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ARTICLE

Harvesting Ambient Vibration Energy over a Wide Frequency Range for Self-Powered Electronics

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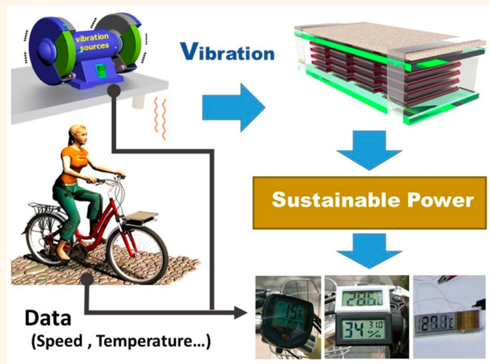
Supporting Information



ABSTRACT: **Vibration is one of the most common energy sources in ambient environment. Harvesting vibration energy is a promising route to sustainably drive small electronics. This work introduces an approach to scavenge vibrational energy over a wide frequency range as an exclusive power source for continuous operation of electronics. An elastic multiunit triboelectric nanogenerator (TENG) is rationally designed to efficiently harvest low-frequency vibration energy, which can provide a maximum instantaneous output power density of 102 W·m^{-3} at as low as 7 Hz and maintain its stable current outputs from 5 to 25 Hz. A self-charging power unit (SCPU) combining the TENG and a 10 mF supercapacitor gives a continuous direct current (DC) power delivery of 1.14 mW at a power management efficiency of 45.6% at 20 Hz. The performance of the SCPU can be further enhanced by a specially designed power management circuit, with a continuous DC power of 2 mW and power management efficiency of 60% at 7 Hz. Electronics such as a thermometer, hygrometer, and speedometer can be sustainably powered solely by the harvested vibration energy from a machine or riding bicycle. This approach has potential applications in self-powered systems for environment monitoring, machine safety, and transportation.**

KEYWORDS: *mechanical energy harvesting, triboelectric nanogenerator, elastic structure, vibrational energy*

With the increasing worldwide demand in energy, new techniques of energy harvesting to power electronics are gaining more and more attention in various fields. Specifically, sustainably driving electronics using harvested energy from ambient environment is one of the most interesting topics because it enables electronics to operate without applying an external power source and eliminates the need for replacement of batteries.[1,2] Vibration is one of the most common ambient energy sources that can be found in our daily activities, industrial plants, moving vehicles, and building structures.[3,4] There are two basic requirements for scavenging such ambient vibration energy to continuously drive electronics: one is that the energy harvesters should be able to retain a high energy conversion efficiency over a wide frequency range, especially the low-frequency range since the natural oscillation frequencies for ambient vibrations are generally under 50 Hz;[5,6] the other one is that the electricity generated by the energy harvesters should be effectively collected to the energy storage devices of the self-charging power unit (SCPU).[7−9] Several methods exist for converting vibration energy into electricity, such as the piezoelectric nanogenerators,[10−13] electromagnetic generators,[14,15] electrostatic generators,[16,17] and triboelectric nanogenerators (TENGs).[18−28] While each of these techniques can work under certain conditions, they usually suffer inevitable problems. For example, the piezoelectric coupling of the piezoelectric nanogenerator decreases very fast at micrometric scale, and most piezoelectric nanogenerators focus on scavenging energy at high frequencies (>100 Hz).[10−13] The

