Textile triboelectric nanogenerator for wearable electronics

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Abstract

Textile-based electronics have attracted increasing interests due to the huge demand for wearable technologies. Working as the energy harvesting devices, textile triboelectric nanogenerators (t-TENGs) have exhibited remarkable superiority in mechanical energy harvesting for the future lightweight, portable, flexible, and green energy supply in wearable system. Here, a brief review will be given focusing on the recent progress of t-TENG, including the evolution of device structure, demonstrations of various self-powered systems, further integration capability with other kinds of energy devices, etc. All of these progresses reveal the power of this mechanical energy harvesting technology as a very appealing part in wearable electronics. Copyright © 2018 VBRI Press.

Keywords: Textile triboelectric nanogenerator, wearable technology, energy device.

Introduction

Textile-based electronics attract more and more interests due to the huge increased demand in wearable technologies [**1-3**]. Various electronic elements have been developed including sensors [**4-9**], field effect transistors [**10-13**], energy harvesters [**14-16**], energy storages [**17-20**], etc. Generally, there are two categories of textile-based electronics: (1) textile with classical electronic devices embedded in or attached [**9, 15**], (2) textile of which itself working as the electronic devices [**8, 10, 18**]. Comparing to the first category, textile-based electronics belong to the second category can provide a higher degree of wearing comfort and more flexibility in design. Since the first introduction in 2012 [**21**], as an emerging mechanical energy harvesting technology, high efficiency with simple structure makes triboelectric nanogenerator (TENG) a feasible solution for energy scavenging in diverse application circumstances [**22-32**]. Recently, textile based triboelectric nanogenerators (t-TENGs) belong to the second category have presented their superiority for light-weight, flexible and multifunctional in both motion sensing and energy harvesting for wearable technologies [**33-46**]. In the following, we will introduce several representative works to show how the device structure evolved and their classification. At the same time, various demonstrations of self-powered systems have been done to reveal the diverse application prospects. Finally, integration of t-TENGs with other kinds of energy devices will be reviewed to show the extended capability of this technology for further growth.

Fiber-based structure sewed in fabric

The first representative construction of t-TENG is based on fiber [**33, 34**]. In such construction, the complete device structure is built on a couple of fibers and sewed in fabric to work as the garment for energy harvesting. **Fig. 1** shows a very good demonstration done by J. Zhou and co-workers. As shown in **Fig. 1a**, TENG is fabricated on commercial cotton thread. After hydrophilic pretreatment, the thread was first dip-coated with carbon nanotube inker to possess conductivity with a constant resistance of ~ 0.644 kΩ/cm. Then the carbon nanotube coated cotton thread (CCT) was further treated with polytetrafluoroethylene (PTFE) coating and a sequence annealing process to get the so-called PTFE and carbon nanotube coated cotton thread (PCCT). Finally, a CCT and a PCCT were twisted with each other to form a double helix structure, as shown in **Fig. 1b.** The as-fabricated device shows very good flexibility. **Fig. 1c** shows that it can be easily bent and curved into a circle. The good flexibility makes it possible to sew the modified fibers into fabrics, as shown in **Fig. 1d.** The PTFE surface and the outer layer of the PCCT works as the two different friction surfaces. When the structure was stretched, power was generated, as shown in **Fig. 1e. Fig. 1f** shows that current generation performance of twisted fibers though an external load of 80MΩ with different stimulation strains of 0, 0.54%, 1.08%, 1.61%, and 2.15% for a given frequency of 5 Hz. When the strain increased, the current increased correspondently. Furthermore, a wireless body temperature sensor system

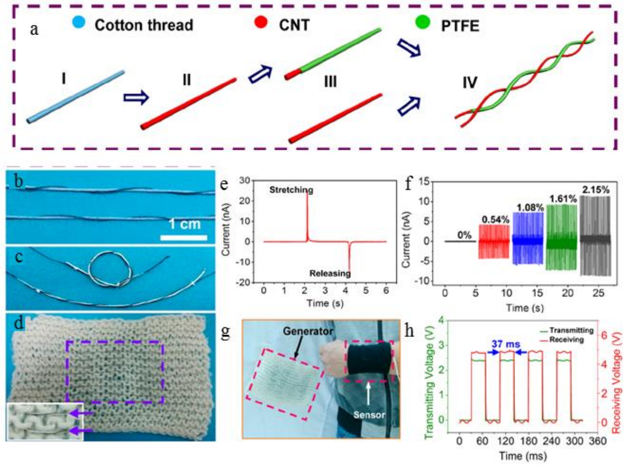

Fig. 1. Construction and characterization of t-TENG is based on fiber. (a) Schematic of TENG fabrication process. (b) A CCT and a PCCT twisted with each other to form a double helix structure and (c) good flexibility of it. (d) The modified fibers sew into fabrics. (e) Power generated when structure is stretched. (f) Current generation performance of twisted fibers though an external load of 80MΩ with different stimulation strains. (g, h) A wireless body temperature sensor system was demonstrated by integrated eight twisted fibers into a fabric to work as a trigger. Reprinted with permission from [33]. Copyright 2014 American Chemical Society.

