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Research Article

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Fully enclosed hybrid electromagnetic–triboelectric nanogenerator to scavenge vibrational energy

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ABSTRACT

We propose a fully enclosed hybrid nanogenerator consisting of five electromagnetic generators (EMGs) and four triboelectric nanogenerators (TENGs). Under a vibration frequency of 15.5 Hz, one TENG can deliver a high output voltage of approximately 24 V and a low output current of approximately 24 μA, whereas one EMG can deliver a low output voltage of approximately 0.8 V and a high output current of approximately 0.5 mA. By integrating five rectified EMGs in series and four rectified TENGs in parallel, the hybrid nanogenerator can be used to charge a home-made Li-ion battery from 1 to 1.9 V in 6.3 h. By using the hybrid nanogenerator to scavenge the vibrational energy produced by human hands, a temperature–humidity sensor can be sustainably powered by the nanogenerator, which is capable of charging the 200 μF system power capacitor from 0 to 2 V in 15 s, and sustainably power the sensor in 29 s.

1 Introduction

Scavenging wasted mechanical energy from the environment has been attracting public attention because of its potential capability to support self-powered environmental sensors [1–3]. Vibrational energy resulting from common mechanical motions can be extensively found in daily life as a byproduct of car engines, air conditioners, and washing machines. Several approaches to scavenge vibrational energy have been attempted, including piezoelectric nanogenerators, electromagnetic generators (EMGs), and triboelectric nanogenerators (TENGs) [4–8]. Hybridizing two types of energy harvesting devices can effectively enhance the energy conversion efficiency; this energy can then be utilized to power some small environmental sensors. Although some hybrid nanogenerators have been implemented by harvesting wind or biomechanical energies [9, 10], no report has yet appeared on the literature concerning hybrid vibrational energy harvesting technologies to obtain self-powered sensor systems. Moreover, environmental conditions such as humidity or temperature can largely affect TENGs, resulting in decreased output performance

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[11, 12]. It is therefore necessary to develop a fully enclosed hybrid nanogenerator to avoid the effects of external environmental variables and achieve sustainable operations of some sensors.

In this study, we propose a fully enclosed hybrid nanogenerator that includes five EMGs and four TENGs to scavenge vibrational energy. Under a vibration frequency of 15.5 Hz, the output voltage of one TENG (24 V) is much larger than that of one EMG (0.8 V), whereas the output current of one TENG (24 μA) is much smaller than that of one EMG (0.5 mA). The hybrid nanogenerator has five rectified EMGs connected in series and four rectified TENGs connected in parallel, and can effectively charge a home-made Li-ion battery from 1 to 1.9 V in 6.3 h. Using the hybrid nanogenerator to scavenge the vibrational energy produced by human hands, a 200 μF capacitor can be charged in 15 s, and a temperature–humidity sensor can be sustainably powered in 29 s.

This research can constitute an important step to foster and push forward the area of hybrid electromagnetic–triboelectric nanogenerator-based self-powered sensor systems.

2 Experimental

2.1 Fabrication of the hybrid nanogenerator

The hybrid nanogenerator consists of both a triboelectric part and an electromagnetic part. The TENG is composed of five steel sheets, fixed on one end and with the other end free. Both surfaces of each steel sheet are plated with copper films, and fluorinated ethylene propylene (FEP) films are attached on the surfaces of the second and fourth sheets to be used as triboelectric material. Two acrylic squares are used to improve the deformation of the steel sheets during vibration, and sponges are used for buffering. When the device vibrates, and given that all the steel sheets can deform at different degrees, periodic contact and separation of the copper layer of one sheet and the FEP film of another sheet can be produced, inducing the TENG output. Moreover, five coils are placed on the five surfaces of the acrylic box, and two magnets are fixed at the end of the middle steel sheet.