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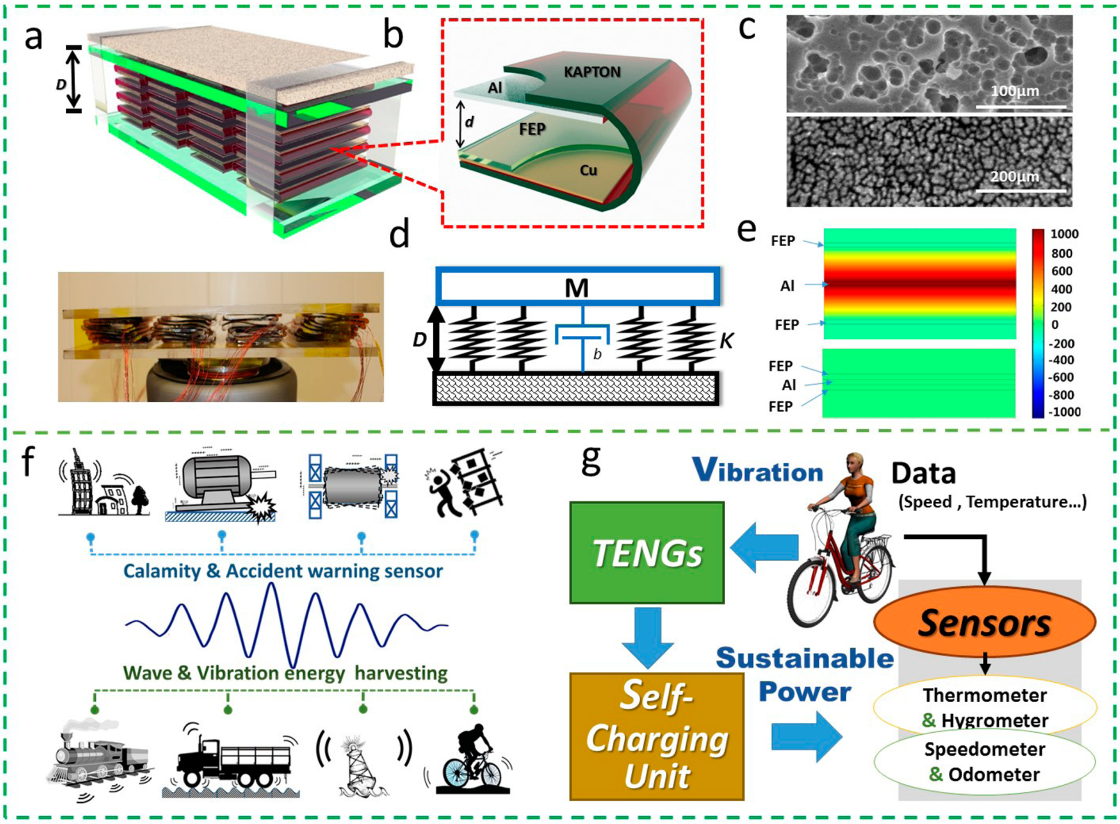

Figure 1. Device structure, basic operation, working principle, and potential application of the elastic triboelectric nanogenerator. (a) Schematic diagram and image of the fabricated multiunit triboelectric nanogenerator (TENG). (b) Detailed structure of the designed TENG. (c) Scanning electron microscopy images of nanostructures on the aluminum and FEP surface. (d) Equivalent mechanical model of an elastic TENG using the mass−spring−damper structure. (e) Simulated potential distributions of the TENG at the open-circuit condition, with the top plate at different positions. (f) Extension of this TENG-based self-powered unit for various applications. (g) System diagram of a bicycle-mounted self-powered system.

output voltage of an electromagnetic generator is generally small, and it is hard to overcome the threshold voltage of the diode rectifier when its volume is small. The recently invented TENGs that are based on the conjunction of contact electrification and electrostatic induction have been recognized as a promising approach for harvesting ambient mechanical energy, especially at low frequency, because they exhibit the desirable characteristics of simple structure, low cost, light weight, high efficiency, and high power density. TENGs have been applied to harvest vibration energy; however, the natural frequency of the previously reported TENGs is still high and the electrical outputs undergo great loss beyond the resonant frequency.[25−27] To apply ambient vibration energy for sustainable operation of electronics, efforts are needed to lower the natural frequency, enlarge the frequency range with low performance loss, and enhance the total efficiency of the SCPU that integrates the energy harvesters and the energy storage devices.[5,7]

In this work, an approach that enables sustainable operation of electronics only by harvesting ambient vibration energy is developed. An elastic multiunit TENG is designed to efficiently convert environmental vibration energy into electrical energy, with an instantaneous output power density of $102 \mathrm{W{\cdot}m^{-3}}$ at as low as 7 Hz. The SCPU combining the TENG and energy storage unit has a power management efficiency of as high as 60% and can provide a continuous direct current (DC) electricity of 2 mW on average power in a regulated manner. The high output of the TENG over a wide range and the high power management efficiency enable the SCPU to continuously power various electronics solely with the ambient vibration energy. Numerous electronics, such as a temperature/humidity indicator, and a speedometer can be continuously powered while operating an industrial machine or riding a bicycle. The harvested vibration energy can also be applied as the only power source to continuously drive a variety of environmental monitoring instruments, such as anemometers, altimeters, barometers, and water quality monitors.