was demonstrated by integrated eight twisted fibers into a fabric to work as a trigger, as shown in **Fig. 1g** and **1h**. The electricity generated by the fabric was used to charge a 10 nF capacitor. When a threshold voltage reached, a wireless body temperature sensor system will be triggered to realize temperature detection and sent out the signal wirelessly to a receiver. This work proof the concept of the fiber based TENG for energy harvesting textile.

Textile as friction surface in two-layer structure

In previously, it has been demonstrated that a rough surface can benefit the triboelectrification process [**36, 37**]. One dominant design of t-TENG is taking the advantage of rich surface morphologies of textile to construct at least one of the friction surfaces [**38-45**]. We take the work done by S.-W. Kim and co-workers as an example to exhibit the feasibility of this approach [**38**]. As shown in **Fig. 2a,** a piece of textile was first coated with Ag, followed by hydrothermal growth of ZnO nanorod arrays and polydimethylsiloxane (PDMS) dip coating. Then an Ag-coated textile and a PDMS nanopatterns based on ZnO nanorod arrays on an Ag-coated textile template were used as the two friction surfaces to construct t-TENG. The whole structure is fully flexible and foldable. The textile's rough surface together with the nanopatterned PDMS ensure a high efficient triboelectrification process. Under a compressive force of 10 kgf, the t-TENG produced a very high output voltage around 120 V and a output current about 65 µA, as shown in **Fig. 2b** and **c,** respectively. Finally, a multilayer-stacked t-TENG is affixed on a jacket. In addition, a LCD screen, six green in-series connected LEDs, a remote control (keyless vehicle entry system), and power controller switches were also embedded in the jacket at different positons. It is schematically shown in **Fig. 2d**. Different demonstrations of self-powered system are done by using the multilayer-stacked t-TENG as the power source. It proves potential applications of t-TENGs in smart clothes for wearable electronics.

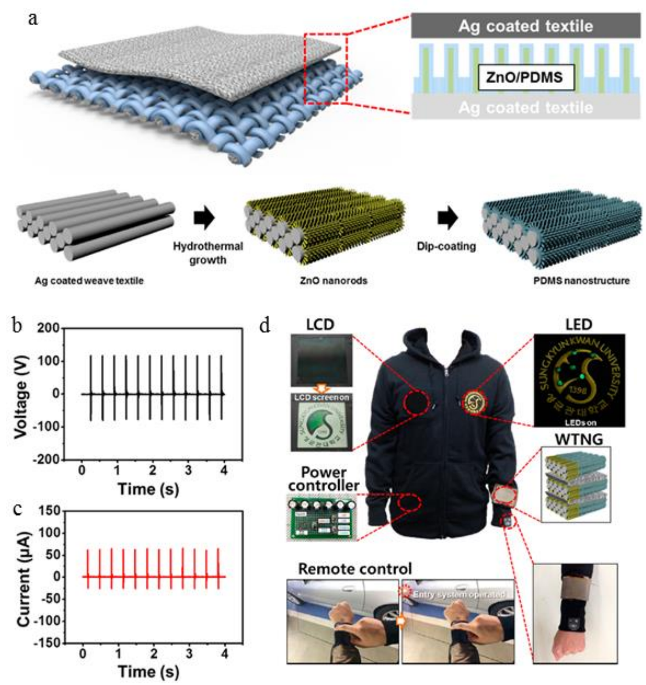

Fig. 2. A dominant design of t-TENG taking the advantage of rich surface morphologies. (a) Schematic of TENG fabrication process. (b, c) Output voltage and output current produced by t-TENG under a compressive force. (d) Different demonstrations of self-powered system by using the multilayer-stacked t-TENG. Reprinted with permission from [38]. Copyright 2015 American Chemical Society.