2.2 Fabrication of the Li-ion battery

We used V_2O_5 nanomaterials as electrodes for the Li-ion battery. First, titanium sheets with a size of 1 cm × 4 cm were ultrasonically cleaned in concentrated hydrochloric acid, deionized water, and absolute ethyl alcohol for 5 min, and then dried at 80 °C for 30 min. In this work, the synthesis of V_2O_5 was based on the calcination of vanadium hydrate precursors, such as VOHs. We firstly dissolved 1 mol of NH_4VO_3 in deionized water and adjusted the pH of the solution to 2 by adding a certain amount of $H_2C_2O_4$. After being mixed thoroughly, the solution was heated in the reaction kettle at 120 °C for 12 h, with the prepared titanium slices immersed in it sideways. The titanium sheets with product on the surfaces were then washed by deionized water and absolute ethyl alcohol for several times, dried at 80 °C for 30 min, and then sintered at 400 °C for 2 h under the protection of N_2, to obtain the final product. The fabricated Li-ion battery was assembled in a protective argon atmosphere, with V_2O_5 nanomaterials working as one electrode and a Li sheet as the other electrode. A Celgard 2300 porous polypropylene film and a mixture of 1 mol/L $LiPF_6$ and ethylene carbon/dimethyl carbonate/ethyl methyl carbonate with a volume ratio of 1:1:1 were chosen as diaphragm and electrolyte, respectively.

3 Results and discussion

3.1 Device structure

Figure 1(a) depicts a schematic diagram of the fabricated hybrid electromagnetic–triboelectric nanogenerator. The TENGs are based on five cantilevers. The Cu and FEP films were attached on the cantilevers as triboelectric materials. Two magnets were fixed at the end of the middle cantilever. Five coils were attached on the five surfaces of the acrylic box. When the cantilevers vibrate, the change in distance between the magnets and the coils can induce simultaneous operation of the five EMGs. Moreover, vibration of the cantilevers can also induce periodic contact and separation between the Cu electrodes and FEP films, thus driving the four TENGs. Being subjected to the same vibration conditions, all the EMGs and TENGs

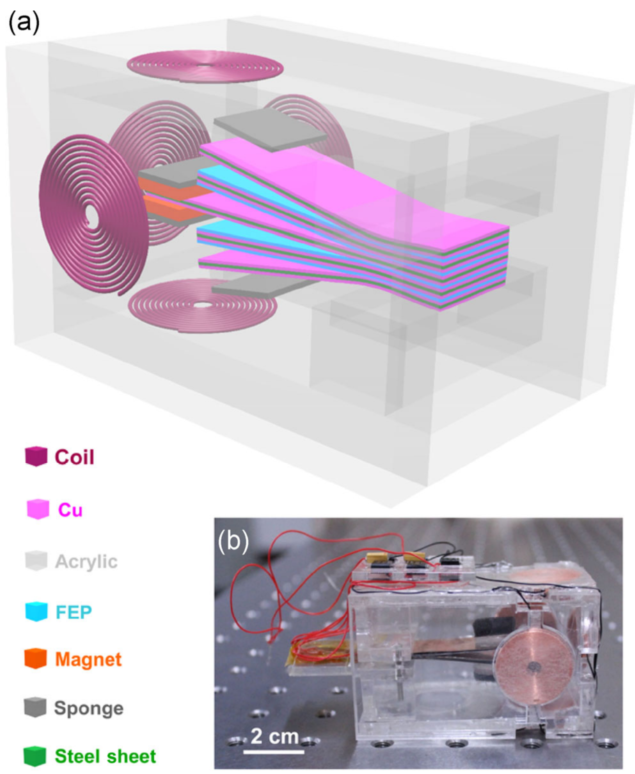

Figure 1 (a) 3D schematic diagram of the hybrid electromagnetic-triboelectric nanogenerator. (b) Photograph of the fabricated hybrid electromagnetic–triboelectric nanogenerator.

operate at the same time. As illustrated in Fig. 1(b), the fabricated hybrid nanogenerator has dimensions of 8 cm × 5.5 cm × 5 cm. The five cantilevers have a thickness of 0.1 mm, and a width of 1.7 cm; the middle cantilever has a length of 6.2 cm, whereas the other four cantilevers have a length of approximately 4.7 cm. The size of the magnets is approximately 2 cm × 1 cm × 1.5 mm. Each coil has a diameter of 2.5 cm and a thickness of 1.3 mm.