RESULTS AND DISCUSSION

The structure of the multiunit TENG is shown in Figure 1a,b, which consists of four elastic multilayered TENGs in parallel. The elastic multilayered TENG used a Kapton thin film (125 μm) as the substrate and was shaped as a zigzag structure by making deformations at evenly spaced intervals, which has a small volume and light weight (5.7 × 5.2 × 1.5 cm/45 g for 15 layers). A layer of aluminum (Al) thin film and a layer of fluorinated ethylene propylene (FEP) film with deposited copper were chosen as the materials for the triboelectric layers due to the great difference of their abilities to attract electrons, contributing to optimized triboelectrification during contact. Micropores and nanowires were fabricated on the surface of the Al film and FEP film, respectively, resulting in an enhancement of triboelectric charge density (Figure 1c). Two acrylic plates were placed at the top and bottom of the generators to make

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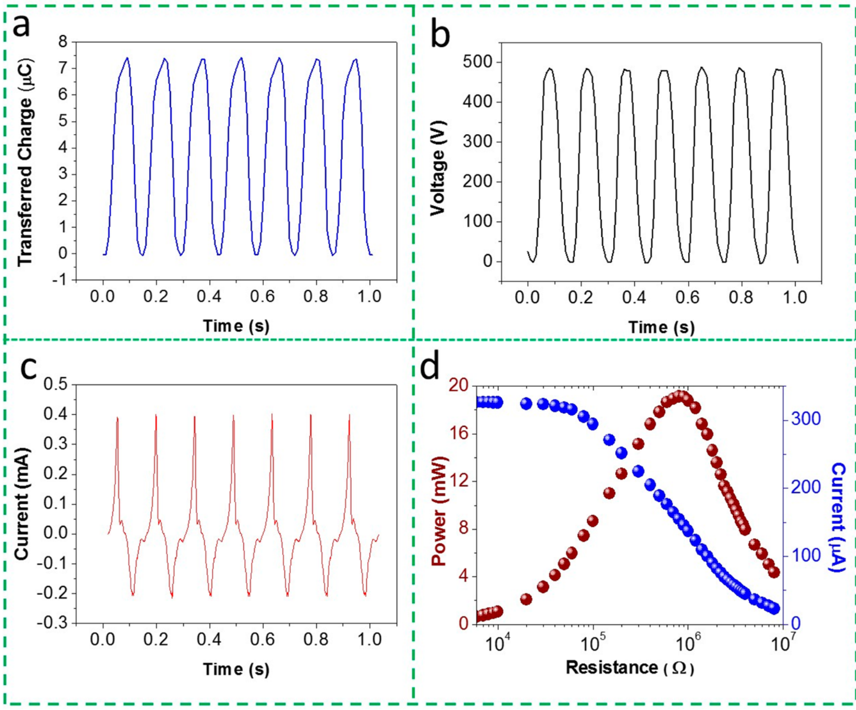

Figure 2. Electrical measurement results of TENGs at 7 Hz. (a) Measured transferred charge. (b) Measured open-circuit voltage. (c) Measured short-circuit current. (d) Dependence of the current and output peak power on the load.

most use of the mechanical force, and steel plates of different weights were overlapped on generators as a counterweight to tune the resonant frequency. The detailed fabrication process of the multiunit TENG is presented in the Experimental Section.

The elastic property of the multilayered TENG is mainly attributed to the good flexibility, light weight, and proper stiffness of the Kapton substrate, which allows the device to behave like a zigzag "spring" in response to an external vibration. The interval space D between the two acrylic plates can be concisely controlled by wrapping tape strips around both ends, ensuring the steady electrical outputs in some violent vibrating conditions. Note that decreasing D can lead to a decrease in the open-circuit voltage and short-circuit transferred charge (Figure S1). The elastic multiunit TENG can be modeled as single degree-of-freedom second-order spring–mass systems (see Figure 1d) as first described by Williams and Yates.[30] The principle of the proposed converter can be illustrated with reference to a mono-dimensional nonlinear system formed by a mass m, the damper b, and a spring with stiffness k, with the addition of an effect produced by a force F that symmetrically pushes the mass away from equilibrium. Such a system is characterized by a natural or resonant angular frequency (ω) given by