T-TENG with woven structure

Another big category of t-TENG is based on woven structure. In this case, constructing fibers or strips were first modified, and then woven into the final form [**47-51**]. One of the representative works is shown in **Fig. 3** [**47**]. In this work, nylon fabric, polyester fabric and conductive silver fabric were first cut into strips with a width of a few millimeters. Then silver fabric were sandwiched and encapsulated between two nylon fabric strips or two polyester fabric strips to construct two kinds of building blocks, respectively. Finally, they were woven together to form an energy harvesting garment. The corresponding procedure is sketched in **Fig. 3a**. The garment is working as one of the friction surface in freestanding mode. One of the general working statuses is shown in **Fig. 3b**, which is called as deformation mode. When there is a lateral deformation happened in the garment, the actual contact area between the t-TENG and the freestanding polyester substrate will decrease and increase alternatively, generating an alternating current in the load. To demonstrate the potential applications of the WTENG, it is integrated to shoes, coats, and trousers to harvest different kinds of mechanical energy from body movements, including foot stepping, joint bending, etc., which are summarized in **Fig. 3c-j**.

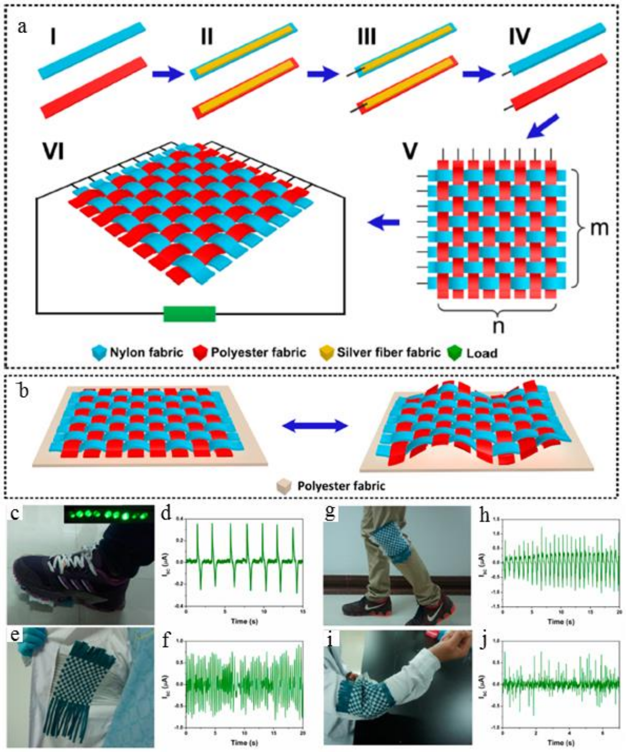

Fig. 3. T-TENG based on woven structure. (a, b) Schematic of TENG fabrication process. (c-j) TENG integrated to shoes, coats, and trousers to harvest different kinds of mechanical energy from body movements. Reprinted with permission from [33]. Copyright 2014 American Chemical Society.

In 2016, we reported that two kinds of modified polyethylene terephthalate (PET) yarns can be woven into an energy harvesting fabric by loom weaving [**49**]. In this rational design, the contact area at each yarn crisscross intersection works as an individual TENG, which takes full advantage of the textile's structure. As shown in **Fig. 4a**, one of the constructing yarns is Cu-coated PET (Cu-PET) warp yarn, and the other one is the polyimide (PI)-coated Cu-PET (PI-Cu-PET) weft yarn. Due to the high breaking strength achieved with these yarns, they can be woven into a fabric by a weaving machine. Triboelectricity generation of this t-TENG is attributed to the contact area change in each yarn crisscross intersection when pressure is applied, as shown in **Fig. 4b. Fig. 4c** shows that when a tapping is applied to the fabric, short circuit current of the t-TENG increased as the tapping velocity increased. Respiration monitoring can be realized by integrated the fabric into a chest strap, as shown in **Fig. 4d**. During each breathing cycle, the expanding and contracting of chest cavity and the abdominal cavity will result in the stretch and release of the t-TENG. The generated signal can be used to identify respiratory rate and depth, which indicates the superior sensitivity of the device. Finally, and most importantly, a machine wash test is carried out, and the t-TENG shows a remarkable washing durability, as shown in **Fig. 4e**. It is worth noting that all the materials used here are well accepted by the textile industry, and the device is fabricated using miniaturized industrial machineries. The textile industry compatibility, the proven machine washability and the sensitivity to subtle human body motions make this demonstrated t-TENG a very promising candidate for further applications in sports, healthcare sectors and many other fields.

