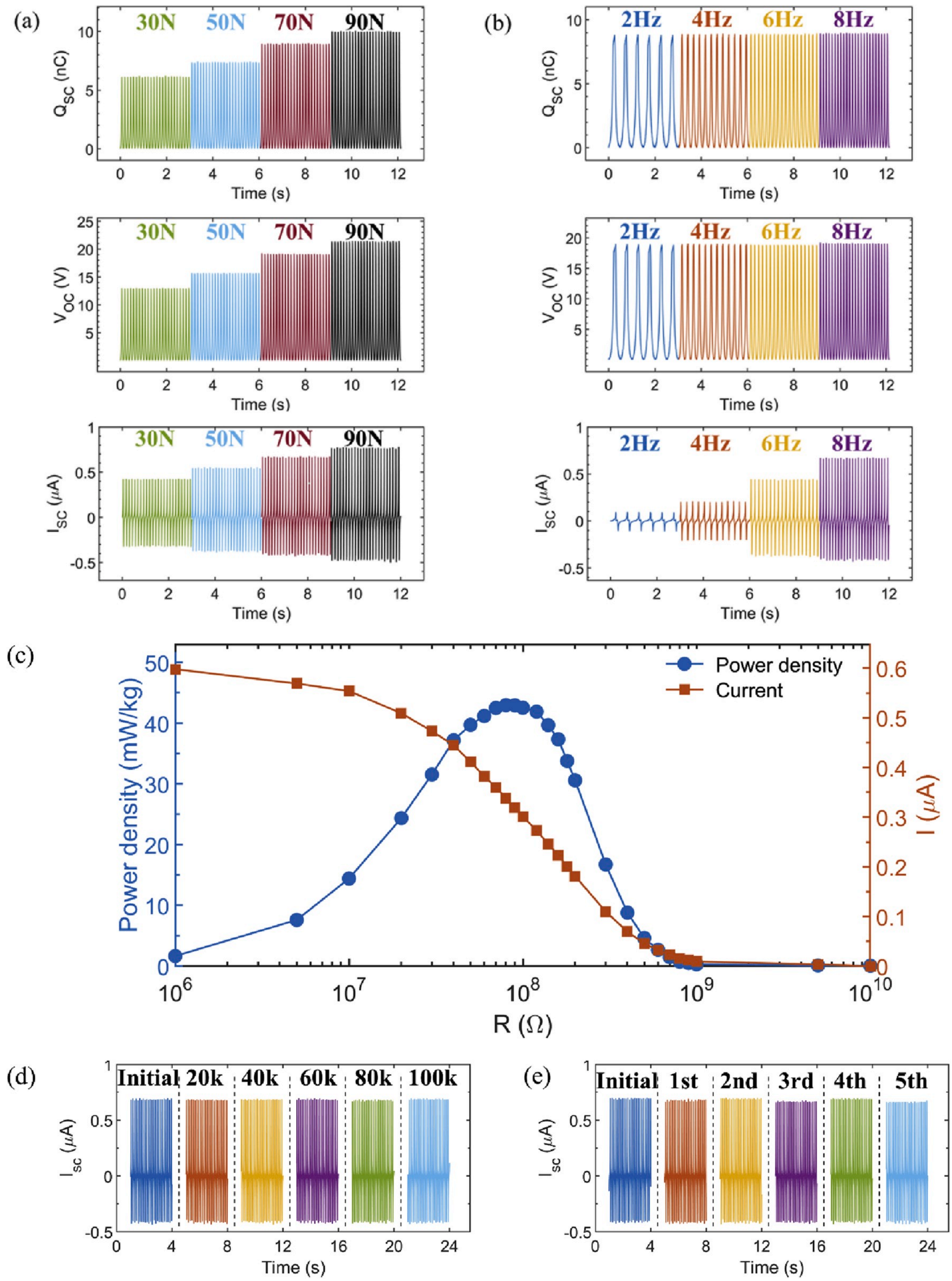

Fig. 4. The electrical output of PP/tungsten FTENG. Q_{SC}, V_{OC}, and I_{SC} of the swatch shown in Fig. 2c. The a) applied force and b) cycle frequency was fixed during the test. c) The current and power density of FTENG when connected to different external loads. d) Durability test. e) washability test. (color print). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