$$\omega = \sqrt{\frac{k}{m}} \tag{1}$$

In general, natural frequency ω has to be designed to match the expected ambient excitation angular frequency. Increasing the top mass m decreases some of the resonant frequencies, while increasing the spring stiffness k increases the frequency band. The vibration-impacting model introduced by Hu can be used to analyze the frequency characteristics of the elastic TENG in this paper.[25] By simply changing the mass of the steel plates on the top acrylic plate, the natural frequency of the TENG can be adjusted to match the ambient excitation angular frequency and thereby produces maximized electrical outputs.

The operating principle of the TENG is based on the coupling of the triboelectric effect and electrostatic induction.[31−33] The multilayered TENG works in a vertical contact/separation mode, which leads to little friction and abrasion of the two surfaces during the contact/separation processes and significantly enhances the durability of the device. The simulation results of the TENG and the detailed illustration for the working mechanism can be found in Figure 1e and Supporting Information Figure S1, Note 1, Figure S2, and Note 2. Intrigued by external vibration, the change in the distance between the two triboelectric layers causes differences in the electrical potential of the two electrodes in the open-circuit condition, which drives electrons to flow through the load.[34,35] Such an elastic TENG has potential applications in various areas such as machine monitoring, calamity warning, marine science, and environmental science as is schematically shown in Figure 1f. On one hand, the TENG can serve as an active sensor for sensing machine vibration and warning for potential accident, which responds to the trigger or change *via* the electrical signal generated by itself and does not need any external power source. On the other hand, with the special features of low cost, simple fabrication, high output power density, excellent robustness, and eco-friendly materials, the designed TENG is desirable to harvest ambient vibration energy and is capable of continuously powering commonly used electronics. For example, a broad range of commercial on-board sensors and electronic devices can be instantly and sustainably driven while riding a bicycle, solely with the vibration energy scavenged by the TENG, as shown in Figure 1g.

Due to the larger inherent contact area and induced capacitance, the elastic multilayered TENG has a lower matched external resistance and higher electrical outputs

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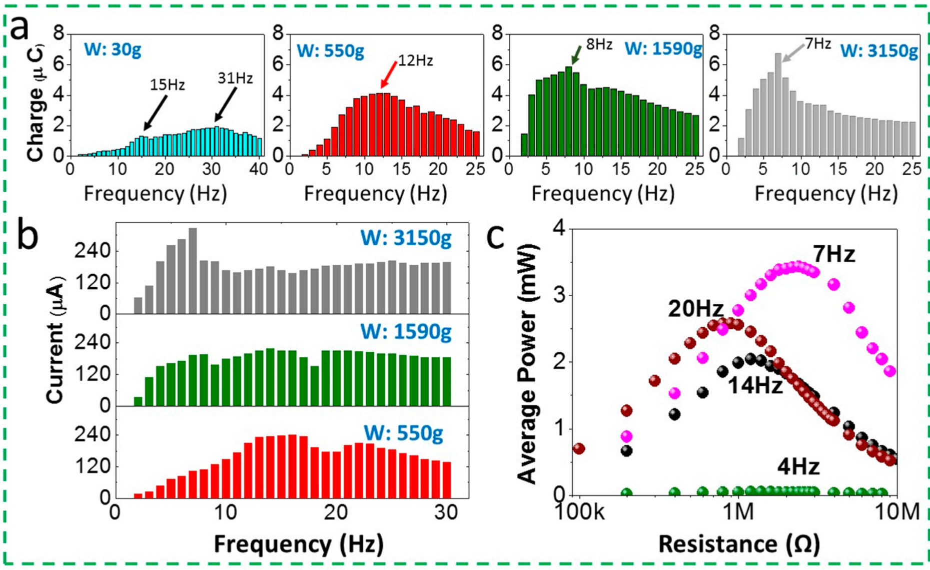

Figure 3. Electrical measurement results of the TENG under different frequencies. (a) Short-circuit charge as a function of vibration frequency with different counterweight. (b) Short-circuit current as a function of vibration frequency. (c) Dependence of the average AC output power on the external load resistance at 4, 7, 14, and 20 Hz.