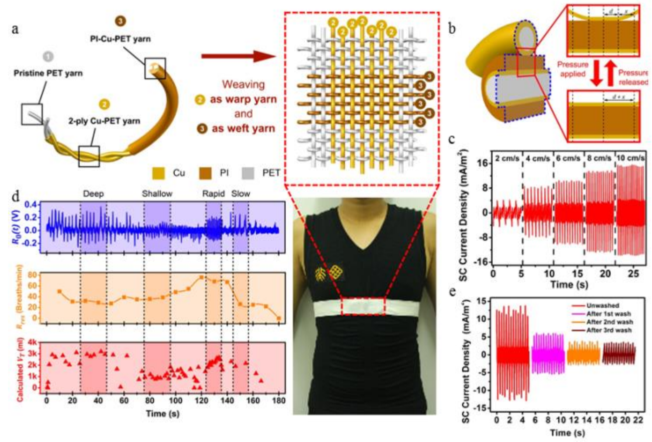

Fig. 4. An energy harvesting fabric by loom weaving. (a, b) Schematic of TENG fabrication process and working principle. (c) Short-circuit current of the t-TENG when fabric is tapped. (d) Respiration monitoring realized by integrated the fabric into a chest strap. (e) A remarkable washing durability. Reproduced with permission [49]. Copyright 2016, WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim.

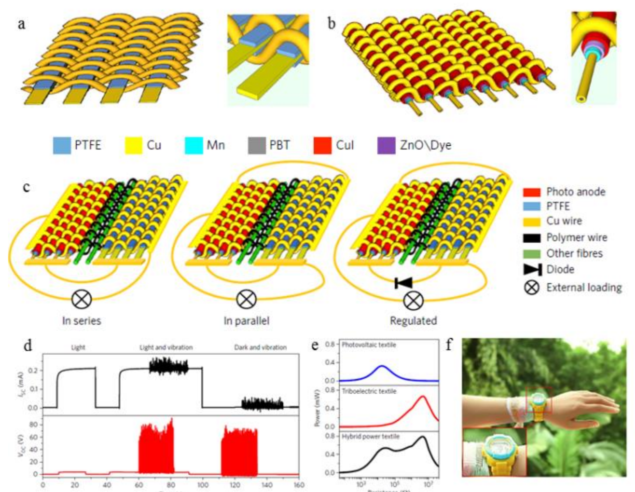

Fig. 5. T-TENG for both solar and mechanical energy harvesting. (a, b) Schematic structure of t-TENG and photovoltaic textile. (c) Solar cells and t-TENG electrical connected in series. (d) Short-circuit current and open-circuit voltage of the hybridizing system under the stimulation of light, vibration and light + vibration. Reproduced with permission [50]. Copyright © 2016, Rights Managed by Nature Publishing Group.

Hybridizing energy harvester textile

In addition to all the progress mentioned above, t-TENG also shows very good compatibility with other kinds of energy harvesting devices to realize multiple-type energy harvesting [**34, 43**]. In one of these works, polymer-fibre-based solar cell is used as the basic component in fabricating a triboelectric nanogenerator for both solar and mechanical energy harvesting [**50**]. **Fig. 5a** and **b** shows the schematic structure of t-TENG and photovoltaic textile, respectively. The Cu-coated polymer fiber works as the counter electrode in solar cell and also one of the electrodes in the t-TENG. Strings of wire-shaped photoanodes, Cu-coated polytetrafluoroethylene (PTFE) stripes and Cu-coated polymer fiber electrodes were woven in a staggered way to achieve the hybrid power textile via a shuttle-flying process. Solar cells and t-TENG can be electrical connected in series, in parallel or regulated with unidirectional blocking diodes for different application circumstances, as shown in **Fig. 5c**. When connected in series or in parallel, **Fig. 5d** shows the corresponding response of short-circuit current and open-circuit voltage of the hybridizing system under the stimulation of light, vibration and light + vibration, respectively. Most importantly, indicated by the data shown in **Fig. 5e,** in addition to the increased output power, the range of load resistance is also expanded when the hybrid power textile is utilized comparing to both individual components. Finally, as a demonstration, the hybrid power textile can be used to continuously drive an electronic watch when it is wrapped around the wrist.