3.2 Working mechanism

Figure 2 displays the working mechanisms of the TENGs and EMGs. The flow of current is described for only one TENG and one EMG; the other TENGs/EMGs operate in the same manner. When contact between the Cu film and the FEP film is established, electrons can be moved from the FEP to Cu, as a result of their different triboelectric polarities [13]. However, these triboelectric charges are fully compensated, which results in no current/voltage signals being observed in external circuits. When the middle cantilever moves up because of vibration, a distance between the Cu and FEP films appears, resulting in a current flow caused by electrostatic induction. Moreover, the distance between the magnets and the top coil can decrease, which can also induce a flow of current in the top coil by electromagnetic induction. When the middle cantilever is moved up to the top position, the triboelectric negative charges on the FEP film are fully compensated by the positive charges on the Cu electrode on the other surface of the FEP film, resulting in no current/voltage output. When the middle cantilever is moved down, a flow of current can be observed between the two Cu electrodes, as a result of the change in distance between the Cu electrode and the FEP film. Moreover, an output current/voltage can be also observed when the distance between the magnets and the top coil changes. Finally, the middle cantilever is moved down and establishes full contact between the Cu electrode and the FEP film, thus completing a full cycle. All TENGs and EMGs can deliver their output current/voltage signals under the same vibration conditions.

3.3 Output performance of the hybrid nanogenerator

Figures 3(a) and 3(b) display the measured output current and voltage of one TENG, respectively; as shown, the TENG has a small output current of about 20 μA, and a large output voltage of about 24 V. As shown in Figs. 3(c) and 3(d), one EMG can deliver an output current of approximately 0.5 mA and an output voltage of approximately 0.8 V. Figure 3(e) shows the measured output current of the TENG under different loading resistances; as shown, the TENG has its highest output power of approximately 0.13 mW under a load resistance of about 0.8 MΩ. Figure 3(f) illustrates the measured output current of the EMG under different loading resistances; as shown, the output current decreases with the increase in the external load resistance, and the EMG has a highest output power of approximately 0.08 mW, for a load resistance close to 3 kΩ.

To increase the output current of the TENG, four rectified TENGs were connected in parallel. As depicted in Fig. 3(g), the total output current of four TENGs can be as high as 33 μA. To increase the output voltage