stored for later uses. Fig. 5a shows that a series of 62 commercial green LEDs were immediately lit up by the FTENG, where the brightness was dependent on the current. Fig. 5b shows the charging curves for commercial capacitors with different capacitances. The standard rectifier circuit was used in the charging. For the three capacitors, which are 0.1 μF, 0.22 μF, and 0.47 μF, respectively, the saturation voltage (55 V) was reached with charging times of 0.8 min, 1.8 min, and 3.6 min, respectively. The charging time is determined by the following formula:

$$Q = CU = It \tag{2}$$

where Q is the charge stored in the capacitor, C is the capacitance, U is

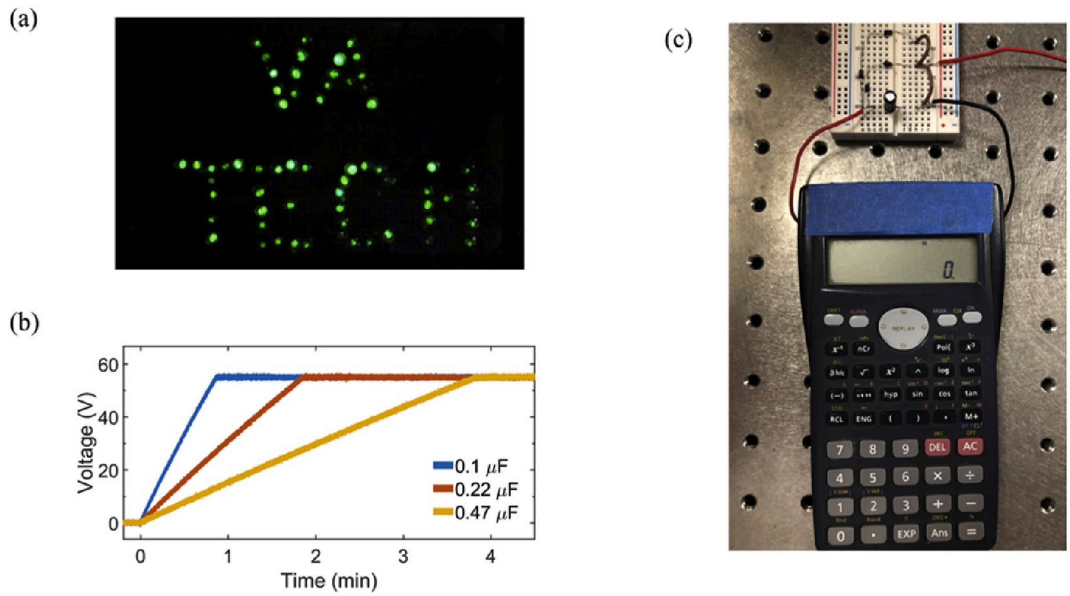

Fig. 5. FTENGs works as power sources. a) A series of 62 commercial green LEDs lit up by rubbing a ~20 cm^2 swatch on a cotton shirt. b) Charing curves of three commercial capacitors. c) Commercial calculator powered by the FTENG. (color print). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

the saturation voltage, I is the charging current, and t is the charging time. Fig. 5c shows that the energy stored in the capacitor was used to power a commercial calculator. In real applications, because the electric output is highly dependent on the amplitude of human motion, and the force and speed can easily exceed the ones used in the tests, we can expect much higher energy harvesting amount to power larger electronics and generate more energy for storage.

