ADVANCED FUNCTIONAL MATERIALS
www.afm-journal.de

ADVANCED SCIENCE NEWS
www.advancedsciencenews.com

Single-Thread-Based Wearable and Highly Stretchable Triboelectric Nanogenerators and Their Applications in Cloth-Based Self-Powered Human-Interactive and Biomedical Sensing

*Ying-Chih Lai, Jianan Deng, Steven L. Zhang, Simiao Niu, Hengyu Guo, and Zhong Lin Wang**

The development of wearable and large-area fabric energy harvester and sensor has received great attention due to their promising applications in next-generation autonomous and wearable healthcare technologies. Here, a new type of "single" thread-based triboelectric nanogenerator (TENG) and its uses in elastically textile-based energy harvesting and sensing have been demonstrated. The energy-harvesting thread composed by one silicone-rubber-coated stainless-steel thread can extract energy during contact with skin. With sewing the energy-harvesting thread into a serpentine shape on an elastic textile, a highly stretchable and scalable TENG textile is realized to scavenge various kinds of human-motion energy. The collected energy is capable to sustainably power a commercial smart watch. Moreover, the simplified single triboelectric thread can be applied in a wide range of thread-based self-powered and active sensing uses, including gesture sensing, human-interactive interfaces, and human physiological signal monitoring. After integration with microcontrollers, more complicated systems, such as wireless wearable keyboards and smart beds, are demonstrated. These results show that the newly designed single-thread-based TENG, with the advantage of interactive, responsive, sewable, and conformal features, can meet application needs of a vast variety of fields, ranging from wearable and stretchable energy harvesters to smart cloth-based articles.

1. Introduction

Wearable technologies have been considered as the next-generation electronics in the near future owing to their promising applications in a vast of fields ranging from biomedical/wellness monitors, wearable human-interactive interfaces, to shape-adaptive military and consumer electronics.[1–4] Typically, those electronics are needed to be powered by rechargeable batteries. However, conventional power sources like electrochemical batteries suffer from heavy weight, bulky volume, and limited capacity and lifetime, largely hindering the practical and sustainable uses of the wearable electronics. Ideally, the need of electric energy can be all or at least partially harvested and converted from surroundings as sustained and self-sufficient power sources.[2–6] For wearable applications, mechanical energy is the most widely distributed and universally available, such as human motion, walking, mechanical triggering, vibration, and so forth; however, the vast majority of those energies is ignored and wasted simply because there is no technology available for high efficient harvesting. To progress sustainable and self-sufficient applications, it is essential to develop large-area wearable energy-harvesting devices to extract energy from human motions.

Besides, one of ultimate goals of wearable electronics is to integrate with textiles and clothes so that the device functions can be conducted along with the fabrics' advantages such as soft, breathability, comfort, and high sustainability.[7–12] Although the textile-based energy-harvesting devices have been demonstrated with the merits including light, and soft,[13–23] the key issues for clothing uses, such as stability, mechanically stretchability, washability, and manufacturability, still need to be addressed. On the other hand, thread-based tactile sensors have shown their potentials in a wide range of applications such as wearable keyboards, user-interactive interfaces, and motion

Prof. Y.-C. Lai, J. Deng, S. L. Zhang, Dr. S. Niu, H. Guo, Prof. Z. L. Wang
School of Materials Science and Engineering
Georgia Institute of Technology
Atlanta, GA 30332-0245, USA
E-mail: zhong.wang@mse.gatech.edu
Prof. Y.-C. Lai
Department of Materials Science and Engineering
National Chung Hsing University
Taichung 40227, Taiwan
Prof. Z. L. Wang
Beijing Institute of Nanoenergy and Nanosystems
Chinese Academy of Sciences
National Center for Nanoscience and Technology (NCNST)
Beijing 100083, P. R. China

DOI: 10.1002/adfm.201604462

sensors.[24–28] By sewing the sensing threads into garment, they can imperceptibly monitore human physiological signals. In literature, Takamatsu et al. demonstrated a wearable keyboard by using capacitive fabric sensors.[25] And, Ge et al. reported a fiber-based resistive-type artificial skin sensor.[26] However, the capacitive- and resistive-type tactile sensing threads are required to be driven by external powers;[24–28] thus, their applications were limited by the bulky and stiff batteries.

Triboelectric nanogenerators (TENGs), which can convert mechanical energy into electricity based on triboelectrification and electrostatic induction, have gained great attention to act as new green and sustainable power providers.[29–33] Advantages of TENGs include efficiency, low cost, stability, robustness, simplicity in manufacturing, and environmental friendliness.[29–33] Not only serving as power generators, the producing electricity from the mechanical triggering reveals the potentials for self-powered sensing uses.[2,3,6,31–34] Developing TENGs based on threads can easily integrate with textile and clothing for large-area scavenging the mechanical energy from body motions as well as self-powered wearable sensing. In previous works, most of the fabrics-based TENGs generated electric output from the contact between two threads or two textiles.[16–21] However, due to the threads and textiles are too soft, it is hard to form perfect contact-separation between triboelectric threads or textiles during human motions, leading to scant outputs in previous textile-based TENGs. Kim et al. demonstrated a stretchable coaxial fiber-structured TENG;[22] however, the needs of large compressive force are impediments for practical uses, and the electrode fabricated by the metal foil is a shortcoming for weaving and wearing applications. Besides, most conducting threads in previous devices were fabricated by physically deposited metals or solution-coated conducting nanomaterials, obstructing the fabric devices to tolerate mechanical deformations and washing in practical uses.[16–26] The stability and uniformity are also challenges for industrial manufacturing. To overcome above issues and progress to a practical level, it is urgently essential to explore new energy-harvesting strategy to simplify the textile-based TENGs.

Herein, we presented a new type of single-thread-based triboelectric energy harvester, which was constructed from a multitwisted stainless-steel thread as the conducting electrode and super-soft silicone rubber as the triboelectric material. The single energy-harvesting thread can harvest human-motion energy through contact with skin. By sewing the energy-harvesting thread into a serpentine shape on an elastic textile, a large-area and highly stretchable energy-harvesting textile (SEHT) was demonstrated for the first time. The generating electric output reached up to 200 V and 200 μA. The capability to harvest different kinds of mechanical energy from human body, including the movement of joints, walking, tapping, etc., was demonstrated. The produced electricity was capable to sustainably power a commercial watch, which can advance the development of self-sufficient wearable and biomedical electronics. Additionally, the triboelectric thread can be applied for sensing static and dynamic forces, serving as active sensors. By sewing the triboelectric threads into a glove, a self-powered gesture sensing glove was performed for identifying digital gestures. The triboelectric thread was also demonstrated to act as wearable human-interactive interfaces for transmitting information from touches. Furthermore, a pulse meter was first realized by using only one triboelectric thread, opening a door for clothing-based imperceptibly monitoring human physiological signal. By integration with microcontroller systems, a wireless wearable keyboard and smart-bed system were applied for more sophisticated applications. It is believed that the newly designed single energy-harvesting thread and the proposed schemes and structures will meet various application needs ranging from wearable and stretchable energy harvesting, thread-based sensing, to biomedical monitoring. The presented methodology is simple, useful, and suitable for mass manufacturing.