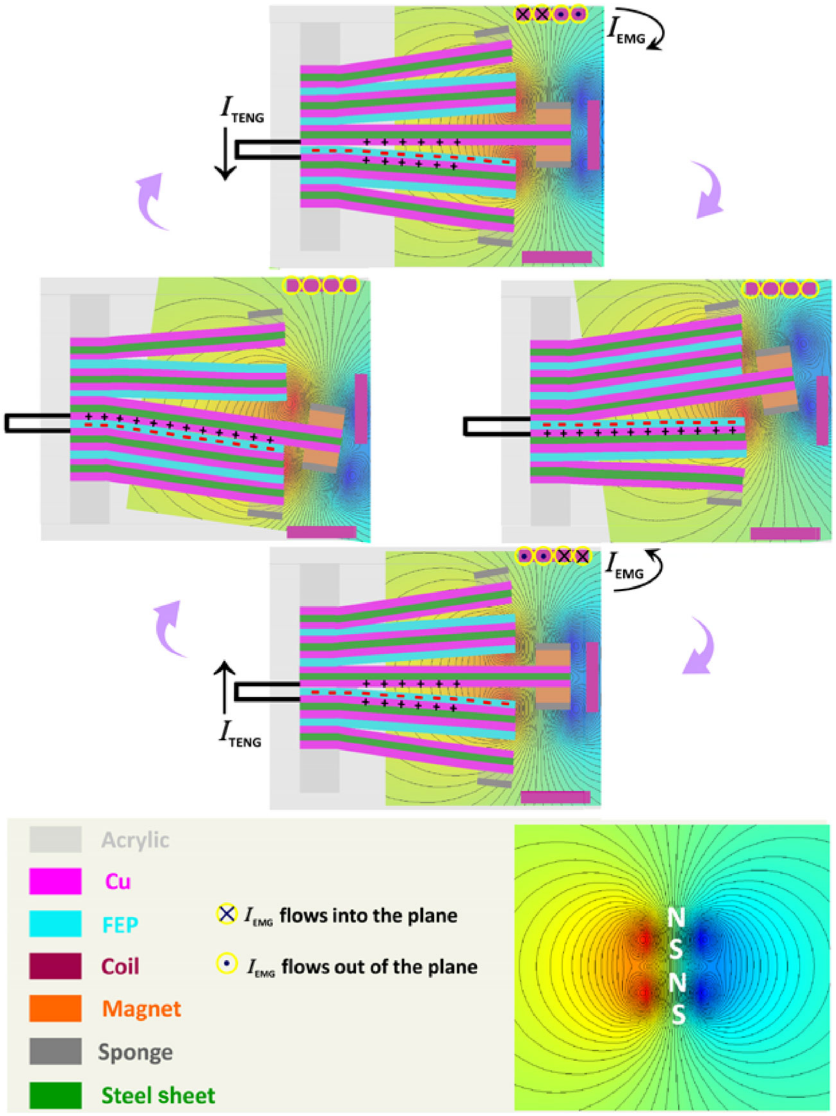

Figure 2 Schematic diagrams of the hybrid electromagnetic–triboelectric nanogenerator working principle; the 2D distribution of the magnetic field was obtained using the COMSOL software package.

of the EMG, five EMGs were connected in series; individual EMGs cannot be rectified because of their small output voltage (< 1 V). The total output voltage of the five EMGs can be as high as 2 V, as shown in Fig. 3(h). The rectified TENGs and EMGs were connected in parallel, to charge a Li-ion battery or a capacitor.

3.4 Charging a home-made Li-ion battery with the hybrid nanogenerator

To store the energy scavenged by the hybrid nanogenerator from mechanical vibrations, a home-made Li-ion battery was fabricated, with V_2O_5 nanomaterials and a Li film as anode and cathode, respectively. Figure 4(a) displays a scanning electron microscopy (SEM) image of the fabricated V_2O_5 nanosheet array. The thickness of the nanosheets is smaller than 100 nm, as shown in Fig. 4(b). Figure 4(c) displays the first time specific charge–discharge capacity curves of the Li-ion battery. The corresponding specific charge and discharge capacities are approximately 64.4 and 67.3 mA·h/cm^2, respectively, resulting in a coulombic efficiency of approximately 96%. The stable charge–discharge characteristics of the Li-ion battery are