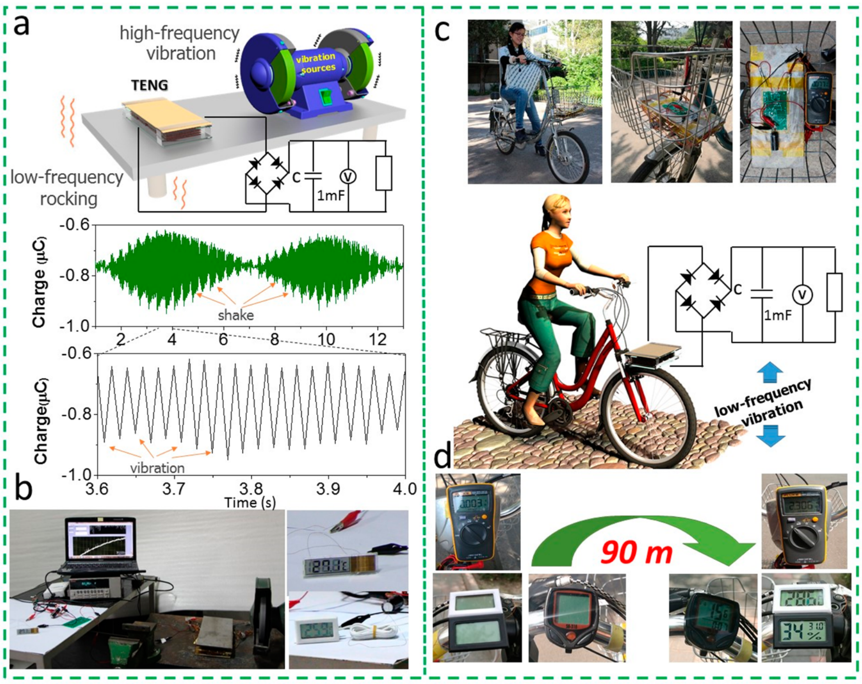

Figure 4. Harvested vibration energy as the exclusive power source for sustainable operation of electronics. (a) System configuration of self-powered sensors for monitoring the running status of equipment, based on the energy harvested from a running grinding machine. (b) Demonstration of sustainable operation for electronic temperature sensor using vibration energy harvested from a grinding wheel. (c) System configuration of a vibration energy harvesting system based on the energy harvested from riding a bicycle. (d) Demonstration of sustainable operation for electronic temperature and humidity indicator and speedometer while riding a bicycle.

compared with those of previously reported TENGs.[25−27] When the device vibrates upon a natural frequency of 7 Hz, the short-circuit transferred charges (Q_{sc}) are ~7.5 μC, the open-circuit voltage (V_{oc}) is ~480 V, and the induced short-circuit current (I_{sc}) is 0.4 mA (Figure 2a−c), respectively. Compared with Figure 1e, the open-circuit voltage in the experiment is lower than that in the simulation. This difference is because the simulation results are based on the ideal model of TENG, which ignores some nonideal effects, for example, the parasitic capacitance. It has been reported by Dai *et al.* that the ambient parasitic capacitance has a remarkable influence on the output of the TENG, which lowers the open-circuit voltage significantly.[36] The output power of the TENG depends on the load resistance, and the instantaneous power will reach a maximum value of ~19 mW (102 W·m^{-3} for volumetric power density, as shown in Figure 2d) at a load resistance of ~0.8 MΩ at 7 Hz, which is much higher than that of the previous state-of-art design at such low frequency.