2. Results

2.1. Device Structure

The fabrication processes for the single energy-harvesting thread and the elastic SEHT are illustrated in **Figure 1**. Stainless-steel thread was used as the conducting thread. Compared with metal-coated threads,[16–26] the conductive thread was entirely spun from stainless-steel fibers, rendering it tarnish-resistant, reliable, washable, and much more stable. The thread shows a very low resistance and light weights of ≈4 ohms of ≈0.2 g per foot, respectively. And, super-soft yet tough silicone rubber was chosen for the triboelectric materials. The energy-harvesting threads were fabricated by coating silicone rubber on the stainless-steel threads. After that, the energy-harvesting threads can be sewn into a serpentine shape onto the both sides of elastic textile to fabricate the SEHT. Figure 1b shows the top-view and front-view scanning electron microscopy (SEM) images of the stainless-steel thread which comprises multitwisted stainless-steel fibers. A cross-section SEM of the energy-harvesting threads was shown in Figure 1c, illustrating the cylindrical shape of the fabricated thread with a radius of about 750 μm. Figure 1d presents the resulted SEHT with sewing serpentine-shape energy-harvesting threads, and the lower image of Figure 1d demonstrates the stretchability of the SEHT. The result shows that the elastic SEHT can well endure a strain up to ≈100%, which is much higher than the reported stretchable coaxial fiber-based TENG (≈25% strain) fabricated by polydimethylsiloxane (PDMS) and Al-foil.[22] The maximum stretchability can be depended on the elastic textile. The combination of stainless-steel fibers and silicone rubber endows the energy-harvesting thread not only soft but also tough and robust. Figure 1e demonstrates the SEHT being folded, twisted, and crumpled, clearly illustrating the flexible yet robust features of the fabricated energy-harvesting thread and textile.

2.2. Working Mechanisms and Device Performances

In the design, the wire was connected to skin. And, skin was acted as another triboelectric electrode in the textile-based energy harvester so that the device can be efficiently simplified to one triboelectric thread. The working principle of the single energy-harvesting thread to extract human-motion energy is illustrated **Figure 2**a, which is based on a conjunction of contact

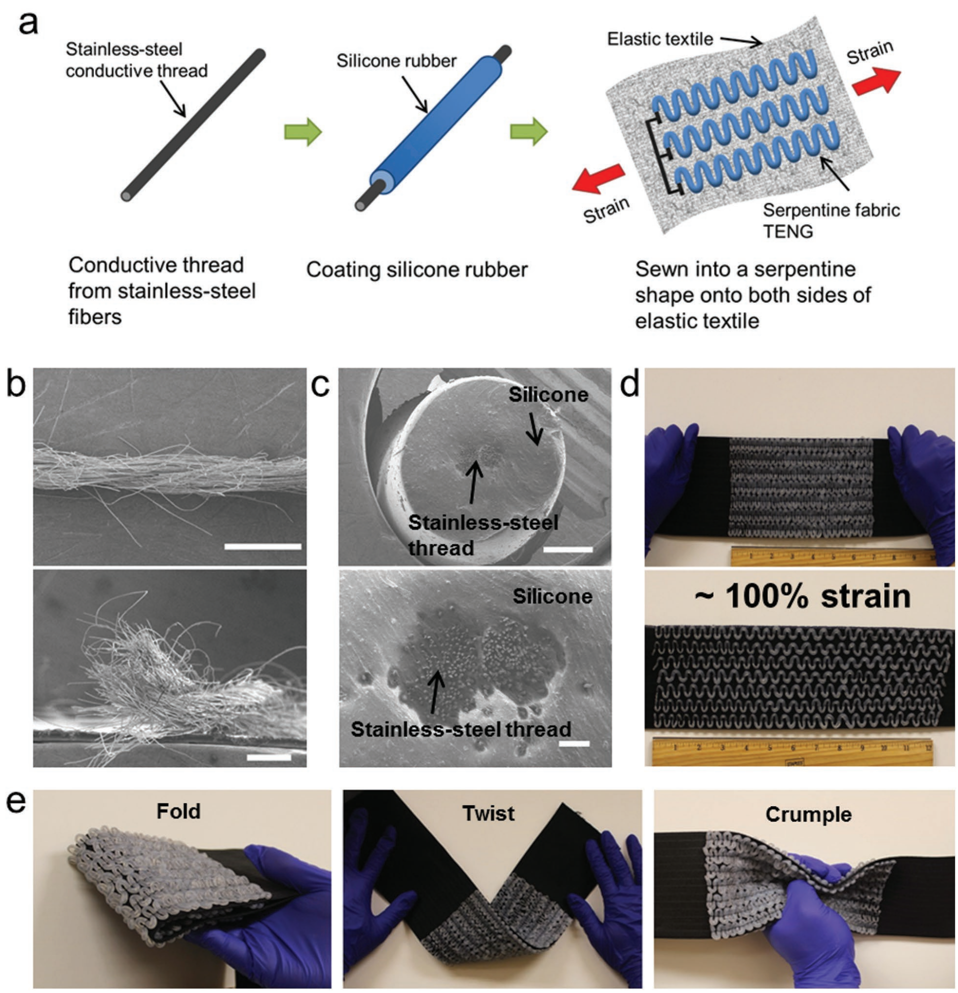

Figure 1. Single-thread-based triboelectric nanogenerator thread and elastically SEHT. a) Schematic diagram for fabrication process of energy-harvesting thread and SEHT. b) Top-view (upper) and front-view (lower) SEM images of multitwisted stainless-steel thread. Scale bars of the upper and lower images are 1 mm and 500 µm, respectively. c) Cross-section view SEM image of triboelectric energy-harvesting thread. Scale bars of the upper and lower images are 500 and 100 µm, respectively. d) Photographs of the as-prepared SEHT with demonstrations of being stretched at ≈100% strain. e) Photographs of device with demonstrations of being different mechanical forces, including folding, twisting, and crumpling.

triboelectrification and electrostatic induction during the contact with skin.[29–33] In triboelectric series, silicone rubber has higher electron affinity than skin.[35] Thus, when the contacts between skin and silicone rubber, electrons will transfer from skin surface to the surfaces of silicone rubber. After these two surfaces are separated, the negative charges on the silicone rubber surface will induce positive charges in the stainless-steel thread, which drives a current flow from skin to the stainless-steel thread. This electrostatic induction process can give an output voltage/current to the load. When negative triboelectric charges on the silicone rubber are equilibrated by the induced charges, no output signals can be observed. Once skin contacts the silicone rubber again, the induced positive charges on the strainless-steel threads decrease, resulting in a current flow from the thread to skin. Continuous contact and separation between skin and the triboelectric thread make continuous electrical outputs from the triboelectric energy-harvesting textile. Figure 2b shows the finite element simulation of the work mechanism, in which the transferred charge density on the top surface of silicone rubber was assumed as -2 µCm^{-2} after skin contact and separation at a distance of 3 cm.