2.3. Self-powered sensors

The FTENG allows for sensors to be distributed on multiple points of the body while being locally powered. Distributing sensors across the body has advantages over a lone sensor at one point on the body because it enables much finer-grained activity classification by monitoring the movements of different locations on the body [71–75]. Besides, the FTENG sensors offer more comfortability than the traditional accessory-based sensors, *e.g.*, watches and glasses, because they are flexible and lightweight. We have demonstrated the self-powered sensors for bio-monitoring and communication uses. As can be seen in Fig. S9, the FTENGs were mounted at the backside and the inner sides of the leg for movement sensing. At the inner side, the FTENG was used as a pedometer by sensing the relative movement between the two legs. Because the open-circuit voltage is proportional to the distance between the two legs, each step corresponds to a peak in Fig. 6a. At the backside, the FTENG was used as a sitting timer by sensing the relative distance between the leg and the chair. When the leg approached the chair, the open-circuit voltage decreased accordingly, and vice versa. Users can also customize the threshold of the sitting voltages (Fig. 6b). Another typical self-powered FTENG sensor is to extract the Morse codes generated by tapping (Fig. S10). The dots and dashes in voltage curves can be controlled by the contacting time (Fig. 6c). With the advantage of the length of the fiber, such a sensor will be useful for long-distance communication in emergencies (*e.g.*, earthquake and oil well explosion) in which plant power and other electronics are damaged. In these cases, the FTENG-based self-powered sensors offer users accuracy, customization, comfortability, and security.

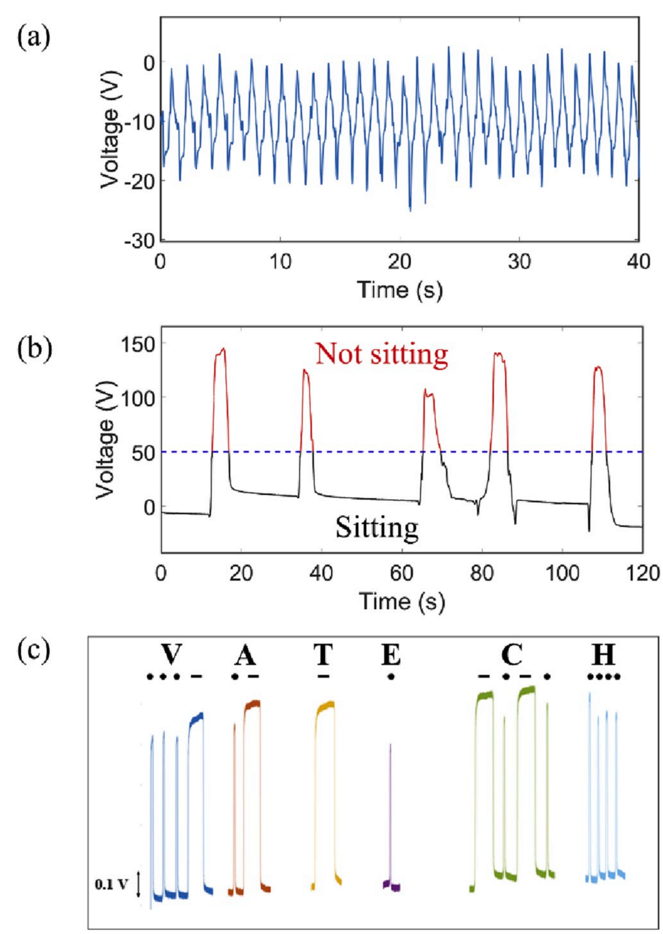

Fig. 6. FTENG works as self-powered sensors. a) pedometer b) sitting timer c) morse code generator. (color print). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

3. Conclusion

In summary, the thermal drawing process is introduced to FTENG fabrication to bridge the gap between the FTENG and the weaving industry. We used an ultrathin metal wire core as the electrode and polymer cladding as the triboelectric material. The fiber's weavability has been significantly improved due to its small diameter, large scalability and high productivity. The FTENG was ~350 μm diameter and ~100 m long. The highest drawing speed was up to 4 m min^{-1}. Both semicrystalline and amorphous materials have been successfully demonstrated as cladding materials in the thermal drawing. The broad options of materials could satisfy not only the electrical but also the aesthetic needs. The fibers were woven into flexible fabrics and can be further tailored to clothes for wearable use. The harvested energy was instantly released to light up 62 commercial LEDs and stored in a capacitor to power up a commercial calculator. The durability and washability tests showed that the electrical output was stable after 100,000 cycles and 5 washing cycles, and the swatches showed good breathability in the air permeability tests, ensuring its great potential for wearable applications. Serving as self-powered sensors, FTENG has the advantage of being mounted in various locations of the human body to be more user-friendly. It can be used to track the body motions with good flexibility and lightweight. Also, it offers an efficient way for emergency communication while being almost imperceptible in other time. The thermally-drawn FTENG makes it possible to distributedly harvest energy and power up electronics. Its versatility as self-powered sensors offers a new direction for biological and communication use. What's more, it could realize these functions by seamlessly embedding itself in the clothes. Such a multifunctional device can serve people with great comfortability in the era of IoTs.