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ACS Nano XXXX, XXX, XXX−XXX

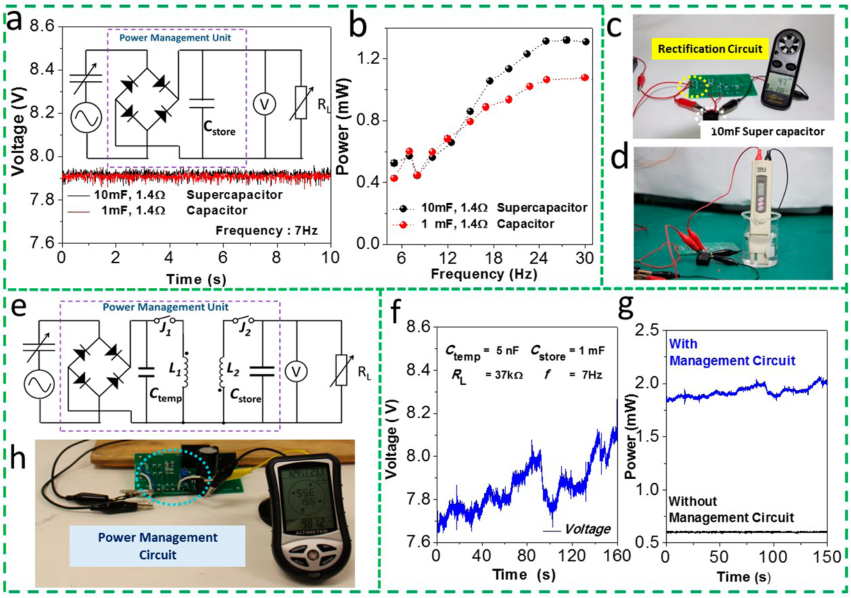

Figure 5. Power management unit design and demonstration of sustainable operation for micro-instruments. (a) Measurement circuit for continuous DC output power and power management efficiency η_{pm}. (b) Comparative study of DC outpower between a capacitor and supercapacitor as the storage device over a wide frequency range. (c) Demonstration of a vibration-powered wind anemometer. (d) Demonstration of a vibration-powered water quality analyzer. (e) Measurement circuit for continuous DC output power and efficiency η_{pm} with a specially designed power management circuit. (f) Measured DC output voltage with the specially designed power management circuit. (g) Comparative study of DC outpower with or without power management circuit. (h) Demonstration of a vibration-powered micro-meteorological instruments.

The frequency response of the elastic multiunit TENG was measured by using an external vibration shaker to guide the vibration frequency swept from 2 to 30 Hz with an increasing step of 1 Hz. Figure 3a shows the output short-circuit transferred charges depending on the weight M applied at the top of the TENG. The weights were 30, 550, 1590, and 3150 g. It is demonstrated that the natural frequency decreases slowly from 15 to 7 Hz when the applied mass increases from 30 to 3150 g. As a result, by adjusting the mass of the upper weight, the natural frequency of the TENG can be adjusted accordingly to meet different vibration needs. It should be noted that although the maximum output is obtained at natural frequency of 7 Hz when 3150 g is applied, the performance with 1590 g applied is more readily able to satisfy the requirement of stable output over a wide frequency range. In particular, the TENG maintains a high level of short-circuit current from 5 to 30 Hz, as shown in Figure 3b.

Besides the instantaneous output power, the average alternating current (AC) power P_a is another important parameter that can characterize the power performance of a TENG for a period of time. As shown in Figure 3c, the P_a at different frequencies was extracted by the TENG resistance-matching measurement (see Supporting Information Note 3 for detailed experimental configuration). The vibration frequency occurred at 4, 7, 14, and 20 Hz, and the weight applied was 3150 g. It is found that the P_a of ~3.5 mW was obtained at a natural frequency of 7 Hz and was decreased with an increased vibration frequency to 14 Hz, but when the frequency was set to 20 Hz, the output power increased again and reached ~2.6 mW. It can be seen that the elastic multiunit TENG not only has a tunable low natural frequency but also can maintain a high level of outputs over a wide low-frequency range. The reason for the multiple output power peaks of the TENG is that, besides the largest amplitude at the natural frequency, other high-order vibration modes exist and can contribute to output power peaks with the increase of the vibration frequency. This kind of characteristics enables the TENG to be effectively applied to harvest the vibration energy in ambient environment.

Since vibration energy can be found almost everywhere such as operating industrial plants, running household appliances, and traveling vehicles, the multiunit TENG has broad applications in everyday life. The TENG can serve as self-powered active sensors for vibration detection and monitoring. It was demonstrated that the TENG can visualize the mechanically loosing failure in mechanical equipment through the brightness and number of the LEDs that it lights (Supporting Information Figure S3 and Movie S1). The TENG can also precisely monitor the running status of industrial machine. As shown in Figure 4a,b, a multiunit TENG was directly put on a platform, side by side, with a high-speed grinding wheel in a factory site. The platform vibrated due to the high-speed wheel running and rocked slightly due to the unsteady placement at the same time. The output of the TENG was recorded to monitor the different types of vibration from the two vibration sources. As shown in Figure 4a and Movie S2, a series of pulse waves with low frequency of about 3 Hz were observed, corresponding to the low-frequency rocking caused by the unstable platform. The running status of the machine can also be obtained from the frequency spectrum, which has an operating frequency of 50 Hz, consonant with the rotational speed of grinding wheel (3000 rpm).