The output performances of the presewn energy-harvesting thread of 5 cm in length were shown in Figure 2c–e. The producing AC-type open-circuit voltage (V_{oc}) and the amount of transferred charge (Q_{tr}) reached about ≈15 V and ≈12 nC, respectively. As a result, the short-circuit current (I_{sc}) reached to ≈7 µA. These values are much higher than previously reported two-fiber-helix-turned TENG (10 nA)[16] and compared favorably with previously reported coaxial-structured TENG (40 V, 10 µA).[22] The thickness (radius) dependence of the device performance was explored in Figure 2f. As increasing the radii of the coated silicone rubbers, the contact areas between the triboelectric threads and skin were increased, resulting in more transferred charges between skin and rubber. Accordingly, both of the increased output V_{oc} and Q_{tr} can be observed. The result is consistent with the trend of simulation results as shown in Figure S1 in Supporting Information. Figure 2g shows the performances of the triboelectric threads that were composed

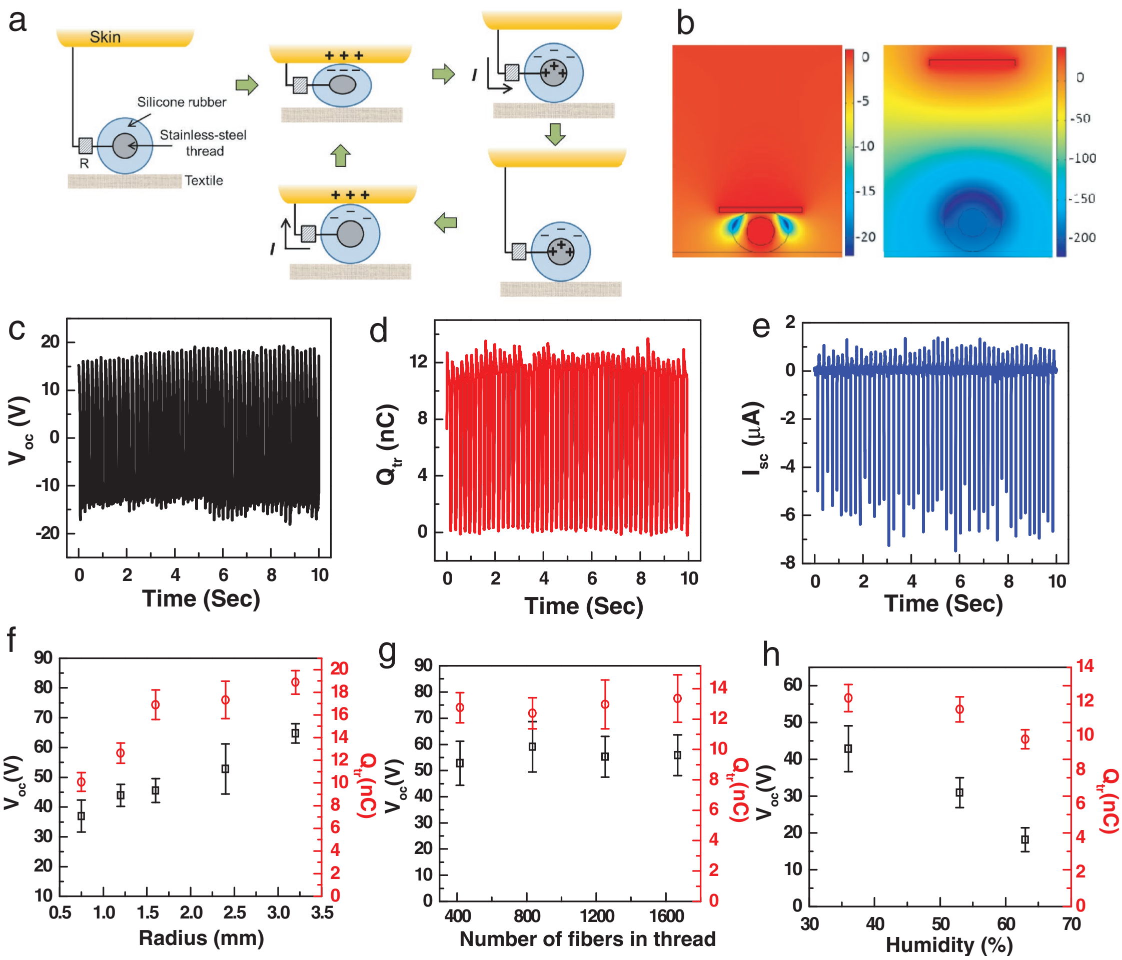

Figure 2. Mechanism and performance of energy-harvesting thread. a) Schematic illustration of working mechanism of single-thread-based energy harvester. b) Finite element simulation of generated voltage difference of single-thread-based TENG when skin contact and separation at a distance of 3 cm. c–e) Output V_{oc}, Q_{tr}, and I_{sc} of 5-cm energy-harvesting thread, respectively. f) V_{oc} and Q_{tr} of single-thread TENGs depending on the radius of coated silicone rubber. g) V_{oc} and Q_{tr} of single-thread TENGs depending on the number of stainless-steel fibers multitwisted in thread. h) V_{oc} and Q_{tr} of single-thread TENGs depending on the environment humidity.

of different number of stainless-steel fibers. The outputs of V_{oc} and Q_{tr} show no significant difference as the number of stainless-steel fibers increases from ≈400 to ≈1600 fibers. This is because the resistance of the stainless-steel thread is quite low. And, in this condition, the contact area (i.e., the radius of silicone rubber here) that governed the amount of transferred charges dominated the performance of the thread TENGs.

Environmental conditions such as temperature and humidity would affect the performance of triboelectric devices.[36] Our group has reported the temperature effect in previous reports.[37] Typically, the TENG performance would be degraded as the room temperature increased, which is due to the fact that the thermal fluctuation lowers the net negative charges on silicone rubber surface and reduces the output.[37] However, the device is aimed to wearable uses; therefore it normally works at a small temperature region from room temperature to body temperature. The humidity dependence on the device performance was investigated in Figure 2h. The output performances of V_{oc} and Q_{tr} degraded as the environment humidity increasing. This is because as the humidity in environment increased, more water in environment was adsorbed onto the silicone rubber surface, preventing the charge transfer between two contacted surfaces and leading to the degraded outputs.[36]

Moreover, Figure S2 in the Supporting Information compares the device performances of the silicone rubber-coated and PDMS-coated threads. PDMS is one common material for designing textile-based TENGs.[13,17,22] As shown in Figure S2 in the Supporting Information, the performances of silicone-rubber-coated threads showed much better output performances than the PDMS-coated threads. This can be ascribed to the facts: (i) the higher difference of the surface electron affinities between the silicone rubber and skin,[35] and (ii) the softer silicone rubber making more conformal contact with skin and endowing more contact surfaces.