4. Materials and methods

Fiber fabrication: The fiber preform consisted of a PP tubing (Mcmaster-Carr) wrapped by acrylic films (SolaTuf). The inner and outer diameter of the PP tubing were 5 mm and 20 mm, respectively. The diameter of the preform was 26 mm. The wrapped structure was baked for consolidation for 30 min at 140 °C. Then, the preform was machined to be 15 cm long. The preform was then drawn with a custom-built fiber draw tower at temperatures of 145 °C (top), 245 °C (middle), and 100 °C (bottom). During the drawing, the tungsten wire (Mcmaster-Carr) was fed into the hollow channel of the PP tubing. After the drawing, the sacrificial acrylic layer was peeled off to expose the PP layer. The fiber diameter was measured by a laser micrometer (Laserlinc, TLAser 222).

Characterization: The optical image of the FTENG was characterized by a microscope (Axiovert 25). A linear motor (LinMot E1200) was used to control the contact and separate motion for the FTENG. The applied force was measured by a sensor interface (Vernier LabQuest 2). The Q_{SC}, V_{OC}, and I_{SC} were measured by a programmable electrometer (Keithley 6514), and the data were exported by a data acquisition (DAQ) device (National Instrument, USB-6211) and LabVIEW programs. The breathability was tested with an air permeability tester (SDL Atlas M021A).

Declaration of competing interest

The authors declare no conflict of interest.

CRediT authorship contribution statement

Ziang Feng: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing - original draft, Visualization. **Shuo Yang:** Conceptualization, Methodology, Writing - review &; editing. **Sixian Jia:** Conceptualization, Methodology. **Yujing Zhang:** Methodology, Resources. **Shan Jiang:** Data curation, Visualization. **Li Yu:** Methodology, Resources. **Rui Li:** Methodology, Data curation. **Guowen Song:** Methodology. **Anbo Wang:** Methodology. **Thomas Martin:** Methodology, Writing - review &; editing. **Lei Zuo:** Supervision, Project administration, Writing - review &; editing. **Xiaoting Jia:** Supervision, Project administration, Funding acquisition, Writing - review &; editing.

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Appendix A. Supplementary data

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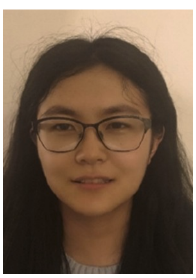
Ziang Feng received his B.S. degree in Optical Information Science and Technology and MEng degree in Optical Engineering from Beijing Jiaotong University in China in 2012 and 2015, respectively. He is currently a Ph.D. candidate in the Bradley Department of Electrical and Computer Engineering at Virginia Tech. His research interests include energy harvesting, multimaterial fibers, and fiber-optic sensors.

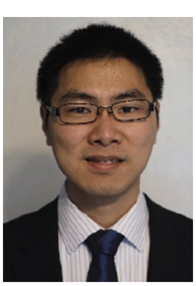
Shuo Yang received his B.E. degree in Electronics Engineering from Shanghai Jiaotong University in China (2014). He is currently a Ph.D. candidate in the Bradley Department of Electrical and Computer Engineering at Virginia Tech under the supervision of Dr. Anbo Wang. His research interests include femtosecond laser micro-fabrication, fiber-optic sensors, fiber interferometers, and special fiber fabrication.

Sixian Jia is currently an undergraduate student in the Department of Mechanical Engineering at Virginia Tech. She is working in the Energy Harvesting and Mechatronics research group under the supervision of Dr. Lei Zuo. Her research interests include fluid energy harvesting and piezoelectric energy harvesting.