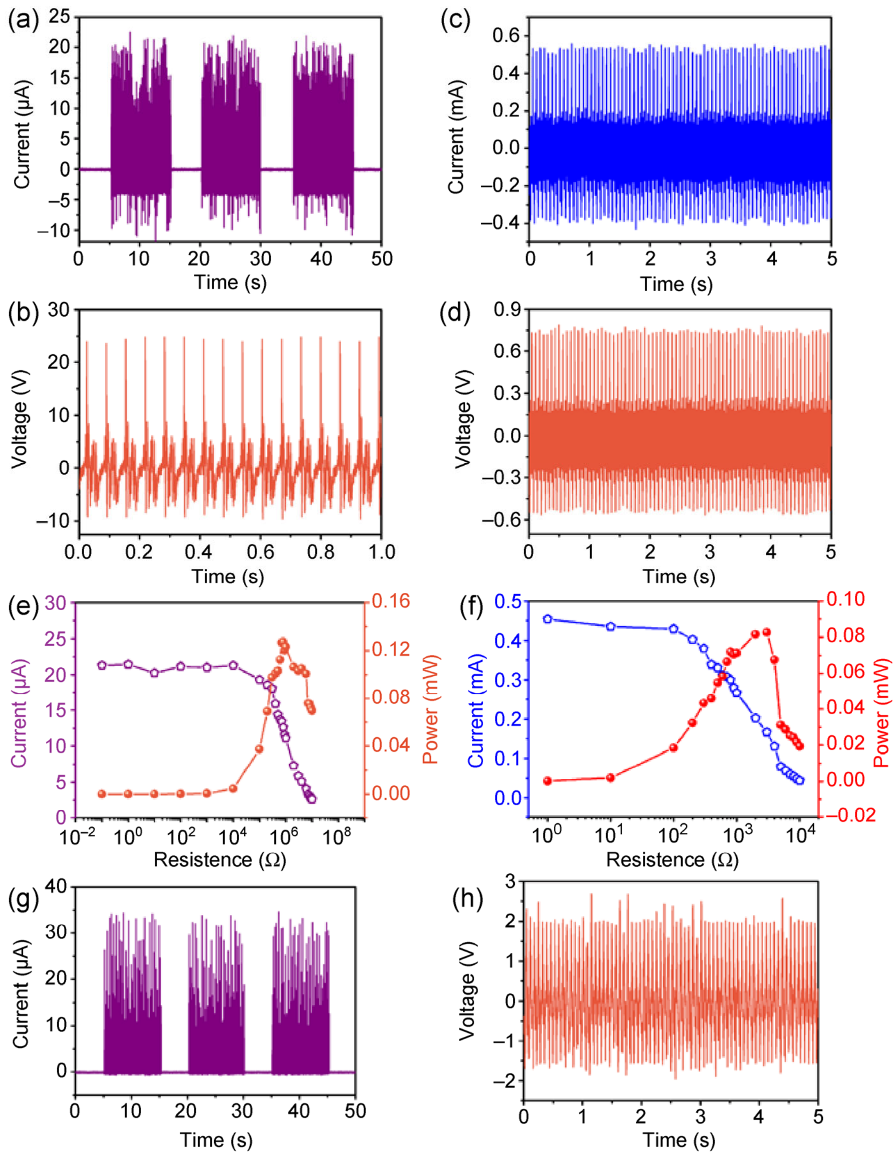

Figure 3 (a) Measured output current of one TENG. (b) Measured output voltage of one TENG. (c) Measured output current of one EMG. (d) Measured output voltage of one EMG. (e) and (f) Measured output currents and corresponding output powers of (e) TENG and (f) EMG, under different load resistances. (g) Total output current of the four parallel connected rectified TENGs. (h) Total output voltage of the five series connected EMGs.

illustrated in Fig. 4(d); the specific charge and discharge capacities after 50 times charge–discharge cycles are approximately 65.9 and 65.6 mA·h/cm^2, respectively.

We found that the voltage of the fabricated Li-ion battery can recover by itself. A controlled experiment to measure the voltage of the Li-ion battery with and without the hybrid nanogenerator charging was performed, as depicted in Fig. 4(e). As can be clearly seen, the voltage of the Li-ion battery when charged by the nanogenerator is much larger than that of the no-charge condition, indicating that the Li-ion battery can be effectively charged by the hybrid nanogenerator. Figure 4(e) illustrates the charging and constant discharging curves; as shown, the voltage of the Li-ion battery can be increased from 1 to 1.9 V after being charged by the hybrid nanogenerator for 6.3 h. Under a constant discharge current of 10 μA, the voltage of the charged Li-on battery decreases to 1 V in 2.2 h, resulting in a stored electric capacity of about 22 μA·h.