Figure 3a–c shows the output performance of the SEHT with a size of 6.5 × 4.5 in.^{2}. The working principle of the SEHT is shown in Figure S3 in the Supporting Information. The resulted SEHT can generate a V_{oc} and Q_{tr} of up to ≈200 V and ≈300 nC, respectively. And, I_{sc} can achieve ≈200 μA. These performances are comparable with previously

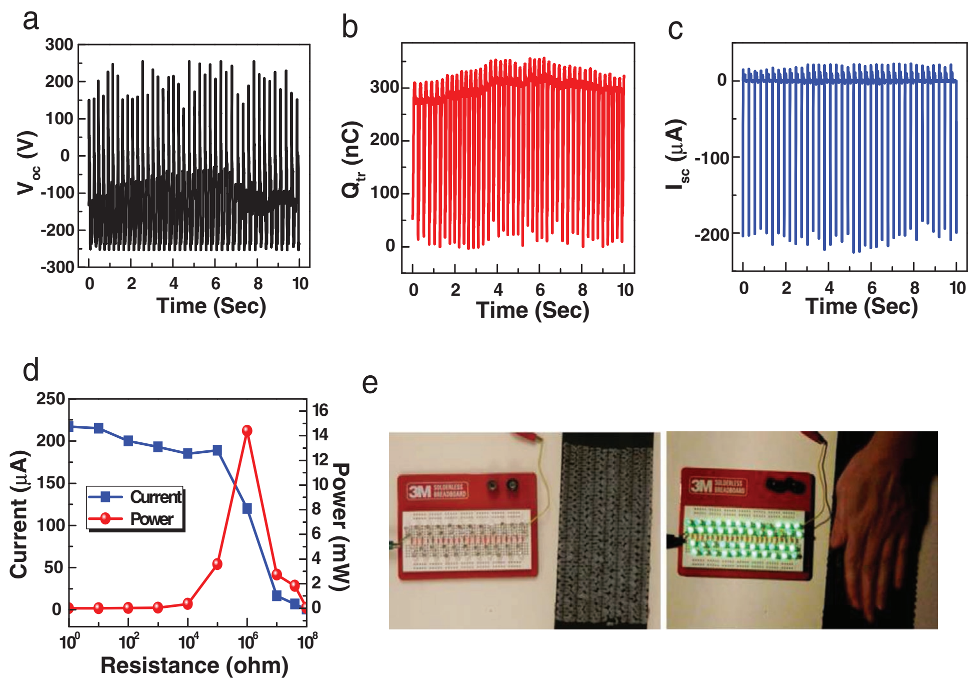

Figure 3. Performances of the serpentine-sewn SEHT. a–c) V_{oc}, Q_{tr}, and I_{sc} of the serpentine-sewn SEHT with an area of 6.5 × 3.5 in^2, respectively. d) Relationship between the instantaneous power and resistance of external load. e) Photograph showing that 48 commercial green LEDs were lit up when the device was touched.

reported textile-based TENG by using two threads or textiles, for example, the TENG woven by using parylene-Ni-coated and Ni-coated polyester strap (≈40 V, ≈20 μA),[19] the TENG woven by polyester/Ag fiber and nylon/Ag fiber (90 V, 2.5 μA),[18] fiber-based TENG fabricated by PDMS/carbon wire and polytetrafluoroethylene (PTFE)/Cu (16 V, 6 μA),[13] and the ZnO-nanopatterned textile-based TENG (120 V, 65 μA).[17] Furthermore, it is worth to note that, in our design, the device can be much more simplified in structure by using only single thread. And, the newly designed serpentine-sewn triboelectric thread allows the TENG fabricated on an elastic textile to tolerate the tension stress. Figure S4 (Supporting Information) shows the relationship between the output performances and the sizes of SEHT. The output power of the elastic SEHT was investigated by externally connecting various loads from 1 Ω to 100 MΩ in series. The output power was calculated as I^2R, where I is the output current across the external load and R is the load resistance. As shown in Figure 3d, the instantaneous output power achieves a peak value of 14 mW when the external load resistance is about 1 MΩ. Figure 3e demonstrates that the SEHT can easily power up tens of light-emitting diodes (LEDs) in series by skin touching.

The elastic SEHT was then worn on various parts of human bodies to evaluate its capability to harvest energy from different types of body motions. **Figure 4**a demonstrates that the SEHT worn on a human's elbow scavenges energy from the flexion and extension of an elbow. The producing electricity from the elbow motions enables to light up tens LEDs, as shown in Figure 4a (left) and Video S1 in the Supporting Information. Figure 4a (right) indicates that the generating I_{sc} reaches about 1.2 μA. Next, the SEHT worn on a knee can harvest energy during the knee flexion and extension, and the producing I_{sc} can achieve ≈2 μA (Figure 4b; Video S2 in the Supporting Information). For exploiting walking energy, the SEHT can wear under the foot and the I_{sc} harvesting from stepping reaches ≈25 μA (Figure 4c; Video S3 in the Supporting Information). And, the device worn on a wrist can generate electricity by hand tapping, and the I_{sc} can reach up to ≈90 μA, as shown in Figure 4d and Video S4 in the Supporting Information. These results are much higher than previous reports by two-electrode woven-structured TENG.[18] With such high output current, for the first time, the human-motion energy harvested by the textile-based TENG can be directly converted for sustainably powering a smart watch after integrating with a power management circuit,[38] as shown in Figure 4e and Video S5 in the Supporting Information.

The energy produced from the SEHT can be stored in a capacitor for later uses.[30] **Figure 5**a shows the charging curve for commercial capacitors with various capacities. The equivalent circuit of charging capacitors was shown in Figure S5 (Supporting Information). To a 2.2 μF capacitor, the charged voltage can reach up to 25 V in around 15 s. And, a capacitor with 10 μF can be charged to 5 V in around 10 s. To the capacitors with larger capacities, it takes longer time to reach a higher charged voltage; however, while the SEHT is worn on human body for a whole-day use, it can be used for storing much more electric energy. Besides, washability is an important issue for textile-based wearable electronics. The washability of the SEHT was tested by a washing machine with adding detergent for each cycle of 25 min, and the device was measured for its performance after running each cycle and drying naturally. It is worth to note that the challenges to the fabric devices include not only