Yujing Zhang received her B.S. degree in physics from University of Science and Technology of China in 2017. She is currently a Ph.D. candidate in the Bradley Department of Electrical and Computer Engineering at Virginia Tech under the supervision of Dr. Xiaoting Jia. Her research interests include multifunctional fiber sensor, soft bioelectronics and biomedical devices.

Shan Jiang received her B.S. degree in School of Materials Science and Engineering in Huazhong University of Science and Technology in China and M.S. in Electrical Engineering in Washington University in St. Louis in 2014 and 2015, respectively. She is currently a Ph.D. candidate in the Bradley Department of Electrical and Computer Engineering at Virginia Tech. Her research interests include multimaterial fibers for biomedical applications.



Li Yu obtained his Ph.D. degree in Electrical Engineering from Virginia Polytechnic Institute and State University in 2018. During his graduate study in the Center for Photonics Technology at Virginia Tech, he has focused on fiber optics, fiber optical sensors as well as design and fabrication of multi-material, multi-functional fibers. He is a member of SPIE, the international society for optics and photonics, and the Optical Society (OSA).

Rui Li, Manger for LABS and special projects, Laboratory for Functional Textiles and Protective Clothing (LABS), Iowa State University. Rui's research focuses on functionality and performance evaluation of textile materials and clothing systems, including testing device development, hazards simulation, and customized assessment protocol development.

Guowen Song, Associate Professor and Noma Scott Lloyd Chair in Department of Apparel, Event and Hospitality Management, Iowa State University. Guowen's academic interest is on textile material and clothing for human safety and health. His work involves modeling studies of textile materials and protective clothing, development of devices and test protocols and analysis of textile and clothing performance. His research aims to develop new textile materials and clothing systems through mechanisms and fundamentals associated with heat and mass transfer between human body, clothing and environment. These studies include application of instrumented manikins (sweating, flash fire, hot liquid, etc).

Anbo Wang received his doctoral degree in optics from Dalian University of Technology, Dalian, China in 1990. He joined the faculty of Department of Electrical and Computer Engineering at Virginia Tech in 1994. He founded the Center for Photonics Technology in 1997. Dr. Wang is an author of 350 journal and conference papers and 25 U S. and international patents in the field of fiber optics and sensors. Dr. Wang has supervised more than 100 graduate students and postdocs during his tenure at Virginia Tech and currently holds the Clayton Ayre Professorship.

Tom Martin is a professor in the Bradley Department of Electrical and Computer Engineering at Virginia Tech, with courtesy appointments in the School of Architecture + Design and the Department of Computer Science. He is the co-director of the Virginia Tech E-textiles Lab and the Deputy Executive Director of the Virginia Tech Institute for Creativity, Arts, and Technology. He received his Ph.D. in Electrical and Computer Engineering from Carnegie Mellon University. His research and teaching interests include wearable computing, electronic textiles, and interdisciplinary design teams for pervasive computing.

Lei Zuo is a professor of mechanical engineering and electrical engineering at Virginia Tech. He is the director of NSF IUCRC Center for Energy Harvesting Materials and Systems, an industry consortium with sites at Virginia Tech, Columbia University, and Penn State University. His research interests include energy harvesting, ocean energy, vibration control, mechatronics design, advanced manufacturing, and thermoelectricity. He has published over 270 papers and received the 2017 ASME Leonardo Da Vinci Award, 2015 ASME Thar Energy Design Award, 2014 R R. Teetor Educational Award, 2015 and 2011 R&D100 Awards. He completed his PhD from MIT and BS from Tsinghua University.

Xiaoting Jia is an assistant professor in the ECE department at Virginia Tech. Her research focuses on multimaterial fibers for wearable and biomedical applications. Before joining Virginia Tech, she was a postdoc associate in the Research Laboratory of Electronics at MIT. She received her Ph.D. in Materials Science and Engineering from MIT (2011), M.S. in Materials Science and Engineering from Stony Brook University (2006), and B.S. in Materials Science from Fudan University in China (2004). She is a recipient of NSF CAREER award, 3 M Non-Tenured Faculty Award, ICTAS Junior Faculty Award at Virginia Tech, and the Translational Fellow at MIT.