The harvested ambient vibration energy by the elastic TENG can serve as the exclusive power source for sustainable operation of electronics, which endows electronics with unlimited lifetime and eliminates the requirement for battery replacement (Figure S4). This sustainable operation of electronics was achieved by combining the TENG with a power management unit to form a SCPU (Figure 4a,c). The

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ACS Nano XXXX, XXX, XXX−XXX

power management unit converts the alternating current of the TENG into stable direct current, which usually includes a rectifier and an energy storage device like a capacitor or a battery. Figure 4b and Movie S3 demonstrate that the energy harvested from the operating industrial machine can continuously drive electronics. After turning on the grinding wheel, the voltage across the Al electrolytic capacitor (1 mF) immediately increases, and it only takes a few seconds to power the electronic thermometer. Noticeably, the voltage of the capacitor keeps rising (4 V/min) while powering the thermometer, which indicates that the harvested power is much larger than the power consumption of the thermometer. Obviously, this self-charging power unit triggered by equipment vibration can supply enough power to maintain a continuous self-powered operation of the temperature sensor.

Besides operating industrial machines, the vibration energy harvested from running vehicles can also be able to sustainably power electronics. As depicted in Figure 4c, the TENG was mounted on the front of a bicycle and the vibration energy from the vehicle bumping was utilized to sense the environmental temperature, humidity, and the speed of vehicle. As shown in Figure 4d, Movie S4, and Movie S5, energy harvested from gentle road bumping within a distance of 90 m can charge a 1 mF Al electrolytic capacitor from 0 to 2.3 V, and sensors to detect the ambient temperature, humidity, and bike riding speed can be continuously powered while riding a bicycle. Considering that vibration is always accompanied by the vehicle traveling, this SCPU can be applied for various areas such as motorsport, vehicle maintenance, and new energy vehicles.

For the SCPU, the efficiency η_{pm} of the power management unit is defined as the ratio of the maximum DC power P_d to the maximum AC power P_a. The value of P_a at different frequencies can be extracted by the TENG resistance-matching measurement (Figure 3c), and the P_d can be measured using the method shown in Figure 5a (see Supporting Information discussion Note 4 for detailed experimental configuration). As presented in Figure 5b, the DC output power and efficiency η_{pm} are high when either an Al electrolytic capacitor or a supercapacitor is utilized as the energy storage unit. At 7 Hz, the P_d values are 0.56 mW for an Al electrolytic capacitor and 0.59 mW for a supercapacitor, and power management η_{pm} values are calculated as 16.2 and 17.1%, respectively. At 20 Hz, the P_d values reach 0.93 mW for the capacitor and 1.14 mW for the supercapacitor, and the η_{pm} values are 37.2 and 45.6%, respectively. The measured efficiency is much higher than that of the direct charging system using other types of TENGs. This improvement of power management efficiency mainly originates from the low inherent TENG impedance of this design, which reduces the impedance mismatch between the TENG and the energy storage unit.[29−32] With the enhanced η_{pm} of the SCPU, electronics with higher power can be continuously driven by the harvested vibration energy. As shown in Figure 5c,d, Movie S6, and Movie S7, the SCPU integrating the TENG and the supercapacitor can sustainably power the anemometer and water quality analyzer without any external power source. This vibration-powered environmental monitoring technology has the potential to enable maintenance-free, autonomous measurement of the weather changes and environmental monitoring, even in the most difficult-to-reach areas.