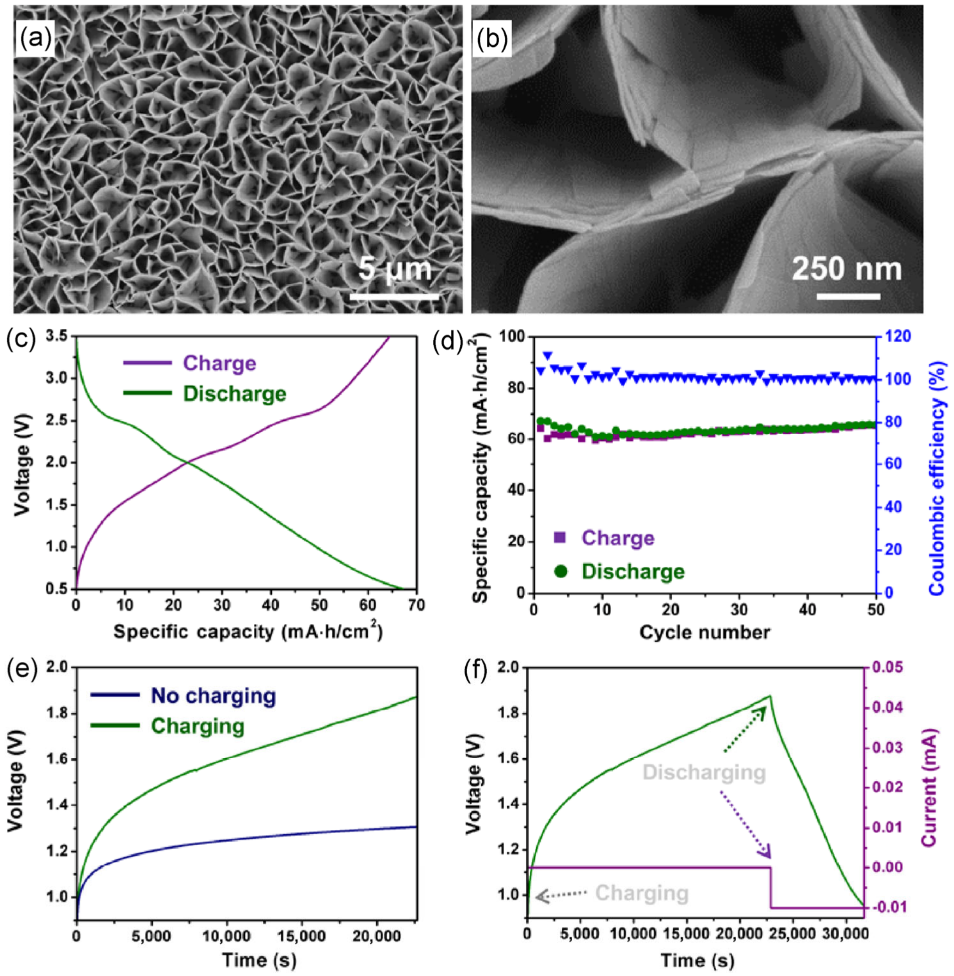

Figure 4 (a) SEM image of the fabricated V_2O_5 nanomaterials. (b) Enlarged SEM image of the V_2O_5 nanomaterials. (c) First galvanostatic discharge/charge curves of the fabricated Li-ion battery. (d) Cycling performance and coulombic efficiency of the Li-ion battery. (e) Comparison between the charging and no/charging Li-ion battery. (f) Charging and constant-current-discharging curves of the fabricated Li-ion battery using the hybrid nanogenerator.

3.5 Application demonstration: Self-powered temperature–humidity sensor

To demonstrate that the fabricated hybrid nanogenerator can be used as a power source to drive some small electronics, a self-powered temperature–humidity sensor system has been fabricated; it includes a temperature–humidity sensor, a capacitor, a bridge rectification circuit, and the hybrid nanogenerator. The hybrid nanogenerator scavenges the biomechanical energy produced by the vibration of human hands, and this energy is stored in the capacitor. The sensor can be powered up after the voltage in the capacitor rises above its working voltage.

Figure 5(a) shows that the voltage of a 100 μF capacitor can be raised from 0 to 2.2 V in 10 s, and power can be supplied for continuous operation of the temperature–humidity sensor in 20 s. As presented in Fig. 5(b), a 200 μF capacitor can be charged from 0 to 2 V in 15 s, and the sensor can be sustainably powered in 29 s. Figure 5(c) illustrates a photograph of the fabricated sensor system. As depicted in Fig. 5(d), the self-powered temperature–humidity sensor system shows that the ambient temperature and humidity are approximately 24.9 °C and 35%, respectively. The vibrational energy produced by human hands can be scavenged by the hybrid nanogenerator to sustainably power the temperature–humidity sensor, as can be also seen in Movie S1 (in the Electronic Supplementary Material).