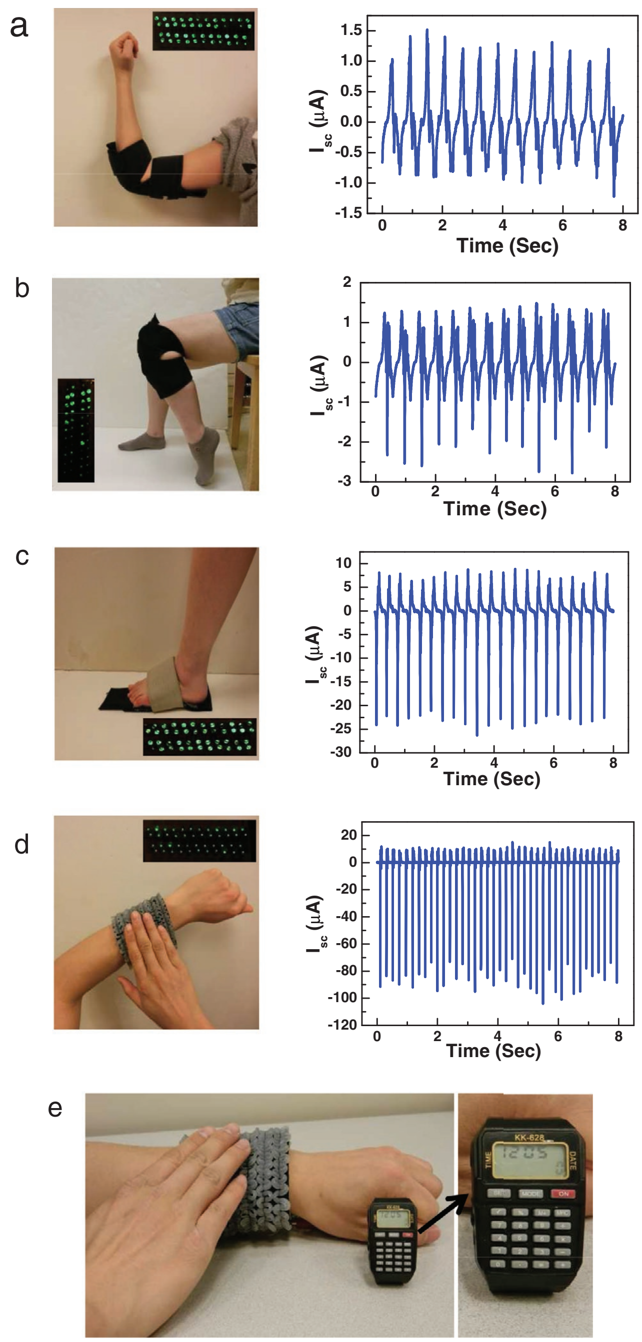

Figure 4. Evaluation of the worn SEHT to harvest different kinds of body motions. a) Left: Photo demonstrating that SEHT powers up LEDs by harvesting energy from elbow motions. Right: I_{sc} from elbow motions. b) Left: Photo demonstrating that SEHT powers up LEDs by harvesting energy from knee motions. Right: I_{sc} from knee motions. c) Left: Photo demonstrating that SEHT powers up LEDs by harvesting energy from stepping. Right: I_{sc} from stepping. d) Left: Photo demonstrating that SEHT powers up LEDs by harvesting energy from tapping on the wrist-worn SEHT. Right: I_{sc} from tapping on the wrist-worn SEHT. e) Demonstration of continuously driving a smart watch by tapping on the wrist-worn SEHT.

the reasons that the water and detergent may wash away the materials coated on the textiles but also the potential damages that may occur when continuously and strongly deforming and

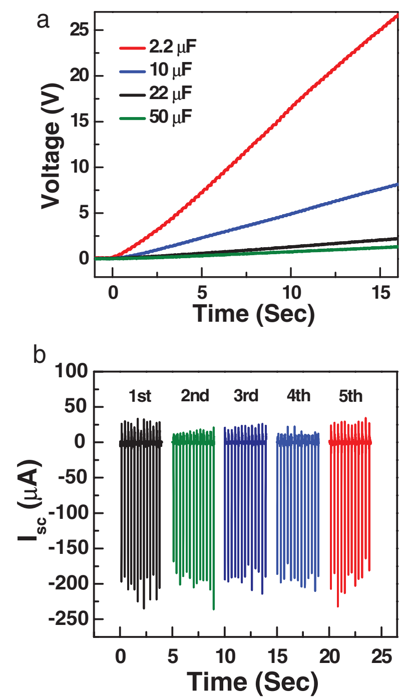

Figure 5. Evaluation of the SEHT for charging a capacitor and after washing in a washing machine. a) Charging curve of different capacitors by SHET. b) I_{sc} after different-times washing in a washing machine.

pulling the device in the washing machine drum. The results after different-times washing are shown in Figure 5b. The capability to harvest energy was well retained without significantly decline, clearly indicating its washability as well as robustness and stability, which is favorable for its practical applications.

2.3. Self-Powered Force Sensing

In addition to serving as power generators, the effective contact area to the elastic and circular surface of silicone rubber depends on the contact forces, showing their capability to sense different contact forces. The generating V_{oc} and I_{sc} were further investigated with different contact forces. Note that in order to have a standard measurement for the uses of sensing force, the triboelectric sensing thread of 1.5 cm was measured by contacting with a copper foil-attached flat acrylic plate that was applied forces by a linear motor. Figure S6 (Supporting Information) illustrates the schematic diagram for the measurement. **Figure 6**a shows a real-time measurement of the generating voltage difference response to the different applied forces by the copper-attached acrylic plate. The relationship between the generating voltage and applied forces is summarized in Figure 6b. The results show that the response voltage difference saturated to a saturation force of ≈6 N. Applied forces larger than the saturation force yield little or no increase in the producing voltages. However, in future applications, force higher than the saturation force can be detected by measuring pressures, which the force can be spread to a rigid plate. The real-time producing I_{sc} response to the different applied forces was investigated and shown in Figure 6c. The measurement was tested by applied

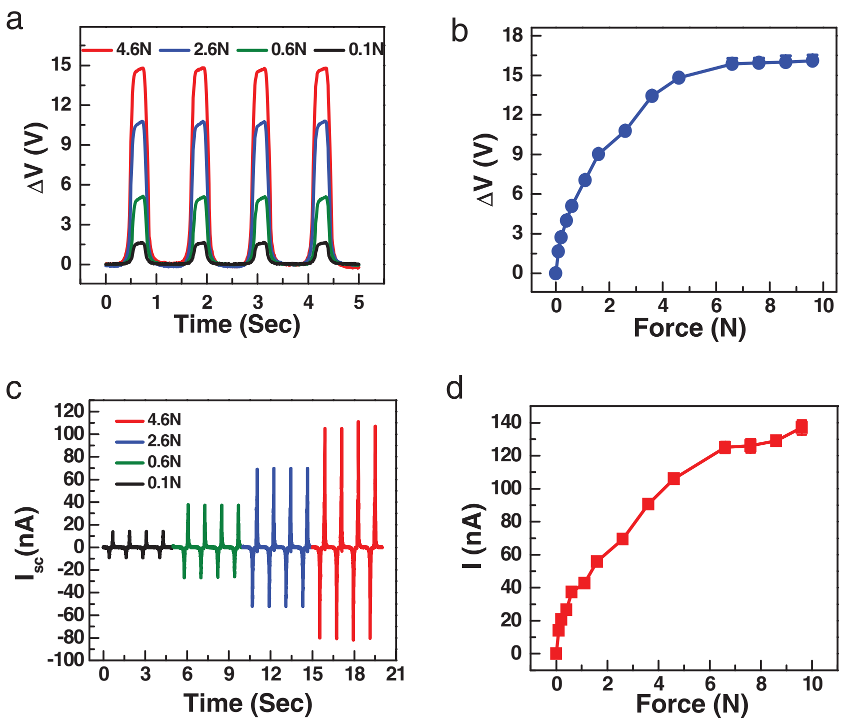

Figure 6. Evaluation of the triboelectric thread for self-powered force sensing. a) Real-time measurement of producing voltage difference responses to different applied forces. b) Relationship of producing voltage difference to difference applied forces. c) Real-time measurement of producing I_{sc} responses to different applied forces. d) Relationship of producing I_{sc} to difference applied forces.