The power management efficiency η_{pm} of the SCPU can be further improved by upgrading the power management unit with a specially designed power management circuit. This designed power management circuit solves the mismatch between the power requirement for electronics and the electrical outputs of the TENG and largely enhances the storage efficiency of the whole SCPU. As shown in Figure 5e, the upgraded power management unit includes a rectifier, a specially designed power management circuit, and a low-leakage energy storage capacitor. The working mechanism and charging strategy for this power management circuit has been described and optimized by Niu *et al.*[7] At 7 Hz, the upgraded SCPU can provide a continuous DC electricity of 2 mW and achieve a power management efficiency η_{pm} of 60% (Figure 5f,g), which is about three times higher than the SCPU without the designed power management circuit. As shown in Figure 5h and Movie S8, the upgraded SCPU can serve as the exclusive power source for a micro-meteorological instrument, which can be used to simultaneously measure humidity, temperature, and atmospheric pressure.

CONCLUSION

In summary, energy harvested from vibration in ambient environment was successfully applied as an exclusive power source for various electronics. An elastic multiunit TENG was designed, which has an instantaneous output power of 19 mW (102 W·m^{-3}) on a load of 0.8 MΩ at a low natural frequency of 7 Hz and can maintain a high level of output over a wide frequency range. This TENG is rationally designed to match the low-frequency external vibration. The TENG can act as an active vibration sensor to monitor the running status of equipment. Moreover, by combining the TENG with a power management unit to form a SCPU, the vibration energy harvested from ambient environment, such as an operating machine and running bicycle, can sustainably power electronics such as thermometers, humidity sensors, speedometers, and a micro-meteorological instruments. When upgrading the SCPU with a specially designed power management circuit, it can provide a continuous DC electricity of 2 mW and achieve a power management efficiency of 60% at 7 Hz. This work managed to sustainably power electronics by harvesting ambient vibration energy with potential applications in self-service equipment supervising systems, unmanned environment monitoring systems, and vehicular electronic power supply systems.

EXPERIMENTAL SECTION

Fabrication of the Elastic Multiunit TENG. A Kapton film (thickness = 125 μm, width = 5.5 mm) was shaped into a zigzag structure with 15 layers. The surface of an aluminum film (thickness = 50 μm) was modified by electrochemical etching. The aluminum film was pretreated with 0.125 mol L^{-1} NaOH solution at 40 °C for 1 min and then rinsed with deionized water. Graphite electrode plates were utilized as the cathode, and aluminum was utilized as the anode for electrochemical etching. The etching solution was composed of 3 mol L^{-1} H_2SO_4 and 1 mol L^{-1} HCl. The etching temperature and constant current density were 80 °C and 150 mA cm^{-2}, respectively. A FEP film (thickness = 125 μm) was etched by the inductively coupled plasma method. The etching time was 60 s. The reaction gases were 15.0 sccm Ar, 10.0 sccm O_2, and 30.0 sccm CF_4. Fifteen pieces of aluminum foil and FEP film were cut to the same size (width = 5 0.2 cm, length = 5.7 cm). A 30 nm Cr/300 nm Cu film was e-beam-evaporated at the backside of each FEP layer. The 15 pieces of aluminum film and FEP film were attached to the zigzag Kapton substrate by Kapton tape. The whole TENG was packaged by fixing the deformed edges of the substrate together. Four generators were placed and arranged side by side between two acrylic plates that were shaped by a laser cutter as substrates with the same dimension (width = 15 cm, length = 30 cm).

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ACS Nano XXXX, XXX, XXX−XXX

Four corners of the top and bottom acrylic substrates were connected by tape to constrain the interval between the two plates. Lead wires were utilized to connect the top and bottom electrodes for electrical measurement.

Measurement of the TENG. A field emission scanning electron microscope (SU 8010) was used to measure the surface morphologies of the etched FEP film and Al foil. To measure the electric outputs of the TENG, a programmable electrometer (Keithley model 6514) and a low-noise current preamplifier (CHI Instrument model 660B) were used. A vibration simulation system (Labworks SC-121) equipped with a vibration shaker (Labworks ET-139) was applied to simulate the motion of mechanical vibration.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acsnano.6b07633.

Figures S1–S4, Supporting Notes 1–4, and additional calculations (PDF)
Movie S1 (AVI)
Movie S2 (AVI)
Movie S3 (AVI)
Movie S4 (AVI)
Movie S5 (AVI)
Movie S6 (AVI)
Movie S7 (AVI)
Movie S8 (AVI)

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⊥X.W., S.N., and F.Y. contributed equally to this work.

Notes

The authors declare no competing financial interest.

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ACS Nano XXXX, XXX, XXX−XXX