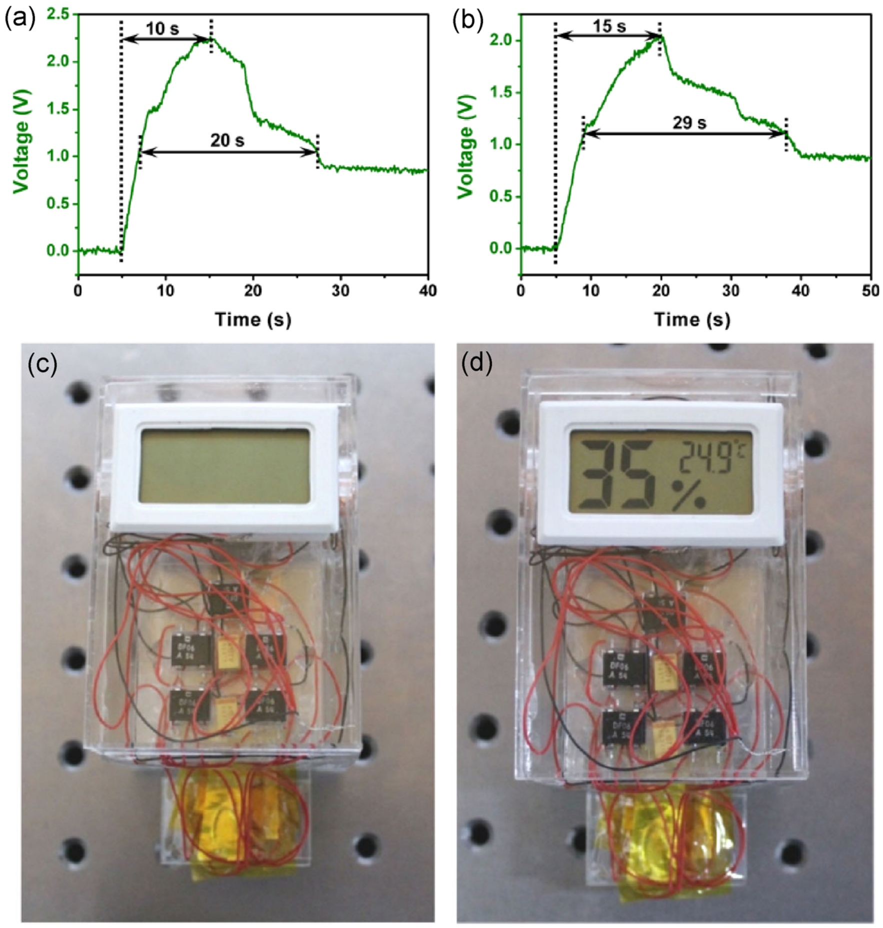

Figure 5 (a) Measured voltage of a 100 μF capacitor connected to the hybrid nanogenerator and a temperature–humidity sensor, where the hybrid nanogenerator in 10 s. (b) Measured voltage of a 200 μF capacitor that was connected to the hybrid nanogenerator and a temperature–humidity sensor, where the hybrid nanogenerator in 15 s. (c) and (d) Photographs of the self-powered temperature–humidity sensor system: (c) before and (d) after being powered.

4 Conclusion

In summary, a fully enclosed hybrid nanogenerator was demonstrated, which included five EMGs and four TENGs that can be used to simultaneously scavenge vibrational energy. A home-made Li-ion battery with a V_2O_5 nanosheet array as the anode was fabricated; this battery can be charged from 1 to 1.9 V in 6.3 h using the hybrid nanogenerator. A self-powered temperature–humidity sensor system was also fabricated; it uses the vibrational energy of human hands scavenged by the hybrid nanogenerator to charge a 200 μF capacitor (from 0 to 2 V in 15 s) and sustainably power the temperature–humidity sensor in 29 s. The hybrid electromagnetic–triboelectric nanogenerator has potential applications in vibrational energy scavenging and, in particular, in self-powered small electronics.

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Electronic Supplementary Material: Supporting information (Movie S1 showing the hybridized nanogenerator for scavenging human hands induced vibration energy for sustainably powering a temperature–humidity sensor) is available in the online version of this article at http://dx.doi.org/10.1007/s12274-016-1109-7.

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