forces at a frequency of 1 Hz. The relationship between the I_{sc} and the applied forces is summarized in Figure 6d. Although the generating I_{sc} also depends on the frequency of the applied forces (Figure S7, Supporting Information),[30] the instantaneous response can be employed for self-powered sensing dynamic movement or touching in real applications.[39]

2.4. Applications for Self-Powered Active Sensing

Due to the simplification in single thread, the sewable triboelectric thread shows superior advantages in a vast range of applications using as self-powered interactive and sensing devices. In the first embodiment, we sewed the triboelectric threads into each knuckle regions of a glove's internal (**Figure 7**a (left)). By the dynamic sensing effects, the glove can be applied for monitoring digital gestures, acting as a self-powered gesture sensing glove. As depicted in Figure 7a (right), the generating current can indicate the digit motion of a user. Moreover, the triboelectric thread can be used as a self-powered human-interactive thread (Figure 7b (left)). In this demonstration, the triboelectric thread was sewn on the back of a glove. Thanks to the static sensing behaviors,[39,40] the triboelectric thread can be applied for identifying the Morse code by detecting the generated voltage from finger touches. The generated voltage by applying temporal or static touches can be standardized sequences of short or long signals in Morse code and transmitted information from human touch to the electronic system. As shown in Figure 7b (right), the produced signals represent the phrase of "SELF POWER" in Morse code. Comparing with the tactile sensors fabricated on plastic or elastic substrates such as polyethylene terephthalate or PDMS,[41–43] the triboelectric thread possesses much more mechanical freedom and flexibility and enables to be conformal on various surfaces like curved ones or human body. Most importantly, it shows the advantages for easier integrating with cloth-based wearable articles. In addition, the triboelectric thread has been demonstrated for monitoring human pulses, as shown in Figure 7c. The wrist pulses were detected by measuring the generating V_{oc} (Figure 7c (right)). This is the first demonstration that the thread-based triboelectric sensors can be successfully used for wellness monitoring. It can foresee that the triboelectric sensing thread can apply as a wrist-wearable pulse meter after integrating into a cuff.

By integration with microcontroller systems, the triboelectric thread can be utilized as an active sensor for more sophisticated and wireless applications. Note that, here, the microcontroller systems of transmitter and receiver were powered by batteries, and the single triboelectric thread was used as an active sensor. In Figure 7d (left), we demonstrated a wireless wearable telephone keyboard, in which twelve triboelectric threads were sewn on the forearm part of a shirt. And, each sewn triboelectric thread represents a key in telephone keypad. The triboelectric thread was connected with a microcontroller system with a wireless transmitter on the circuit. Another unit with wireless receiver was designed to receive the wirelessly transmitted signals from the wearable keyboard. As shown in Figure 7d (right) and Video S6 in the Supporting Information, the triboelectric threads were served as an active key and wirelessly communicate with a computer. Last, the thread-based triboelectric sensor can be stitched into a bedspread using for wirelessly monitoring human motion on a smart bed. When human moves to the edge of bed and triggers the active triboelectric thread, the transmitter will wirelessly transmit the warning signal to the receiver by buzzing and powering up the LED to care the patient or elders, as shown in Figure 7e and Video S7 in the Supporting Information. Above demonstrations show that the energy-harvesting thread with the advantage of interactive, responsive, and adaptive can employ for designing various smart cloth-based articles. It can be expected that more promising applications can be realized by using the triboelectric thread.

3. Discussions

Compared with previous reports,[13,16–22] the device that using only "one" thread to extract human-motion energy shows several remarkable breakthroughs and advantages in fields of