Integration of t-TENGs with textile energy storage devices

To store extra energy harvested by t-TENG for later use, textile based super capacitor and lithium- ion battery are integrated with t-TENG [**35, 44, 45, 51**]. One representative work is shown in **Fig. 6** [**44**]. In this demonstration, an all-solid-state yarn supercapacitor is fabricated by assembling two reduced graphene oxide (rGO) / Ni coated 1D fabric and poly(vinyl alcohol) (PVA)/H_3PO_4 gel as solid electrolyte and separator, which is shown in **Fig. 6a**. The yarn supercapacitor shows very good electrochemical performance and high flexibility. **Fig. 6b** shows that three yarn supercapacitors in series connection are integrated with a t-TENG fabric by weaving at the side of the fabric. The electrical connection and the equivalent circuit of the self-charging power textile are shown in **Fig. 6c**. The current generated by the t-TENG is rectified and stored into the supercapacitors. When the t-TENG is working in a contact-separation motion with a common cloth at motion frequencies of 5 and 10 Hz, these three yarn supercapacitors can be charged by the fabrics at different speeds, where the voltage profile of the supercapacitors is shown in **Fig. 6d**. This Proof-of-concept demonstration shows a prototype of wearable self-charging power textile for future wearable electronics.

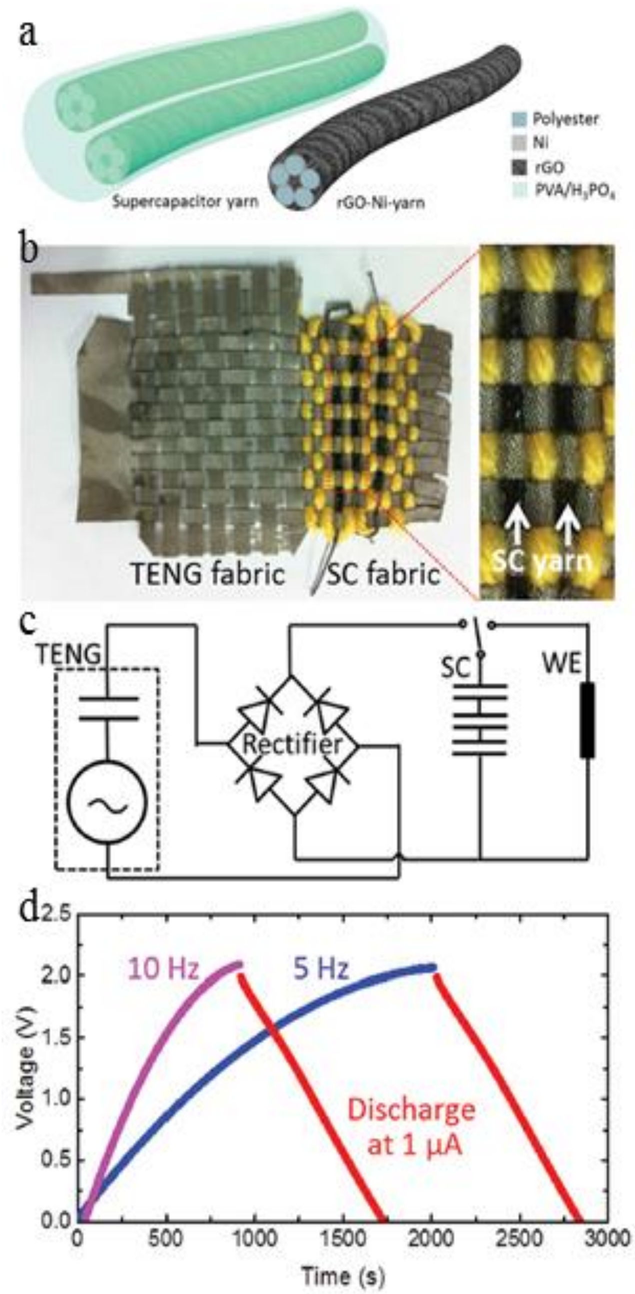

Fig. 6. Textile based super capacitor and lithium-ion battery integrated with t-TENG. (a) Schematic structure of yarn supercapacitor. (b) Yarn supercapacitors in series connection integrated with a t-TENG fabric. (c) The equivalent circuit of the self-charging power textile. (d) Voltage profile of the supercapacitors. Reproduced with permission [44]. Copyright 2016, WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim.

Perspectives

Owning to easy fabrication and promising output performance, t-TENGs have shown great capability to work as the power source in wearable system whether under the form of fibers or garments. The wearing comfort and design flexibility makes t-TENGs very promising for body motion sensing. Various electronic elements have been demonstrated to be powered by t-TENGs as kinds of self-powered system. In the meanwhile, good compatibility with other kinds of energy harvesting devices makes it possible to realize multiple-type energy harvesting.

To store extra energy harvested by t-TENG for later use, textile based super capacitor and lithium- ion battery have been integrated with t-TENG. Further efforts on the material and device design to realize/improve t-TENGs compatibility with textile manufacturing industry for mass production and washability will provide a fantastic solution for the energy issue in wearable technologies in the future.

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