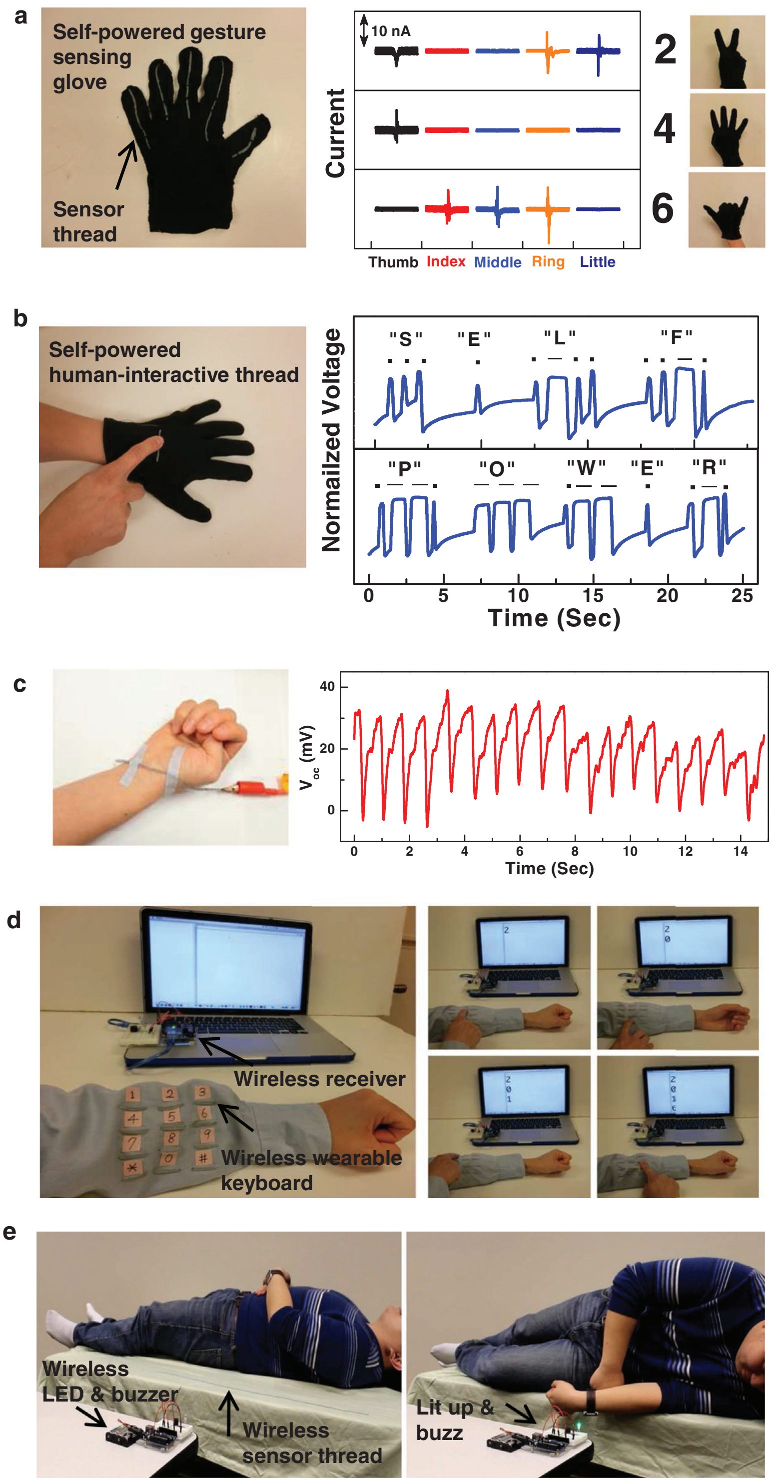

Figure 7. Demonstrations of triboelectric threads in various cloth-based sensing uses. a) Left: Photo of triboelectric threads using for a wearable self-powered gesture sensing glove. Right: Measurement results of different gestures representing the numbers of "2," "4," and "6." b) Left: Demonstration of triboelectric threads using as a self-powered human-system interaction interface. Left: Morse codes produced by touching the triboelectric thread with finger, representing a phrase of "SELF-POWER". c) Left: Photo of triboelectric threads using as a self-powered pulse-meter thread. Right: Measurement result of pulse signals from a 32-year-old female. d) Demonstrations of triboelectric threads for using as a wireless wearable keyboard. e) Demonstrations of triboelectric threads for wirelessly detecting human motion on bed.

textile-based energy harvester, sensors, and human-interactive interfaces.

First, the working scheme that using skin as one of triboelectric electrodes in textile-based energy harvesters was proposed so that the device can be efficiently simplified to one triboelectric thread. This strategy is more straightforward and efficient in both human-motion energy harvesters and thread-based human-machine interfaces. And, the generated electricity was comparable with the devices that were utilized by two threads or textiles.[13,16–22] Also, it is the first textile-based sensor that can be used for monitoring human physiological signals by only one thread, opening a door for imperceptible healthcare uses in smart clothes. Second, the super-soft silicone rubber provides a conformal contact to skin without the need of constructing nanostructure on the threads.[17,22] The simplified processes are beneficial for industrial manufacturing. Third, an in-planar serpentine structure on the elastic textile was successfully demonstrated for stretchable and endurable textile-based energy-harvesting uses. Furthermore, the single triboelectric thread can be used as self-powered sensing. Competing to resistive- and capacitive-pressure-sensing, threads suffer from the need of external battery and two threads.[24–28] Finally, the single triboelectric threads are able to integrate with microcontrollers for multifunctional uses, showing their promising uses in versatile areas such as smart garment and internet of things wearable controllers.

4. Conclusion

In summary, a single-thread-based triboelectric nanogenerator as well as a highly stretchable energy-harvesting textile and related cloth-based self-powered and active sensing applications have been demonstrated for the first time. The triboelectric thread constructed by a silicone rubber-coated stainless-steel thread can harvest human-motion energy by contact with skin. By sewing the triboelectric thread into a serpentine shape on an elastic textile, a highly stretchable energy-harvesting textile can be realized for extracting various kinds of human motions. The extracted energy by the textile-based TENG was demonstrated to be capable of sustainably driving a commercial smart watch. Moreover, the washability has been tested by a washing machine, showing its stability, flexibility, and robustness. The simplified single triboelectric thread also shows superior merits in thread-based self-powered sensing applications including gesture sensing gloves, wearable human-interactive interfaces, and thread-based wellness monitors. By integration with micro-controllers, more functional applications can be reached by the single triboelectric thread. The devices are simple yet reliable, useful, and efficient, and the processes are cost-effective and suitable for industrial manufacture. These works pave a practical way for textile-based stretchable and large-area harvesting human-motion energy, which is timely and beneficial for a wide range of wearable electronics. And, its capability in self-powered and active sensing can meet a vast variety of applications that need thread-based sensors such as wearable user-input interfaces, biomedical monitors, and smart clothing.

5. Experimental Section

Fabrication of Energy-Harvesting Thread and Elastic Energy-Harvesting Textile: Stainless-steel thread (Sparkfun electronics) was inserted into a tube and clamped at the one side of tube. Super-soft silicone elastomer (Smooth-on, Ecoflex 00-10) was prepared by mixing part A and part B with the ratio of 1:1 in weight. After mixing, the solution of silicone elastomer was degassed in vacuum for ≈5 min to remove the bubbles. Then, the solution of silicone elastomer was syringed into the tube with stainless-steel thread. Then, the other side of tube was clamped. After curing at room temperature for at least 4 h, the tube was peeled off and the silicone rubber-coated triboelectric thread can be completed. For stretchable energy-harvesting textile, the silicone rubber-coated conductive thread was manually sewn into an in-planar serpentine shape onto both faces of an elastic textile. The wavelength and straight section of the serpentine are ≈0.5 and ≈0.7 cm, respectively. And, the width of each sewn serpentine-shaped energy-harvesting thread and the elastic textile are ≈1.2 and ≈9 cm, respectively. After sewing the serpentine-shaped energy-harvesting threads to a desired length, the silicone elastomers were stripped from the end of the energy-harvesting threads to expose the conducting stainless-steel threads for further measurement.

Characterization: The SEM image of the energy-harvesting thread was characterized by a Hitachi SU-8010. The open-circuit voltage and transferred charge were measured by a Keithley 6514 system electrometer, while the short-circuit current was measured by using an SR570 low-noise current amplifier (Stanford Research System). As a wearable TENG, the electrical output performance was directly measured by practical hand tapping. As a force sensor, an external force was applied by a flat copper-foil-attached acrylic plate and controlled by a commercial linear motor for the standard measurement. The applied force was measured by Vernier LabQuest Mini.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

Acknowledgements

This work was supported by the Hightower Chair Foundation, KAUST and the "Thousands Talents" program for pioneer researcher and his innovation team, China. Y.-C.L. thanks Chao-Min Chen for her help in some experiment. Y.-C.L. thanks the funding support from the Ministry of Science and Technology, Taiwan. J.D. would like to express his sincere gratitude to the China Scholarship Council (CSC) for the support.

Received: August 29, 2016
Published online: November 3, 2016

[1] S. Choi, H. Lee, R. Ghaffari, T. Hyeon, D. H. Kim, *Adv. Mater.* **2016**, *28*, 4203.
[2] Y. Khan, A. E. Ostfeld, C. M. Lochner, A. Pierre, A. C. Arias, *Adv. Mater.* **2016**, *28*, 4373.
[3] T. Q. Trung, N. E. Lee, *Adv. Mater.* **2016**, *28*, 4338.
[4] S. H. Lee, C. K. Jeong, G.-T. Hwang, K. J. Lee, *Nano Energy* **2015**, *14*, 111.
[5] S. Bauer, S. Bauer-Gogonea, I. Graz, M. Kaltenbrunner, C. Keplinger, R. Schwödiauer, *Adv. Mater.* **2014**, *26*, 149.
[6] R. Hinchet, S.-W. Kim, *ACS Nano* **2015**, *9*, 7742.
[7] W. Zeng, L. Shu, Q. Li, S. Chen, F. Wang, X. M. Tao, *Adv. Mater.* **2014**, *26*, 5310.
[8] M. Stoppa, A. Chiolerio, *Sensors* **2014**, *14*, 11957.
[9] J. Berzowska, *Textile* **2005**, *3*, 58.
[10] A. K. Yetisen, H. Qu, A. Manbachi, H. Butt, M. R. Dokmeci, J. P. Hinestroza, M. Skorobogatiy, A. Khademhosseini, S. H. Yun, *ACS Nano* **2016**, *10*, 3042.
[11] S. Lee, W. Ko, Y. Oh, J. Lee, G. Baek, Y. Lee, J. Sohn, S. Cha, J. Kim, J. Park, *Nano Energy* **2015**, *12*, 410.
[12] Y. Zhang, Y. Zhao, J. Ren, W. Weng, H. Peng, *Adv. Mater.* **2015**, *28*, 4524.
[13] J. Wang, X. Li, Y. Zi, S. Wang, Z. Li, L. Zheng, F. Yi, S. Li, Z. L. Wang, *Adv. Mater.* **2015**, *27*, 4830.
[14] Y.-H. Lee, J.-S. Kim, J. Noh, I. Lee, H. J. Kim, S. Choi, J. Seo, S. Jeon, T.-S. Kim, J.-Y. Lee, *Nano Lett.* **2013**, *13*, 5753.
[15] N. Zhang, J. Chen, Y. Huang, W. Guo, J. Yang, J. Du, X. Fan, C. Tao, *Adv. Mater.* **2016**, *28*, 263.
[16] J. Zhong, Y. Zhang, Q. Zhong, Q. Hu, B. Hu, Z. L. Wang, J. Zhou, *ACS Nano* **2014**, *8*, 6273.
[17] W. Seung, M. K. Gupta, K. Y. Lee, K.-S. Shin, J.-H. Lee, T. Y. Kim, S. Kim, J. Lin, J. H. Kim, S.-W. Kim, *ACS Nano* **2015**, *9*, 3501.
[18] T. Zhou, C. Zhang, C. B. Han, F. R. Fan, W. Tang, Z. L. Wang, *ACS Appl. Mater. Interfaces* **2014**, *6*, 14695.
[19] X. Pu, L. Li, M. Liu, C. Jiang, C. Du, Z. Zhao, W. Hu, Z. L. Wang, *Adv. Mater.* **2016**, *28*, 98.
[20] X. Pu, L. Li, H. Song, C. Du, Z. Zhao, C. Jiang, G. Cao, W. Hu, Z. L. Wang, *Adv. Mater.* **2015**, *27*, 2472.
[21] S. Li, Q. Zhong, J. Zhong, X. Cheng, B. Wang, B. Hu, J. Zhou, *ACS Appl. Mater. Interfaces* **2015**, *7*, 14912.
[22] K. N. Kim, J. Chun, J. W. Kim, K. Y. Lee, J.-U. Park, S.-W. Kim, Z. L. Wang, J. M. Baik, *ACS Nano* **2015**, *9*, 6394.
[23] M. Shi, J. Zhang, M. Han, Y. Song, Z. Su, H. Zhang, presented at 2016 IEEE 29th Int. Conf. Micro Electro Mechanical Systems (MEMS), Shanghai, China, January **2016**.
[24] Y. Cheng, R. Wang, J. Sun, L. Gao, *Adv. Mater.* **2015**, *27*, 7365.
[25] S. Takamatsu, T. Lonjaret, E. Ismailova, A. Masuda, T. Itoh, G. G. Malliaras, *Adv. Mater.* **2015**, *28*, 4485.
[26] J. Ge, L. Sun, F. R. Zhang, Y. Zhang, L. A. Shi, H. Y. Zhao, H. W. Zhu, H. L. Jiang, S. H. Yu, *Adv. Mater.* **2016**, *28*, 722.
[27] L. M. Castano, A. B. Flatau, *Smart Mater. Struct.* **2014**, *23*, 053001.
[28] Y. C. Lai, B. W. Ye, C. F. Lu, C. T. Chen, M. H. Jao, W. F. Su, W. Y. Hung, T. Y. Lin, Y. F. Chen, *Adv. Funct. Mater.* **2016**, *26*, 1286.
[29] K. Y. Lee, M. K. Gupta, S.-W. Kim, *Nano Energy* **2015**, *14*, 139.
[30] F.-R. Fan, Z.-Q. Tian, Z. L. Wang, *Nano Energy* **2012**, *1*, 328.
[31] Z. L. Wang, *ACS Nano* **2013**, *7*, 9533.
[32] F. R. Fan, W. Tang, Z. L. Wang, *Adv. Mater.* **2016**, *28*, 4283.
[33] Z. L. Wang, J. Chen, L. Lin, *Energy Environ. Sci.* **2015**, *8*, 2250.

[34] X. Wang, L. Dong, H. Zhang, R. Yu, C. Pan, Z. L. Wang, *Adv. Sci.* **2015**, *2*, 1500169.
[35] R. C. Allen, *EE-Eval. Eng.* **2000**, *39*, S4.
[36] V. Nguyen, R. Zhu, R. Yang, *Nano Energy* **2015**, *14*, 49.
[37] X. Wen, Y. Su, Y. Yang, H. Zhang, Z. L. Wang, *Nano Energy* **2014**, *4*, 150.
[38] S. Niu, X. Wang, F. Yi, Y. S. Zhou, Z. L. Wang, *Nat. Commun.* **2015**, *6*, 8975.
[39] L. Lin, Y. Xie, S. Wang, W. Wu, S. Niu, X. Wen, Z. L. Wang, *ACS Nano* **2013**, *7*, 8266.
[40] G. Zhu, W. Q. Yang, T. Zhang, Q. Jing, J. Chen, Y. S. Zhou, P. Bai, Z. L. Wang, *Nano Lett.* **2014**, *14*, 3208.
[41] L. Pan, A. Chortos, G. Yu, Y. Wang, S. Isaacson, R. Allen, Y. Shi, R. Dauskardt, Z. Bao, *Nat. Commun.* **2014**, *5*, 3002.
[42] C. L. Choong, M. B. Shim, B. S. Lee, S. Jeon, D. S. Ko, T. H. Kang, J. Bae, S. H. Lee, K. E. Byun, J. Im, *Adv. Mater.* **2014**, *26*, 3451.
[43] S. Lee, A. Reuveny, J. Reeder, S. Lee, H. Jin, Q. Liu, T. Yokota, T. Sekitani, T. Isoyama, Y. Abe, Z. Suo, T. Someya, *Nat. Nanotechnol.* **2016**, *11*, 427.

